Multi-Objective Optimization of Vertically Mixed Lateral Systems

by

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Abstract

This thesis explores the advantages of using vertically mixed lateral systems in rectangular buildings consisting of uniform bay dimensions. Three forms of lateral systems i.e. moment frames, steel cross bracings and concrete shear walls are utilized at varying elevations of the building to determine an optimal set of results. Besides analyzing structural optimality, the MATLAB algorithm developed as a part of this research paper also evaluates each system for its overall structural weight, material cost and embodied carbon. By taking a multi-objective optimization approach at the design of lateral load-resisting systems in buildings, this research devises a practical tool that can be used by designers to assess and examine the advantages and disadvantages of various layouts of lateral systems. The algorithm also enables the user to specify the location and type of certain lateral elements, which may correspond to practical architectural constraints, and juxtapose results from user-defined layouts with the optimized solution.

Key terms: Multi-Objective optimization, Vertically mixed lateral system, Composite lateral systems, Embodied carbon of lateral systems, Cost analysis of lateral systems

Thesis Supervisor: Gordana Herning
Title: Postdoctoral Lecturer of Civil and Environmental Engineering

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1. Introduction

1.1 Scope

All structures require a lateral load-resisting system integrated with a gravity system to properly carry horizontal loads, caused by wind and seismic forces, down to the foundation level. Lateral systems also increase the stiffness of the building, thus reducing deflections and improving serviceability. Lateral load-resisting systems have evolved over centuries to warrant the architectural evolution of structures. This continuous development of new systems, and the desire to build larger and taller structures, can be attributed to human's inherent desire to build lasting structural monuments.

Rigid moment-resisting frame lateral systems have been part of the building industry for more than a century, and have attained their peak popularity in tall building construction during the first half of the 20th century. Up until the 1930s, such systems were predominantly used in buildings less than 25 stories (Taranath, 2011). Around this time, engineers also developed structural systems that incorporated steel plated shear walls and staggered trusses. Nonetheless, these methods were still generally only adequate for buildings less than 30 stories, requiring innovative systems that could support taller designs (Taranath, 2011). As a result, outrigger systems were integrated into high-rise building construction over the last 35 years (Taranath, 2011). In such systems, a truss element ties an inner core to an outer shell, to improve the lateral stiffness of the structure. In more recent years, frame tube systems and bundled tube systems have been analyzed and implemented in building designs. These systems generally engage the overall three-dimensional shape of the building to develop and maximize the structure's lateral stiffness. As a result, framed tube systems and bundled tube systems are often implemented in structures that are considerably tall and require a high lateral load-resisting capacity.

Over time, three forms of lateral systems i.e. moment-resisting frames, braced frames and concrete shear walls, have emerged as common and practical options for most building designs. Moment frames are a viable solution for low-rise to mid-rise buildings. However, for structures surpassing 25 stories, the amount of materials needed to properly provide lateral stability using moment frames increases significantly. Braced frames and concrete shear walls are common choices for lateral systems in taller buildings. In some cases, combinations of various systems are utilized to provide lateral stability in structures. Schematic diagrams of concrete shear walls, cross braced frames and moment frames are shown in Figure 1-1.

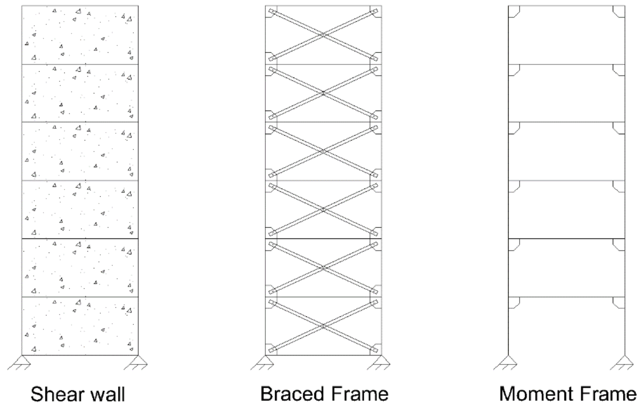


Fig. 1-1 Common Types of Lateral Systems

The choice of a lateral system is often governed by architectural decisions, site conditions and finance. However due to these interconnected parameters, lateral systems in buildings are often not fully optimized for structural efficiency. There is a large potential to push the frontier of lateral system design in buildings, and innovate a decision approach that is both efficient and practical. By analyzing the impact of critical parameters, such as i) material, ii) type of loading, iii) magnitude of loading, iv) height of structure and v) geometry of lateral systems, on structural performance and efficiency, recommendations for an optimized design procedure can be developed. These parameters can be modeled as part of a composite objective function, where the criteria are i) structural weight, ii) cost and iii) embodied carbon of structure. For this research, a series of computer generated models are created and analyzed to assess the correlations between the design parameters and each of the output parameters of the composite function. Finally, a general design method is generated that outputs the optimal solution for a lateral load-resisting system for a given set of design parameters.

1.2 Motivation

The primary motivation for this research is to develop a procedure for analyzing the options for lateral systems in buildings in a more inclusive and comprehensive manner than conventional design methods may suggest. By varying the location of lateral framing between different bays within the building, and by utilizing separate lateral systems along the height of the building, additional insight on structurally optimal solutions may be gained. This research also intends to evaluate each solution for its structural weight, material costs, and embodied carbon. In many cases, the structural weight of a building is indicative of foundation expenses. Also, costs can assess the structure's economic feasibility, while the amount of embodied carbon quantifies the structure's impact on the environment. By understanding the relationships between each of these parameters that govern the design of a lateral system in a building, design professionals can adopt a final design that holistically responds to the specific needs for the project.

1.3 Research Objective

The objective of this research paper is to formulate a procedure that analyzes and designs the lateral system of a building with rectangular and square floor plans, and with specific configurations of bays with equal dimensions, using vertically mixed lateral load-resisting systems. Three types lateral load-resisting systems: i) moment frames, ii) steel cross bracings and iii) concrete shear walls are considered at varying floors to propose an optimal layout. The optimality of the solution depends on three objective functions: i) structural weight of the lateral system, ii) material cost and iii) embodied carbon of the structure. A MATLAB (Mathworks, Version R2016b) code that accesses SAP2000 (Computer and Structures, Inc., Version 15) using CSI's Open Application Programming Interface (OAPI) is created to generate structural models for analysis. By taking a multi-objective optimization approach to design lateral load-resisting systems in buildings, this research attempts to create a practical tool that can be used by designers to assess the performance each lateral system layout based on the design criteria. The user may also compare a user-defined structure against the optimal solution, and engage in an iterative process to improve the efficiency of the user-defined design through program feedback.

1.4 Thesis Layout

This paper is divided into five main chapters. Chapter 1 serves as a general introduction for the paper. Chapter 2 provides background information on the development of lateral systems in buildings, along with literature review pertinent to the present study. Chapter 3 outlines the methodology used to conduct this research, and provides an overview of the analysis processes applied to the results. Chapter 4 summarizes the findings of the research, and discusses relevant results and their significance. Finally in Chapter 5, a summary of the paper and suggestions for future work in this field are provided.

2. Background and Literature Review

Optimization of lateral systems in buildings has been the focus of extensive research around the world. With the advent of modern computational tools and software, pioneers in the field are pushing the forefront of research on lateral systems using finite element methods and iterative processes. However, despite the improved computational capabilities, the intricate process of selecting a design for a building's lateral system remains labor intensive and time consuming. Due to factors such as architectural constraints and constructability contributing to the overall design development process, the traditional structural design procedure for a building often relies on trial-and-error and the engineers' experience and intuition.

The recent development of structural analysis and design software, coupled with advances in finite element analysis, has allowed architects and engineers to explore innovative forms. This leads to an overarching concern over a growing separation between the *designer* and the *design*. Since lateral systems in most modern buildings are analyzed primarily through computer generated models, there is an added layer of opacity between the engineer's input and resulting designs. This distancing between the engineers and their designs may lead to a disconnect between structural optimization and practicality (Chok, 2004). A primary obstacle in the path of using computer aided design software is thus a lack of integration between industry values and structural designs. Since most current engineering software are intended for response analysis of structures, they typically do not account for constructability of the structure, or overall economic feasibility of the project (Chan, 2000). While a computer-generated model may optimize the overall volume of steel used in a moment frame system, for example, it may overlook potential financial savings from using readily available steel members.

Hence the most effective methods for analyzing lateral systems in buildings rely on considering the impact from the parameters that guide the overall design process. According to Fazlur Khan (1972), the performance of tall structures depends on lateral sway criteria, thermal movements, and structural and architectural interactions. Lateral criteria for a building are predominantly governed by the building's geometry, loads, applicable codes and standards, and the type of lateral system utilized in the design process. Architectural aesthetics of tall buildings can be seen as an extension of utilizing the structural design to express a desired form. Therefore, aside from thermal movement and long-term effects, the stability and reliability of a building's lateral system can be attributed to the following three criteria:

- Design Criteria and Loading Conditions
- Building Geometry
- Type of Lateral System

The following sections delves into existing research pertaining to each of the three criteria mentioned above, and explores their contingency on the research scope of this paper.

2.1 Design Criteria and Loading Conditions

The governing design criteria play a significant role in determining the global, as well as local, design of structural elements within a building. Standardized design codes provide minimum design criteria for structural elements, and guide engineers through the design process. These design codes, such as the International Building Code (IBC) and the former Uniform Building Code (UBC) provide design guidelines that incorporate a wide spectrum of proven structural conditions. Government jurisdictions often adopt these standards with key amendments depending on prevalent local practices, occupancy considerations and loading conditions. Occasionally government agencies may issue their own design guidelines to accommodate certain conditions pertinent to specific geographic locations.

The design of a lateral system for a building is fundamentally driven based on whether the building is critical under wind loading, seismic loading, or a combination of both. While designs for taller buildings are generally governed by wind loads, low to mid-rise buildings in seismically active regions may be governed by seismic design. Choosing an adequate lateral system that addresses the external loading conditions is a critical step in the early design phase, since the choice of lateral system often guides the overall design for the building. Depending on governing loads, the lateral system for the building needs to meet both strength criteria and deflection criteria specified by design codes. While strength criteria ensure that individual elements within the building are structurally adequate to safely carry the design loads, deflection criteria and permanent deformation criteria ensure that the structure can be occupied without imposing any discomfort from short-term and long-term movements of the building. There are two primary serviceability performance constraints for tall buildings. The first constraint addresses lateral deflection under static equivalent wind loads, while the second one addresses dynamic wind-induced motion (Chan, 2000).

Wind forces generally exert pressure along both the vertical and the horizontal axes. However, in multi-story buildings with straight vertical facades, the horizontal wind force is significantly stronger than the vertical force. The vertical uplifting wind pressure is counteracted by the self-weight of the structure (Fatima, 2014). It is important to note that such a simplification of the loading conditions cannot be made for structures with sloped roofs, or with sloped or curved facades. As mentioned earlier, the wind loading on any building can be either classified as static or dynamic. Generally, if the wind gust reaches its peak value and diminishes over a time period much longer than the natural period of the building, the wind load is considered to be static. Conversely, if the wind gust reaches its peak value and diminishes over a time period shorter than the natural period of the building, the wind load is considered to be dynamic (Fatima, 2014). For the purposes of this paper, all wind loads are considered to be static.

Besides limiting deflection of the building to comfortable human standards, vibration and deflection criteria also protect non-structural components such as cladding and flooring from damage caused by excessive movement of the building (Chan, 2000). For wind loading, typically two different deflection parameters are checked. The first parameter i.e. the overall building drift ratio, is defined as the total lateral deflection at the top of the structure per unit length of the overall height of the structure. The overall building drift ratio represents the average lateral movement relative to the height of the building. However, to account for localized excessive movements, a second parameter, known as the inter-story drift ratio, is also calculated and checked. The inter-story drift ratio expresses the relative lateral movement between the top and bottom of any particular story. For any given building, the inter-story drift ratio can be expressed as (Chan, 2000):

$$d_{csl} = \frac{(\delta_{csl} - \delta_{cs-1l})}{h_s} \leq d_s^U \dots\dots\dots\dots\dots\dots\dots\dots\dots (Eq. 2-1)$$

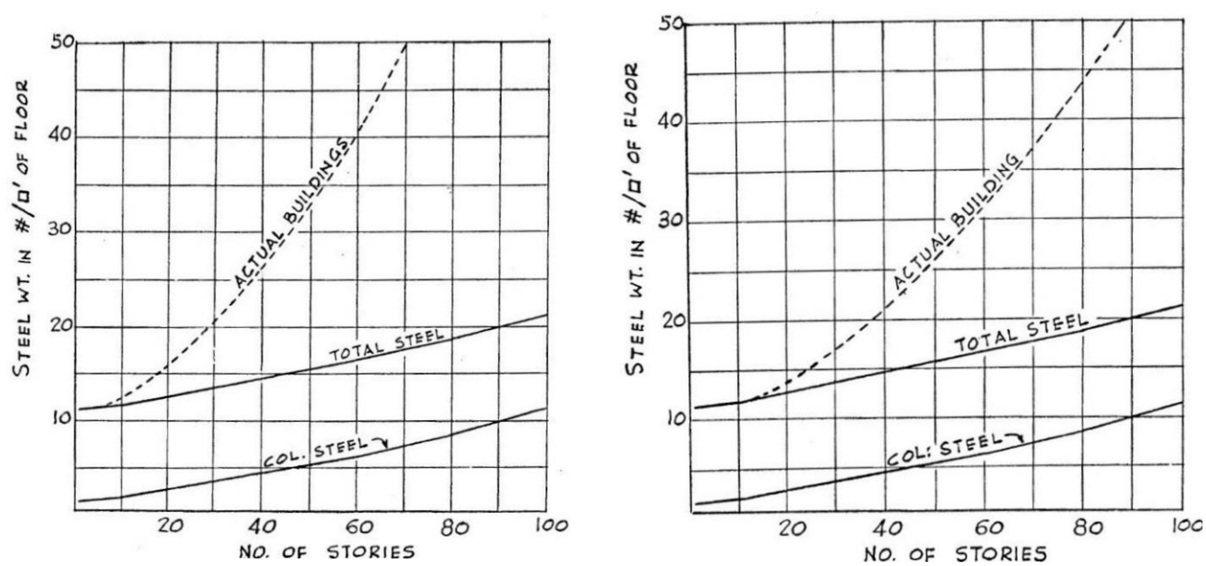
Equation 2-1 defines the inter-story drift ratio d_{csl}, where δ_{csl} and δ_{cs-1l} represent the lateral translations on a column line c at two adjacent s and s – 1 floor levels under lateral loading condition l. h_s is the height of story s, while d_s^U is the allowable inter-story drift limit (Chan, 2000).

Various structural elements may be considered to reduce deflections caused by wind loading. A study done at the Queensland University of Technology, Brisbane, Australia showed that outrigger trusses can be used to significantly reduce lateral deflections (Fatima, 2014). For a rectangular 42-story steel building, adding outrigger belt-trusses at the top and mid-height of the structure reduced lateral deflections by approximately 23% (Fatima, 2014). In contrast, adding double outrigger belt-trusses at the top and mid-height of a 57-story rectangular building reduced deflections by an average 20% (Fatima, 2014). These results support the intuitive notion that increasing the stiffness of a building's exterior increases its resistance against deflections caused by lateral loads.

Seismic loads frequently govern the design for buildings located in earthquake prone regions. Seismic loads are defined as forces transmitted to the structure through earthquake-generated excitations in the ground. Similar to wind loads, seismic loads also have a vertical component that is ignored for design purposes. Seismic design, as outlined by American Society of Civil Engineers (ASCE) 7-10, is governed by a series of parameters that encompass site soil condition, weight of the building, and frequency of exposure and intensity of seismic activity. The same research from Queensland University of Technology by Fatima (2014) that analyzed the effects of belt-trusses on deflection caused by wind loads also analyzed the effects of similar laterally bracing belt-truss structures on deflections caused by seismic loads. For the same 42-story rectangular building that was analyzed under wind loading, adding outrigger belt-trusses at the top and mid-height of the structure reduced lateral deflections caused by seismic loads by approximately 17% (Fatima, 2014). Similarly, adding double outrigger belt-trusses at the top and mid-height of the 57-story rectangular building reduced deflections by an average 15% (Fatima, 2014). It is important to note that the reduction in deflection is considerably lower under seismic loading compared to wind loading, as seismic loading is not a static linear load applied in a constant direction on the structure. To further reduce deflections due to seismic loads, base isolators can be used to decouple the structure from the ground, and minimize horizontal agitation of structural elements. Structural fuses can also be implemented to absorb seismic forces through controlled plastic deformations, while preventing damage to primary structural elements.

2.2 Building Geometry

Alongside design criteria and loading conditions, the geometric parameters of a building play an important role in determining the structure's overall response to gravity loads and lateral loads. The most significant factor affecting the design of lateral systems in buildings is the height-to-width ratio (Khan, 1965). If the floor plan and lateral support of a building are kept constant, while the height is increased, the weight of structural elements required to satisfy strength requirements and drift requirements gradually increases. Figure 2-1a plots the relationship between the amount of steel required versus the height of a building assuming three bays of lateral resistance. As the graph suggests, beyond 8 stories, the amount of steel required to provide sufficient lateral stiffness surpasses the amount of steel required for gravity design. However, the drift of a building can be reduced by adding more lateral load-resisting bays along the direction of the loading. Figure 2-1b shows the relationship between the amount of steel required versus the height of a building assuming five bays of lateral resistance. By adding two additional bays of lateral resistance, the height at which the amount of steel required to provide sufficient lateral stiffness matches the amount of steel required for gravity design increases to 12 stories (Khan, 1965).

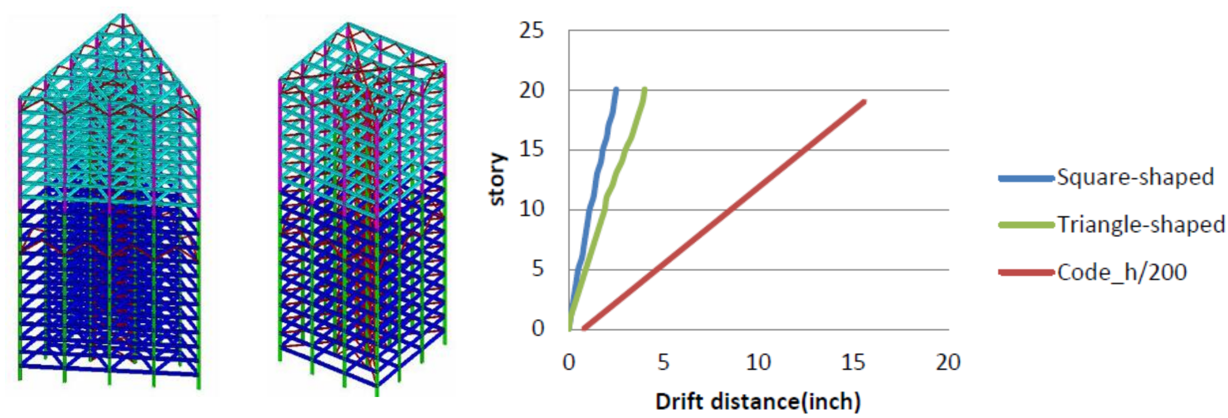


(a) 3 Bays of Lateral Support

(b) 5 Bays of Lateral Support

Fig. 2-1 Relationship Between Weight and Building Height (Khan, 1965)

For most conventional steel buildings, the practical limit for height-to-width ratio is around 7 (Khan, 1965). Beyond this limit, conventional lateral systems become excessively expensive. Another important geometric factor that drives the lateral design of a building is the plan layout of the structure. Although various plan layouts may be chosen for a building due to site constraints and architectural reasons, the geometry of the floor can significantly impact the magnitude of load induced in the lateral system. The orientation of loading with respect to the geometry of the structure is a significant consideration for lateral systems. While loading along the axis of mirror symmetry creates pure translation along the vertical plane of the building, asymmetrical loading induces torsion within the structure. O'Connor (2012) studied the impact of wind loads on different floor layouts. Two 20-story structures, one triangular and one rectangular, of roughly the same floor area were subjected to wind loads along their axis of mirror symmetry. Isometric views of the two models are shown in Figure 2-2a, while their response to the lateral loading is shown in Figure 2-2b.



(a) Isometric View　　(b) Drift of Triangular and Rectangular Buildings

Fig. 2-2 Systems and Drift of Triangular and Rectangular Buildings (O'Connor, 2012)

As Figure 2-2b suggests, the triangular building experiences a greater deflection compared to the rectangular building when subjected to the same lateral loading. However, as mentioned earlier, these results do not account for torsion induced by asymmetrical loading. To design buildings for natural wind loading conditions, ASCE 7-05 states that certain wind load cases with asymmetrical loading need to be analyzed as part of the design process for lateral systems. The study by University of Southern California by O'Connor (2012) also analyzed the impact of asymmetrical loading on torsional effects on buildings with different floor geometries. ten different geometries, shown in Figure 2-3, were subjected to asymmetrical wind loads of equal magnitude.

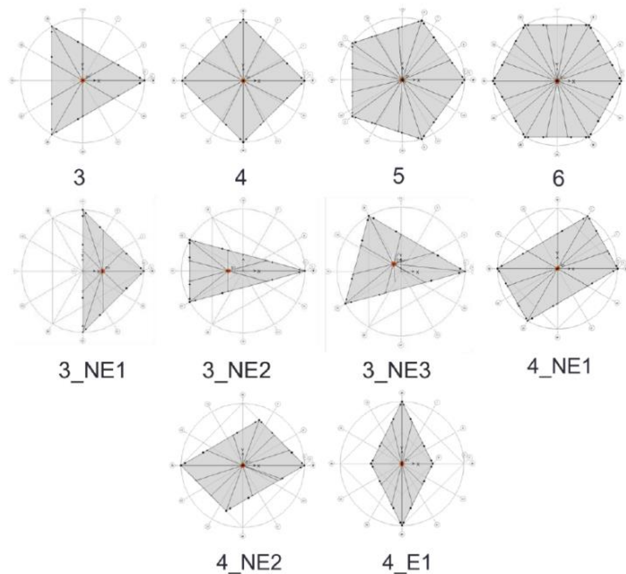


Fig. 2-3 Geometric Floor Layouts (O'Connor, 2012)

The torsional effects on buildings with the floor geometries shown in Figure 2-3 are summarized in Figure 2-4. As indicated in Figure 2-4, the highest torsional effects occurred in shape 3_NE2, which has the highest height-to-width ratio. This is likely due to the structure's center of stiffness being furthest away from its center of mass compared to the other shapes.

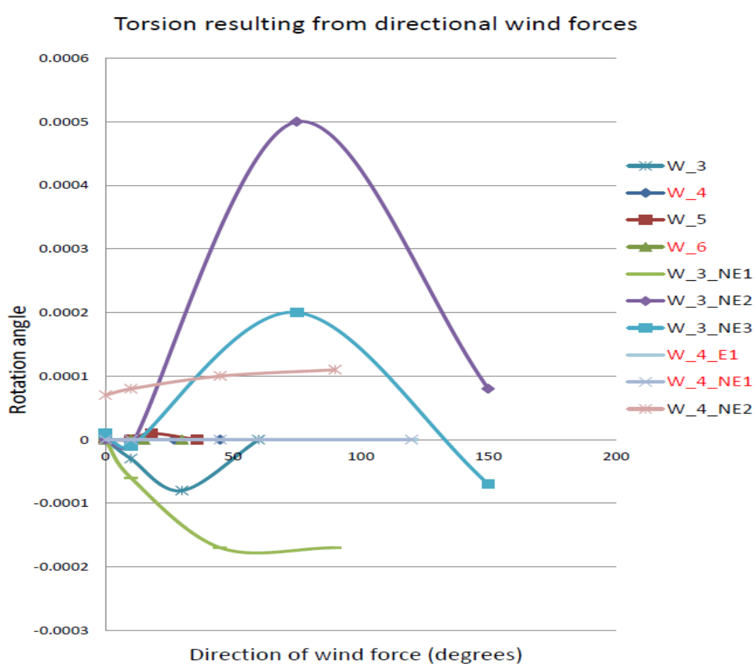


Fig. 2-4 Torsional Effects on Geometric Floor Layouts (O'Connor, 2012)

2.3 Type of Lateral System

Structural engineers have developed several lateral load-resisting systems to provide lateral stability and stiffness for building construction. As buildings are built taller and narrower, engineers often challenge the limits of these systems to meet necessary drift and strength requirements, while minimizing the impact on architectural elements (Chok, 2004). This continuous drive towards lateral systems that efficiently provide load paths and additional capacity has given rise to distinct systems that have their unique advantages and disadvantages. While some of these systems have been implemented with consistency over a long period of time, other more experimental systems are only used to meet specific structural and architectural demands. The primary types of lateral systems commonly used in building construction can be classified into the following categories:

- Steel Moment Frames
- Steel Braced Frames
- Concrete Shear walls
- Composite Systems

2.3.1 Steel Moment Frames

Steel moment frame construction is defined as a form of lateral load-resisting system where the lateral load is transferred along a column line through continuous moment-resisting connections between the column elements and girders (Chok, 2004). Moment connections are frequently seen in low-rise to mid-rise buildings made in the first half of the 20th century. Moment framed lateral systems provide some appealing advantages that make it a suitable choice for many low-rise to mid-rise buildings. The repetitive layout across different floors and bays allow for simple construction procedures. However, the biggest advantage of moment frames is the unobstructed bays that allow for flexible orientation and location of openings in walls.

Moment frame construction also has several disadvantages. For example, the excessive amount of fixed-end connections between girders and columns requires costly on-site field welding. Moment frames also result in large fixed end moments in the columns and girders, leading to large element cross sections. In addition, since the gravity system and lateral system in a moment framed structure are combined into a single system, floor beam and girder sizes need to change over the height of the building, creating an iterative design process.

The biggest disadvantage of a moment frame lateral system is that it is only a practical solution for low-rise to mid-rise buildings. As the height of the building increases, the amount of steel required to meet drift requirements increases significantly. As a result, in taller buildings, the amount of steel required to meet stiffness and drift requirements significantly outweighs the quantity of steel required for strength design only. A study conducted at Northwestern University by Chok (2004) found that for a 20-story building with rectangular plan and moment frames, the volume of steel required to satisfy drift criteria was roughly 350% higher than the volume of steel needed to only meet strength criteria. This discrepancy grew larger as the height of the building increased. The findings of the study are summarized in Figure 2-5.

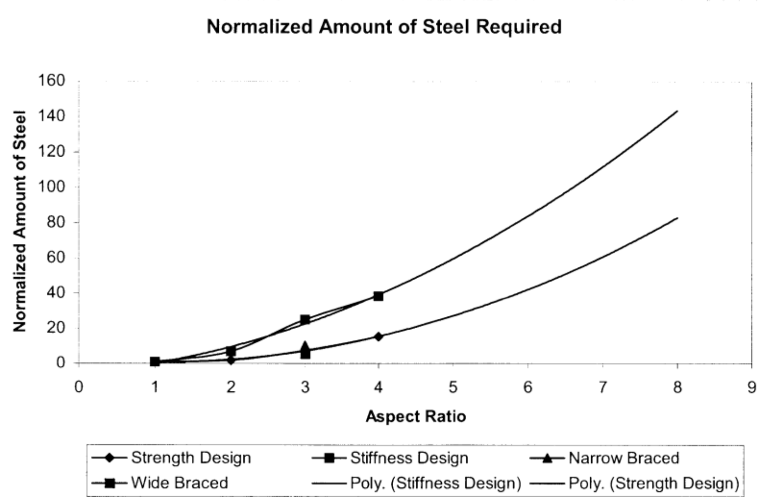


Fig. 2-5 Relationship Between Aspect Ratio and Volume of Steel in Moment Frames (Chok, 2004)

2.3.2 Steel Braced Frames

Another common type of lateral load-resisting system that utilizes steel elements is a steel braced frame system. The term braced frame incorporates several different design methods, including but not limited to vertical single-story bracing, vertical multi-story bracing, belt-trusses and horizontal bracing. Braced frames can be employed for a wide variety of building geometries, ranging from low-rise to high-rise structures. Steel braced frames can also be used in conjunction with other lateral load-resisting systems such as concrete shear walls to provide additional lateral stability. For the purposes of this paper, only research on vertical steel braced frames is considered.

The biggest advantage of steel braced frames is that it relies on axial capacity of structural elements rather than flexural capacity, thus yielding on average much higher efficiency relative to moment frame systems (Chok, 2004). The separation between the gravity system and the lateral system of the structure also expedites the design process, and allows the repetitive design of floor elements for typical floors. Furthermore, braced frames generally require less on-site labor intensive welding and bolting, thus reducing the overall cost of the project (Chok, 2004).

One major disadvantage of braced frame systems is that it often interferes with architectural constraints by occupying large areas in elevation. However, this disadvantage may be counteracted by the fact that a separation between the gravity system and the lateral system in a building allows for larger column spacing, thus increasing architectural flexibility. In many cases, such as the John Hancock Center in Chicago and the Bank of China Tower in Hong Kong, the structural form of braced frames was adopted as a part of the architectural design.

Chok (2004) also analyzes the effects of aspect ratio on the overall volume of steel needed for a braced frame system. The study reveals that unlike moment framed lateral systems, the additional volume of steel required in a steel frame building is relatively low with an increase in aspect ratio. The comparison between a strength design and a stiffness design for 30-story buildings with varying aspect ratios is shown in Figure 2-6.

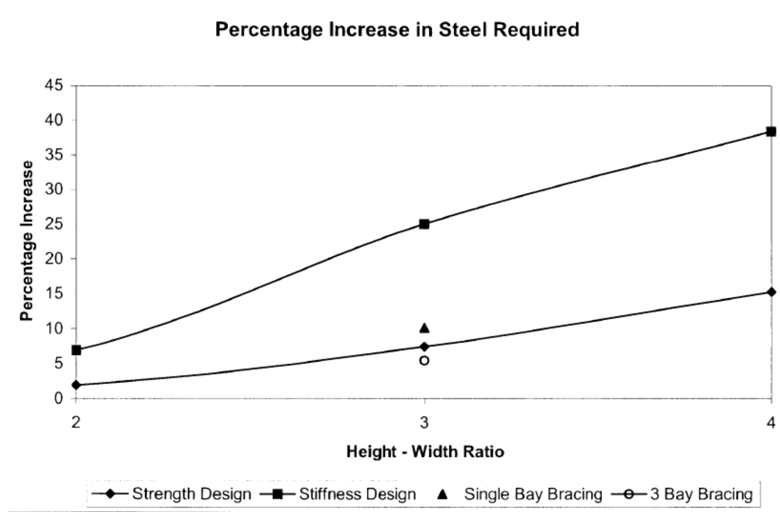


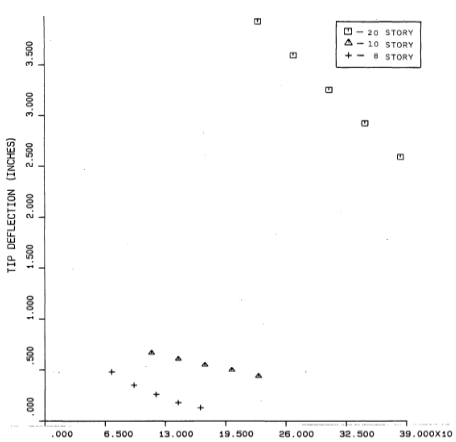
Fig. 2-6 Relationship Between Aspect Ratio and Volume of Steel in Braced Frames (Chok, 2004)

In comparison to a building with identical geometry and a moment framed system, the building using braced frame system required approximately 450% less steel. This trend explains the use of braced frame design in tall buildings, such as the John Hancock Center, which only uses 29.7psf of steel per unit area of the building despite having a large aspect ratio of 7.9 (Chok, 2004).

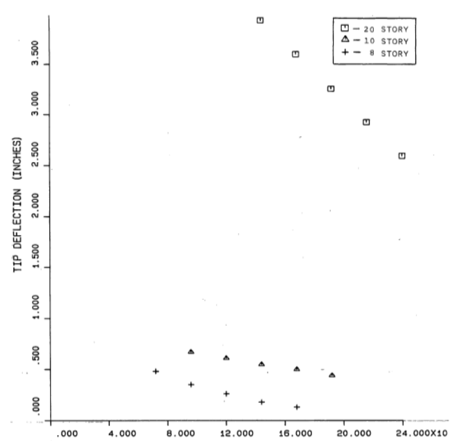
2.3.3 Concrete Shear walls

For taller buildings that draw a substantial amount of lateral force, concrete shear walls may be used in lieu of heavy steel framing to provide lateral stiffness. Many buildings that utilize a steel framing system for gravity loads also contain concrete shear walls, often arranged as a structural core, to increase resistance to lateral loading. Shear wall-braced frame interaction often leads to a reduction of internal design moments within the wall (Brun & Kostem, 1986). In most cases, shear walls can be subjected to additional moments from lateral loading within a 33% increase in allowable stresses in the shear wall (Brun & Kostem, 1986).

Arguably the biggest advantage of concrete shear walls is their relative low cost. While structural steel fabrication and connections may add a significant cost to the project's budget, cast-in-place concrete shear walls can achieve the same lateral performance at a fraction of the cost. Architecturally, shear walls may also be used to frame stairwells and elevator openings, thus removing them from usable floor space. Brun and Kostem (1986) analyzed different geometric parameters of a shear wall, and their impact on the building's global drift. As Figure 2-7a and 2-7b suggest, both the surface area and length of a shear wall are intuitively inversely proportional to deflection of the structure (Brun & Kostem, 1986).



(a) Global Drift vs. Shear Wall Area



(b) Global Drift vs. Shear Wall Length

Fig. 2-6 Relationship Between Global Drift and Shear Wall Area and Length (Brun & Kostem, 1986)

Although concrete shear walls are a popular and effective lateral load-resisting system for many buildings, they also have noticeable disadvantages that need to be accounted for in the design process. Since shear walls rely on shell action to transfer loads, it is often structurally inefficient to cut openings in them. This may pose many architectural constraints that need to be addressed early on in the conceptual design phase (Brun, 1986). Also, since it uncommon to step or transfer structural cores along the height of the building, the location of the interior shear walls plays a significant role in the architectural and structural design of the building.

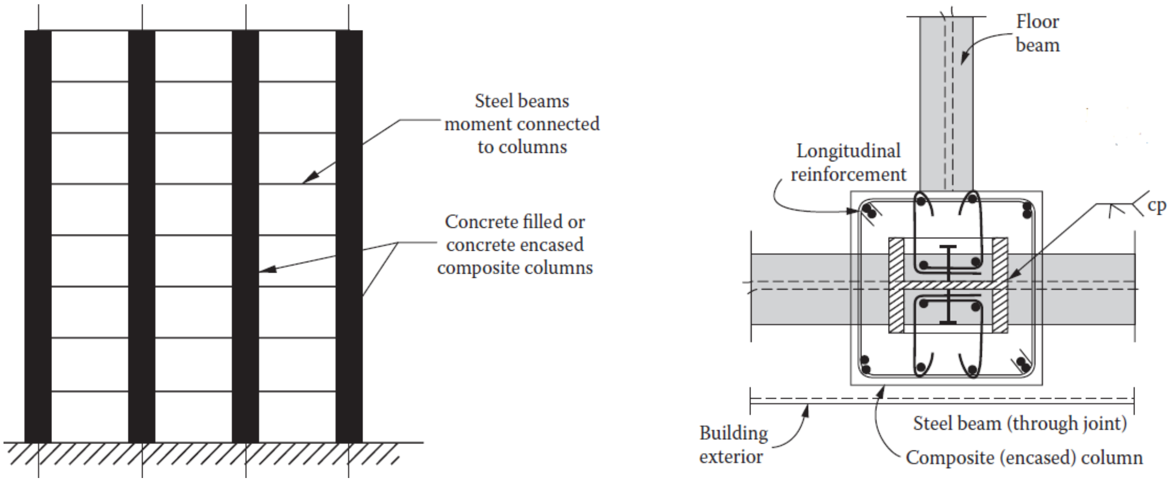
2.3.4 Combined Systems

In many instances, a lateral load-resisting system for a building that is made predominantly either from steel or concrete may not satisfy all the design requirements for the structure. In other cases, designers may choose an atypical lateral system to address specific structural and architectural needs. For such scenarios, combined lateral systems may be considered. Combined systems can be defined as a mixed system of steel and concrete structural elements, where the different components act conjointly as part of a single system. Combined steel and concrete construction has been used in the United States for over a century, with its first appearance in 1894 for an arch bridge in Rock Rapids, Indiana designed by engineer Josef Melan (Taranath, 2011). In the building design industry, combined lateral systems are classified into two major categories:

- Composite Systems
- Vertically Mixed Systems

2.3.4.1 Composite Systems

Composite lateral systems are defined as a broad spectrum of lateral load-resisting systems where the steel and concrete elements exhibit composite behavior, induced by encasement or steel studs in concrete. Such systems may use any combination of composite beams, columns or shear walls to transfer lateral loads between elements. By using composite elements, designers often bypass the disadvantages of systems consisting primarily of a single material. For example, in the United States, composite lateral systems in areas of low seismic activity mainly consist of welding steel beams to concrete encased steel columns (Taranath, 2011). These laterally braced bays are often located along the edge of the building to maximize the global stiffness of the structure (Taranath, 2011). Such a system provides the advantage of having open bays as steel moment frames discussed in section 2.3.1, while also minimizing the excessive amount of steel required to meet deflection criteria. Figure 2-8a and 2-8b show a typical elevation and connection detail for a composite lateral system, respectively.

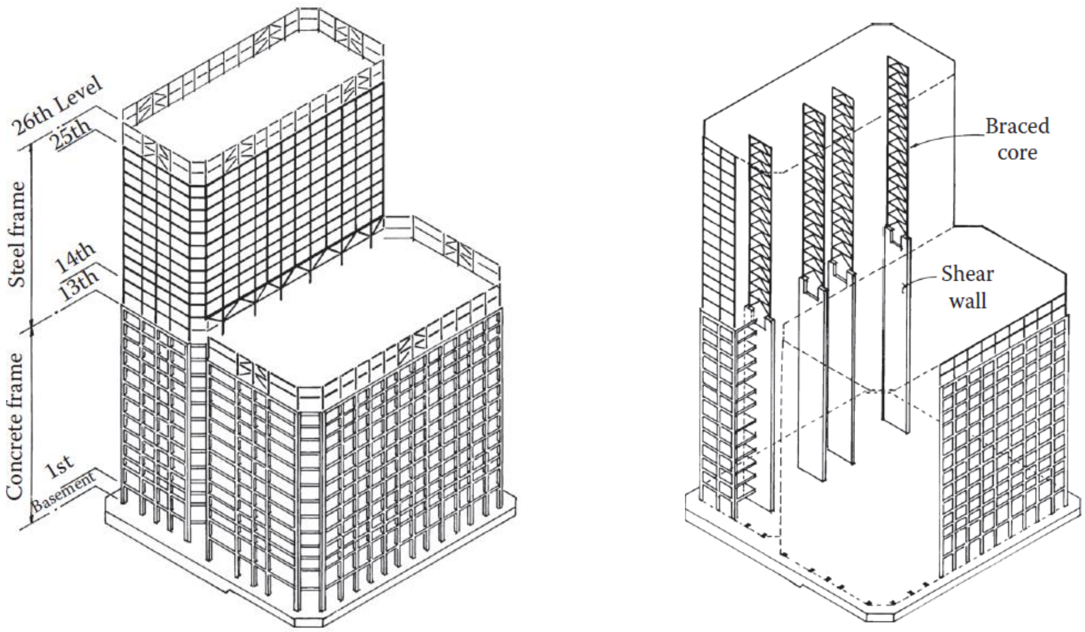


(a) Composite Framing Elevation (b) Beam-Column Connection

Fig. 2-8 Composite Moment Frame (Taranath, 2011)

2.3.4.2 Vertically Mixed System

Unlike composite systems where steel and concrete elements act together to create localized composite behavior, the two systems in vertically mixed systems remain separate over the height of the building. Such systems can be particularly useful in buildings where floors are grouped together for distinct occupancies. For example, while offices typically prefer open floor spaces with large column spacing of approximately 40 feet, residential floors may require beamless flat ceilings. In such a scenario, additional columns may be introduced in the residential floors of the building to provide minimum floor depth. Therefore, the architectural layout of the floorplan dictates the structural system of building. Hence to optimize the utility of structural elements, it is practical to vertically diversify the lateral system to meet the local load demands. For example, the lower floors of a building that take the maximum overturning moments caused by lateral loading may be designed using concrete shear walls, while the upper and middle floors may be designed using a combination of braced frames and moment frames. This vertical separation of the lateral system offers many advantages. The option of using different lateral systems provides architectural freedom, where the designer may choose to use a certain system to increase the functionality of the building. For example, if an opening is desired in a laterally braced bay, the architect may select a moment framed system. The integration of different lateral systems may be seen as an opportunity to optimize the structural design of the building, leading to minimum structural weight and maximum structural efficiency. Schematic designs of a vertically mixed lateral system are shown in Figure 2-9.



(a) Schematic Perimeter Frames (b) Interior Components

Fig. 2-9 Vertically Mixed Lateral Load-Resisting System (Taranath, 2011)

Despite having several advantages, vertically mixed lateral systems also come with some disadvantages. The largest disadvantage of such a system is its constructability. Although a fully optimized lateral system that accounts for the local load demand at each floor may minimize material costs and overall weight of the structure, such a design may significantly increase labor costs, and the time and effort needed to produce structural details. Another disadvantage of a vertically mixed lateral system that incorporates steel and concrete is designing proper load transfers between the two materials. Adequate connections need to be designed for the interface where shear forces and bending moments are transferred from steel braces or moment frames to concrete shear walls. However, these limitations can be temporary hurdles; as the building industry gains experience with vertically mixed lateral systems, designers and contractors alike may be able to adapt to more efficient design and construction procedures.

2.4 Case Studies

Several buildings around the world have used different combinations of lateral load-resisting systems to provide lateral stiffness. In many cases, these designs were inspired by specific structural demands, while in other cases they were based on, and complemented, the architectural vision. Two of these structures are briefly discussed below.

2.4.1 U.S. Bank Tower First Interstate World Center, Los Angles, California

The primary structural system for the 75-story tall U.S. Bank Tower located in Library Square, Los Angles, California, consists of two main components: an inner steel braced frame and an outer moment frame system. A schematic drawing of the lateral components of the structure is shown in Figure 2-10. The square braced spine, measuring approximately 73 feet in each direction, spans the entire height of the structure and provides the primary lateral support. A structural analysis of the structure indicates that approximately 50% of the overturning moment is supported by the core (Taranath, 2011). The orientation and size of the core leaves the remaining columns exposed to gravity loads only. To achieve maximum structural efficiency, the number of gravity columns is reduced, and the columns are drawn outward to the perimeter of the structure, with expanded tributary widths (Taranath, 2011). The exterior frame, consisting of moment frames, utilizes a strong-column/weak-beam combination to meet seismic design requirements. This exterior structural tube adds to the moment resisting capacity of the core. By using both the interior and exterior of the structure as lateral load-resisting systems, the moment-arm is significantly reduced leading to a much more optimized design. It is important to note the engineers' decision

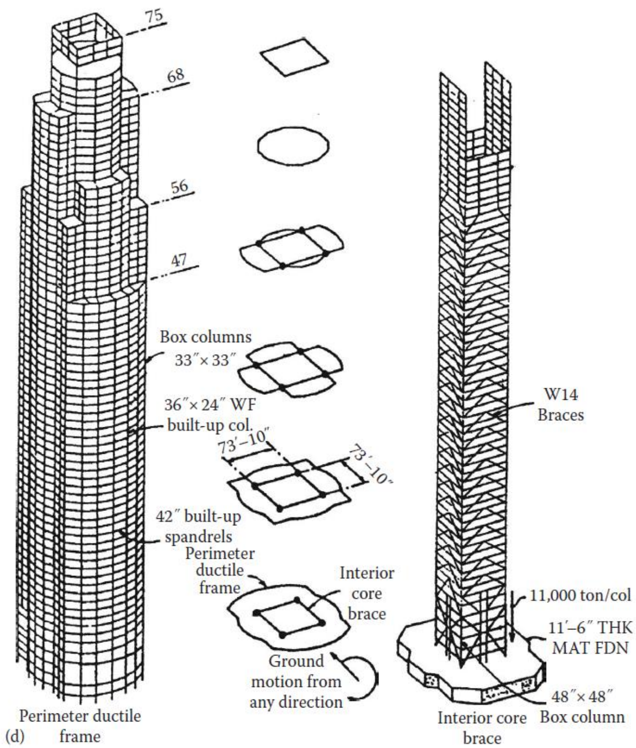


Fig. 2-10 U.S. Bank Tower – Elevation View: Structural System (Taranath, 2011)

to use moment frames instead of bracing on the exterior of the building, since the exterior of the structure is designed to act as a ductile system. Due to relative rigidity of the inner and exterior systems, the majority of the loading is drawn towards the inner braced core (Taranath, 2011).

2.4.2 Jin Mao Tower, Shanghai, China

The main lateral load-resisting component for the 88-story mixed-use Jin Mao Tower in Shanghai consists of a central concrete core. The octagonal core, which measures 90 feet from flange to flange, extends the entire height of the structure and provides remarkable torsional resistance. The core is linked to exterior mega-columns using outrigger trusses as shown in Figure 2-11 (Taranath, 2011). The dual-story steel outrigger trusses connect the inner core to the outer mega columns between the 24th and 26th, 51st and 53rd, and 85th and 87th stories, and transfer lateral loads between the different structural elements of the building, enabling a combined global structural response. The exterior composite mega columns, which measure 5 feet X 16 feet at the foundation level, share the lateral load applied on the building with the inner core. This integrated lateral system consisting of trusses, columns and a core allows the building to safely and functionally act as a vertical cantilever under lateral loading, with tension and compression induced in the windward and leeward columns, respectively. This composite lateral system responds well to the significant lateral loads applied on the structure. With design wind speed at the top of the building reaching a maximum 125 mph over a 10-minute period (Taranath, 2011), any single lateral load-resisting system for this 88-story building may have easily led to an over-designed structure. However, the Jin Mao Tower serves as an example to demonstrate how the advantages of different lateral load-resisting systems can be incorporated into a single composite system to yield an efficient design.

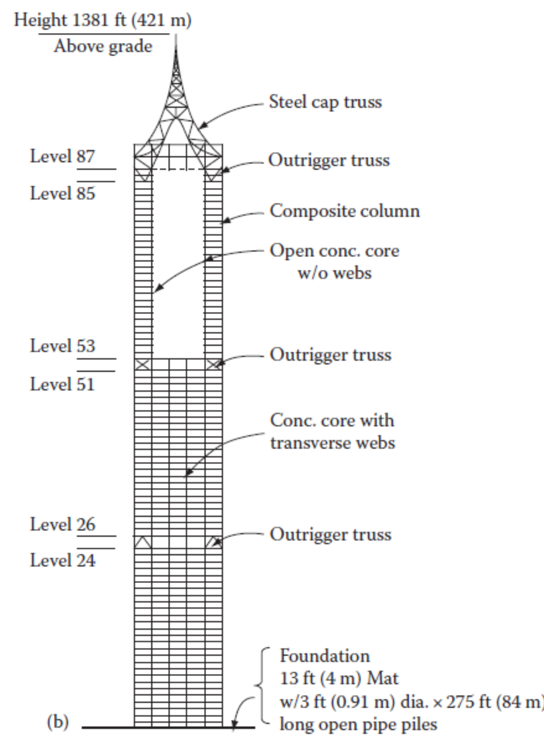


Fig. 2-11 Jin Mao Tower – Elevation View: Structural System (Taranath, 2011)

3. Methodology

3.1 Loading Conditions

For this research, the buildings under consideration are assumed to be located in Lower Manhattan, New York City. Therefore, New York City Building Code 2014 (NYCBC 2014) is used as the guideline for all design aspects. NYCBC 2014 references ASCE 7-05 and ASCE 7-10 for wind and seismic loading, respectively. For steel and concrete design, NYCBC 2014 references AISC 360-05 and ACI 318-11, respectively. NYCBC 2014's wind and seismic design parameters include the structure's Occupancy/Risk Category, as specified in the Table 1604.5 in NYCBC 2014. The structures analyzed for this research are considered to belong to occupancy/risk category III. Using the Occupancy/Risk Category, the importance factors for wind and seismic are determined using NYCBC 2014's Table 1604.5.2, and are shown in Table 3.1.

Table 3.1 – Lateral Loading Importance Factors (Adapted from NYCBC 2014, Table 1604.5)

Occupancy/Risk Category	**Wind Importance Factor, I**	**Seismic Importance Factor, I**
III	1.15	1.25

A fundamental assumption made for this research is that the lateral system of the building is not affected by any gravity loading, except for self-weight. The primary purpose of this assumption is to isolate the effects of lateral loading on the structure. Furthermore, since gravity loads, particularly live loads, are dependent on the occupancy of the building, the separation between the gravity load-resisting system and the lateral load-resisting system in the building leads to a more general structural solution, which can be applied to a wide array of buildings with varied usage.

3.1.1 Wind Loads

NYCBC 2014 prescribes ASCE 7-05 as the design standard for wind loading. ASCE 7-05 proposes two main methods for designing structures for wind loading: i) the simplified procedure as outlined in ASCE 7-05's section 6.4 and ii) the analytical procedure as outlined in section 6.5. For the purposes of this research, all buildings are analyzed through the analytical procedure, since the structures being studied do not meet all requirements indicated in ASCE 7-05's section 6.4.1.1, in order to be eligible for the simplified procedure.

The following parameters, as defined below, are used by ASCE 7-05 to analyze the effects of wind loading on a structure:

Basic Wind Speed V: The 3-second gust speed at 33 feet above ground.

Exposure Category: The exposure of structures to wind loading depending on surrounding surface roughness and vertical clearance.

Wind Directionality Factor K_d: A load reduction factor less than 1.0, intended to account for the probability that the design wind event aligns with the building's worst-case aerodynamic geometry.

Velocity Pressure Coefficient, K_h or K_z: A coefficient calculating relative exposure of building to wind loading based on the building's exposure category, and height being considered.

Topography Factor K_{zt}: A parameter indicating site location relative to the surrounding surface.

Gust Effect Factor G: A factor accounting for wind load amplification during gusts.

Enclosure Classification: A classification indicating the ratio of openings in a structure relative to its surface area. The enclosure of a structure may be classified as i) open, ii) partially open or iii) enclosed.

Internal Pressure Coefficient GC_{pi}: A coefficient accounting for the internal pressure within a structure. This coefficient varies based on the building's enclosure classification.

External Pressure Coefficient C_p: A coefficient accounting for the varying pressure difference between the windward and leeward sides of the building.

Velocity Pressure q_z: The wind pressure assuming a fluid motion acting against a flat plane.

Design Wind Pressure p: The final calculated design wind pressure.

The values of each parameter mentioned above, along with their corresponding references are shown in Table 3.2.

Table 3.2 – Wind Load Parameters

Parameter	Value	Reference
V	98 mph	NYCBC 2014 Section 1609.3
Exposure Category	C	NYCBC 2014 Figure 1609.4.3 (1)
K_d	0.85	ASCE 7-05 Table 6-4
K_h or K_z	$2.01\left(\frac{z}{900}\right)^{0.21}$	ASCE 7-05 Table 6-3 [(a)]
K_{zt}	1.0	ASCE 7-05 Section 6.5.7

G	0.85	ASCE 7-05 Section 6.5.8
Enclosure Classification	Enclosed	ASCE 7-05 Section 6.5.9
GC_{pi}	± 0.18	ASCE 7-05 Figure 6-5
C_p	0.80, 0.50	ASCE 7-05 Figure 6-6
q_z	K_z*24 psf	ASCE 7-05 Section 6.5.10 (b)
p	$qGC_p – q_h*GC_{pi}$	ASCE 7-05 Section 6.5.12

a. z is defined as the height under consideration in feet.
b. The value of q_z, as calculated using Equation 6-15, is a function of the structure's height.

In Figure 6-9, ASCE 7-05 provides four possible load cases to analyze the effects of wind loading on a structure. Case 1 accounts for the full wind loading applied perpendicularly to each major axis of the structure. Case 2 applies three-quarters of the design wind in each principal direction in addition to a torsional moment. Cases 3 and 4 are similar to Cases 1 and 2 respectively, but consider 75% of the specified wind value acting simultaneously in both principal directions of the structure. Considering windward and leeward directionality, the load cases used in this research for wind loading are summarized in Table 3.3, where loading angle, e_x and e_y indicate the angle between the line of loading and the principal axis under consideration of the structure, the eccentricity in the x-direction, and the eccentricity in the y-direction, respectively.

Table 3.3 – Wind Load Cases

Load Case	Description
1	Loading Angle: 0°, e_x: 0.00, e_y: 0.00
2	Loading Angle: 90°, e_x: 0.00, e_y: 0.00
3	Loading Angle: 0°, e_x: 0.15, e_y: 0.00
4	Loading Angle: 0°, e_x: -0.15, e_y: 0.00
5	Loading Angle: 90°, e_x: 0.00, e_y: 0.15
6	Loading Angle: 90°, e_x: 0.00, e_y: -0.15
7	Loading Angle: 0°, e_x: 0.15, e_y: 0.15
8	Loading Angle: 90°, e_x: -0.15, e_y: -0.15
9	Loading Angle: 0°, e_x: 0.15, e_y: 0.15
10	Loading Angle: 0°, e_x: 0.15, e_y: -0.15
11	Loading Angle: 90°, e_x: -0.15, e_y: 0.15
12	Loading Angle: 90°, e_x: -0.15, e_y: -0.15

3.1.2 Seismic Loads

According to NYCBC 2014, ASCE 7-10 is used as the design standard for seismic loads. ASCE 7-10 proposes three main methods for designing structures for seismic loading: i) the equivalent lateral force analysis per ASCE 7-10's section 12.8, ii) the modal response spectrum analysis as per section 12.9, and iii) the seismic response history procedure as per Chapter 16. For the purposes of this research, all buildings are analyzed using the equivalent lateral force analysis based on the design criteria outlined in ASCE 7-10's section 12.6.

The following parameters, as defined below, are used by ASCE 7-10 to analyze the effects of seismic loading on a structure:

Site Class: A classification of site based on soil condition.

Mapped Acceleration Parameter S_S: The mapped Maximum Considered Earthquake (MCE_R) spectral response acceleration parameter at short periods.

Mapped Acceleration Parameter S_1: The mapped MCE_R spectral response acceleration parameter at 1 second.

Site Coefficient F_a: The short period site coefficient corresponding to S_S.

Site Coefficient F_v: The long period site coefficient corresponding to S_1.

Earthquake Response Parameter S_{DS}: The design earthquake spectral response acceleration parameter at short period.

Seismic Design Category: A classification assigned based on S_{DS} that governs the seismic design procedure for a structure.

Approximate Fundamental Period T_a: The approximate fundamental period of a structure that may be calculated as per Table 12.8-2 based on the lateral load-resisting system and height of structure.

Long-period Transition Period T_L: The long-period transition period of a structure dependent on geographic location.

Response Modification Coefficient R: A factor dependent on the type of lateral system.

Seismic Response Coefficient C_S: A parameter indicating the percentage of self-weight that is applied as the seismic load at each story of the building.

The values of each of the parameters mentioned above, along with their corresponding references are shown in Table 3.4.

Table 3.4 – Seismic Load Parameters

Parameter	**Value**	**Reference**
Site Class	D	ASCE 7-10 Section 11.4.2
S_S:	0.280	ASCE 7-10 Figure 22-1

S_1:	0.072	ASCE 7-10 Figure 22-2
F_a	1.58	ASCE 7-10 Table 11.4-1
F_v	2.4	ASCE 7-10 Table 11.4-2
S_{DS}	0.30	ASCE 7-10 Equation 11.4-3
Seismic Design Category	B	ASCE 7-10 Table 11.6-1
T_a	$0.016 * h_n^{0.9}$	ASCE 7-10 Equation 12.8-7 [a]
T_L	6s	ASCE 7-10 Figure 22-12
R	6	ASCE 7-10 Table 12.2-1
C_S	Dependent on h_n	ASCE 7-10 Equations 12.8-2 – 12.8-6 [a]

a. h_n is defined as the height of the structure in feet.

Seismic loads are calculated as per parameters shown in Table 3.4, and applied at the center of mass of each floor, along each principal axis. Therefore, two main seismic load cases are considered, acting along each principal axis of the building. For both wind loads and seismic loads, the floors are assumed to behave as rigid diaphragms, distributing the lateral loads to all lateral load-resisting elements based on their respective stiffness.

3.2 Deflection Criteria

The structural deflection criteria required by NYCBC 2014 can be divided into two primary categories i.e. a) deflection criteria and b) drift criteria. Deflection criteria, as indicated in NYCBC 2014 Table 1604.3 specify the deflection limits of individual structural elements. A summary of relevant structural deflection criteria is shown in Table 3.5.

Table 3.5 – Deflection Limits (Adapted from NYCBC 2014, Table 1604.3)

Construction	Live Load	Snow/Wind Load	Dead Load + Live Load
Floor members	l/360	-	l/240
Exterior walls and interior partitions	-	l/120	-

While deflection criteria limit the local movement of structural elements relative to their restraints, drift criteria limit the overall deflection of a structural system. Such criteria are often imposed on buildings to meet serviceability and comfort requirements. They also ensure that structural elements do not move excessively relative to architectural cladding, causing cracking and disengagement in the long run. ASCE 7-10 Appendix C states that “Lateral deflection or drift of structures and deformation of horizontal diaphragms and bracing systems due to wind effects shall not impair the serviceability of the structure.” To meet ASCE’s requirement, a recommended inter-story drift limit of H/400 is considered for all structural systems, where H represents the total height of the structure (Griffis, 1993). All deflection and serviceability requirements are considered under unfactored service loads as per ASCE 7-10 Chapter 2.4.

3.3 Embodied Carbon

Embodied carbon, often expressed in units of $CO_{2\text{-}e}$ i.e. carbon equivalent, measures the amount of carbon dioxide emitted during the manufacture, transport and construction process for a structure. $CO_{2\text{-}e}$ is often used as a standard measure to quantify the impact of structures on the environment and the global carbon footprint. For this research, only embodied carbon from materials used as part of the lateral system for the building is considered. A summary of $CO_{2\text{-}e}$ coefficients for steel and concrete is shown in Table 3.6.

Table 3.6 – Embodied Carbon Coefficients (Adapted from Nadoushani & Akbarnezhad, 2015)

Material	Embodied Carbon Coefficient ($CO_{2\text{-}e}$/lb)
Steel	3.37
Concrete	0.25

3.4 Cost

From schematic design to construction and post-construction maintenance, financial considerations heavily influence decisions in the building industry. A primary incentive for an optimized structural system is its potential to considerably reduce superfluous expenses that can be avoided both in the design and construction phases of a project. Since lateral systems in buildings often require iterative design processes and demand expensive construction techniques, optimizing these systems can significantly reduce the overall project budget. In this research, the effect of a vertically mixed lateral system on the cost of construction is taken into consideration. Since cost of construction procedures vary greatly based on the method of construction, geographical location, and multitude of other factors, only the cost of construction material is considered. Also, an additional $750.00 per connection cost for constructing moment frames, based on professional references, is taken into consideration to account for on-site welding. A summary of all relevant costs is shown in Table 3.7.

Table 3.7 – Cost of Structural Systems

Structural System	Cost (USD)
Moment Frame	$750/connection + $0.75/lb of steel
Braced Frame	$0.75/lb of steel
Shear Wall	$0.022/lb of concrete

3.5 Model Formulation

A combination of MATLAB (Mathworks, Version R2016b) and SAP2000 (Computer and Structures, Inc., Version 15) is used to generate and analyze the structures studied for this research. The CSI Open Application Programming Interface (OAPI) is utilized to assemble and run SAP2000 commands through MATLAB scripts. This enables an iterative design process, where structural design parameters are incrementally changed, and the structural model is analyzed for each incremental change. The three objective function parameters i.e. structural weight, cost and embodied carbon are determined and saved for each structural model generated by the script. The following assumptions are made during the model formulation process:

1. The building is a rectangular prism, with equal bay dimensions in each direction.
2. Steel and concrete elements have strength of Fy = 50 ksi and f'c = 4000 psi, respectively.
3. Concrete shear walls, if present, are always located below steel bracing and moment frames. Steel bracing, if present, is always located below moment frames. This assumption is based on the drift response of each of the lateral load-resisting systems. Typically, steel braces have a lower stiffness compared to shear walls, and moment frames have a lower stiffness than steel braces. Therefore, since the required lateral load resistance in a building increases from top to the base, designing lower floors using stiffer lateral components poses a valid design approach.
4. The thickness of concrete walls remains constant over the height of the building.
5. Shear walls have 5/8-inch diameter reinforcement bars placed at 12 inches on center at each face in each direction.
6. Floors do not contribute to the overall weight of the structure, since only the weight of the lateral system is considered for this research.

When first initialized, the primary MATLAB script, which serves as the main link between the user and SAP2000's OAPI function, prompts the user to input various basic design parameters such as material definitions, building height and shear wall thickness. Next, the user is given the option to choose between the following two modules (variations) of the program:

Module 1: Module 1 enables the user to manually input specific lateral load-resisting bay locations within the building, and indicate the stories which have moment frames, braces and shear walls. This module allows the user to check a certain lateral load-resisting layout with optimized results generated by Module 2.

Module 2: Module 2 of the program determines the optimal vertically mixed use lateral system given a certain layout of lateral load-resisting components. The script iterates through all possible combinations of vertical placement of shear walls, braces and moment frames, with respect to model formulation assumption #3, and determines the combination that results in the minimum multi-objective function value consisting of the three objective parameters i.e. weight, cost and embodied carbon.

If Module 1 is chosen, the user is prompted to specify the locations of the lateral load-resisting bays in the building, and the vertical placement of each of the three structural systems. If Module 2 is chosen, the user is asked to select between the following two building layouts:

Layout A: Layout A is a square building with three 16 feet wide bays in each direction. This layout represents geometric conditions for buildings with a low aspect ratio.

Layout B: Layout B is a rectangular building with four and two bays along the length and width of the building, respectively. In each direction, all bays are 16 feet wide. This layout represents geometric conditions for buildings with a high aspect ratio.

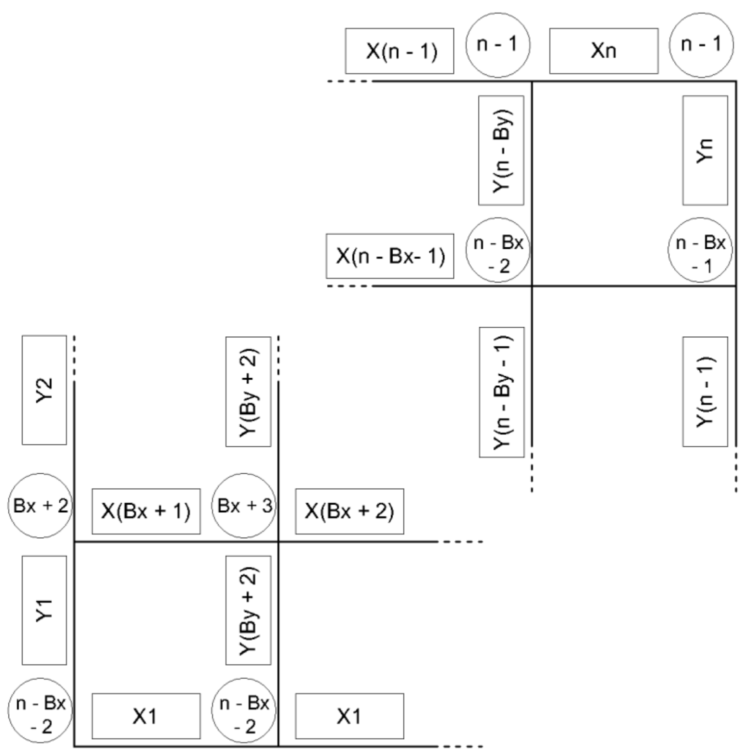


Fig. 3-1 Schematic Layout of Joints and Bays

Regardless of which module is selected, the program next initializes a separate MATLAB function, named *BuildingGeometry*, to create the geometric layout of the building based on the user input. The *BuildingGeometry* script starts by assigning joint labels along the x and y directions. Next, the code assigns bay labels based on the joint labels assigned earlier. A sample assignment procedure is shown in Figure 3-1, where joint labels are shown in circles and bay labels are shown in boxes.

Once the building's geometric setup is created, the main script allows the user to select one of the four configurations listed below and shown in Figure 3-3.

Configuration 1: Configuration 1 assigns a lateral load-resisting core in one corner of the building, with two laterally braced bays in the x direction and one in the y direction. Such a layout may be used in buildings to maximize unrestricted floor space. However for such layouts, since the center of stiffness (C.S.) is located near a corner of the structure, the building is exposed to a significant amount of torsion from lateral loading. Also, due to the misalignment of the C.S. with the center of mass (C.M.), additional overturning moments are induced in the structure from the structure's self-weight.

Configuration 2: Configuration 2 assigns a lateral load-resisting core in the center of the building, with one laterally braced bay in the x direction and two in the y direction. Central lateral cores are quite frequently used in buildings, since they provide significant structural advantages over cores placed eccentrically with respect to the C.M. The central location of the C.S. minimizes magnification of torsional effects due to lateral loads, and the proximity of C.S. and C.M. eliminates additional moments induced by gravity loads.

Configuration 3: Configuration 3 assigns a set of two lateral load-resisting bays in opposing corners of the building. This layout maximizes the open floor space in the building, while still keeping the C.S. in the geometric center of the building. Similar to configuration 2, the central location of the C.S. minimizes torsional effects, and eliminates additional moments induced by gravity loads. The large moment-arm between the opposing corners also minimizes the forces in the lateral load-resisting bays.

Configuration 4: Configuration 4 assigns lateral load-resisting bays in opposing sides of the building in each direction. This configuration is similar to configuration 3, in that the moment-arm for the tension-compression force couple resisting the overturning moment due to the applied lateral load extends to each face of the building. However an additional advantage of this configuration is that each bay primarily resists loads parallel to its length, unlike configuration 3 where both corner bays are exposed to loading in both principal axes.

Once a configuration is chosen, the primary script runs the *SAPAPI* script, which is written as a MATLAB function. *SAPAPI* initiates the model formulation process using the output from *BuildingGeometry*. Once *SAPAPI* is run, the main script retrieves the necessary data and creates a results matrix. The overall design and analysis procedure and the layouts and configurations are summarized in Figures 3-2 and 3-3, respectively.

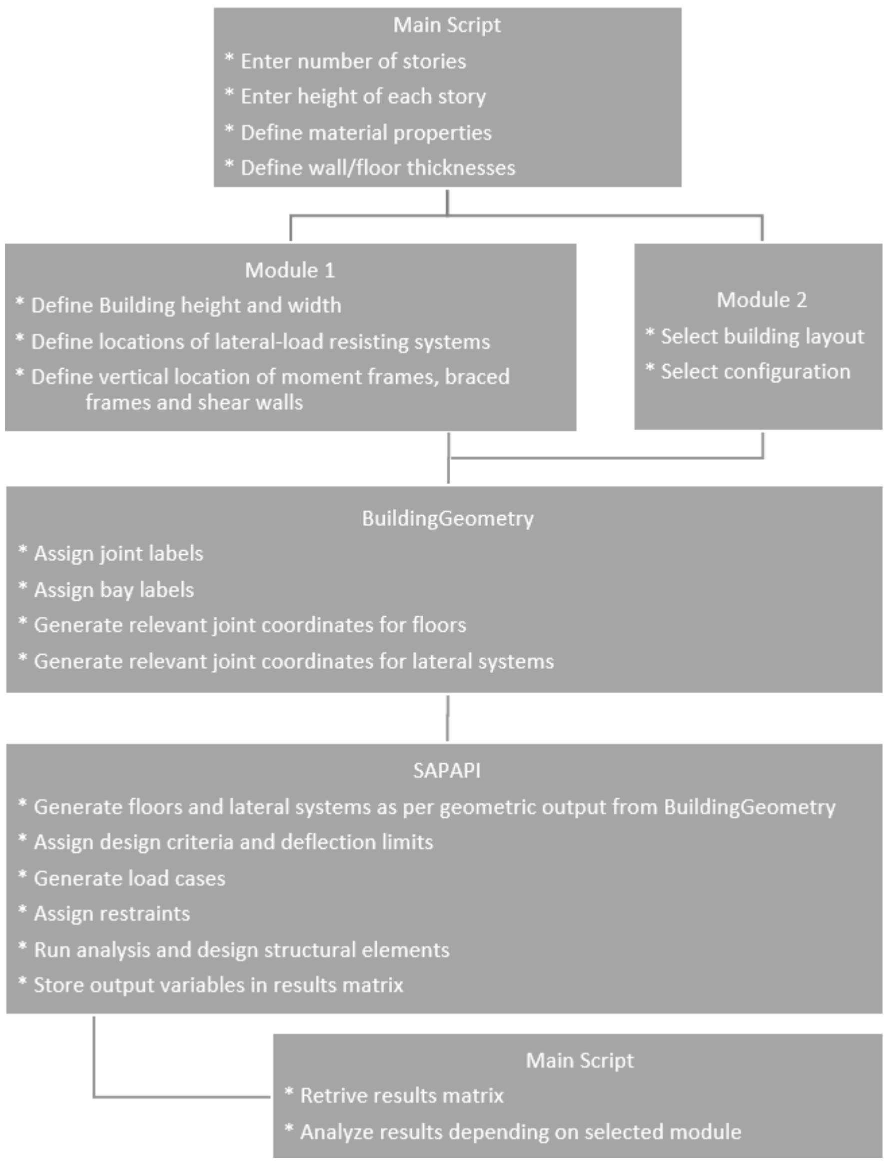


Fig. 3-2 Model Formulation Procedure

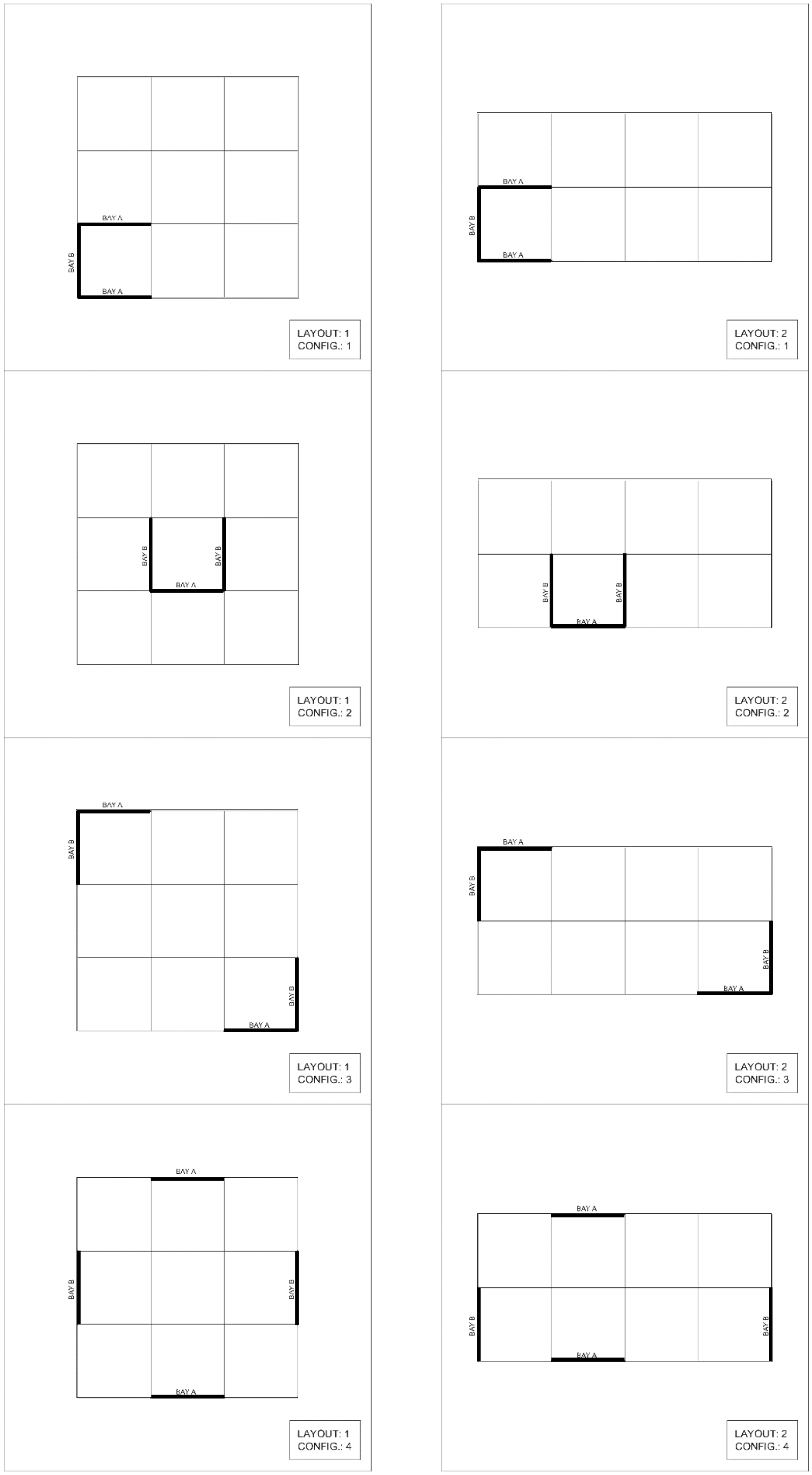


Fig. 3-3 Building Layout and Configurations

3.6 Analysis

3.6.1 Hand Calculations

A series of hand-calculations are conducted to validate the results obtained via the computer-generated models. The forces in each bay for a sample 5 story building is calculated, and compared with corresponding results from the code generated structures. Different layouts and configurations of the lateral systems are considered, to account for torsional effects under varying geometric conditions. The following steps are taken to manually calculate internal loads for the structures:

1. Wind load parameters are calculated as per ASCE 7-05 chapter 6.5.
2. 12 wind load cases, as indicated in Table 3.3 are generated based on the calculated wind load parameters.
3. Seismic load parameters are calculated as per ASCE 7-10 chapter 12.6.
4. The seismic load along each of the principal axes is calculated based on the seismic load parameters, and self-weight of the building.
5. The x and y coordinates of the center of mass of the structure (x_m, y_m) are calculated using Equations 3-1 and 3-2, respectively. In these two equations, x_i, y_i and m_i represent the x coordinate of the geometric center of the i^{th} floor, the y coordinate of the geometric center of the i^{th} floor, and the mass of the i^{th} floor, respectively.

$$x_m = \frac{\sum m_i x_i}{\sum m_i} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (Eq. 3-1)$$

$$y_m = \frac{\sum m_i y_i}{\sum m_i} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (Eq. 3-2)$$

6. The x and y coordinates of the center of stiffness of the structure (x_{cs}, y_{cs}) are calculated using Equations 3-3 and 3-4, respectively. In these two equations, x_i, y_i and k_i represent the x coordinate of the i^{th} lateral load-resisting element in the y direction, the y coordinate of the i^{th} lateral load-resisting element in the x direction, and the stiffness of the i^{th} element, respectively.

$$x_{cs} = \frac{\sum k_i x_i}{\sum k_i} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (Eq. 3-3)$$

$$y_{cs} = \frac{\sum k_i y_i}{\sum k_i} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (Eq. 3-4)$$

7. For each floor the torsion for each of the 12 wind load cases is calculated as per ASCE 7-05 Figure 6-9. For the structures with eccentric lateral load-resisting systems, the torsional effects are amplified to account for the eccentricity between the center of mass and center of stiffness.
8. For each floor, the forces in lateral load-resisting element i in the x direction and y direction are calculated using Equations 3-5 and 3-6, respectively, where M represents the torsional moment at the floor under consideration, and r_i represents the distance between the center of stiffness of the floor and the centroid of lateral load-resisting element i.

$$F_{ix} = \frac{k_i x_i}{\sum k_i} + \frac{k_i r_i}{\sum k_i r_i^2} M \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (Eq. 3-5)$$

$$F_{iy} = \frac{k_i y_i}{\sum k_i} + \frac{k_i r_i}{\sum k_i r_i^2} M \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (Eq. 3-6)$$

Once the forces in each of the bays are calculated for all the floors, the results are compared with the corresponding results from the code generated structures. A total of (8) such comparisons are performed, and are summarized in Appendix A. Assuming no P-Δ effects, the results from the hand calculations are within reasonable bounds of the results generated by the computer.

Forces in four planar five-story frames, (2) moment frames and (2) braced frames, are calculated by hand and compared with corresponding forces from the computer-generated models. These comparisons are also summarized in Appendix A. For the moment frames, the largest discrepancy between hand-calculations and computer generated models for the axial forces in the braces is 7%. For the braced frames, the largest discrepancy for the end moments in the beams is 8%.

To verify the local behavior of the structure, the internal forces for (1) one-story moment frame and (1) one-story braced frame subjected to a unit lateral force are calculated by hand and compared with models created in SAP2000. The largest difference is 1%, which can be considered negligible.

3.6.2 Module 1

Using Module 1 of the program, each of the (8) combinations of layouts and configurations, as shown in Figure 3-3, are analyzed for 5, 10, 20 and 40 story buildings. To minimize run-time for the script, 6 predetermined lateral load-resisting vertically mixed system combinations (VMSC) are modelled and analyzed. The 6 combinations for each building height are shown in Table 3.8.

Table 3.8 – Predetermined Vertically Mixed System Combinations (VMSC)

# Story	Vertically Mixed System Combination					
	1	2	3	4	5	6
	100% S.W.[a]	100% Brace	100% Mom.[b]	~50% S.W. ~50% Brace	~50% Brace ~50% Mom.	~33% S.W. ~33% Brace ~33% Mom.
5	5 – S.W.	5 – Brace.	5 – Mom.	3 – S.W. 2 - Brace	3 – Brace 2 – Mom.	2 – S.W. 2 – Brace 1 – Mom.
10	10 – S.W.	10 – Brace.	10 – Mom.	5 – S.W. 5 – Brace	5 – Brace 5 – Mom.	4 – S.W. 3 – Brace 3 – Mom.
20	20 – S.W.	20 – Brace.	20 – Mom.	10 – S.W. 10 – Brace	10 – Brace 10 – Mom.	7 – S.W. 7 – Brace 6 – Mom.
40	40 – S.W.	40 – Brace.	40 – Mom.	20 – S.W. 20 – Brace	20 – Brace 20 – Mom.	14 – S.W. 13 – Brace 13 – Mom.

a. S.W. indicates concrete shear wall
b. Mom. Indicates moment framed system

Analyzing 6 VMSCs for 2 layouts and 4 configurations, for each of the 4 building heights results in a total of 192 models. The output parameters i.e. structural weight, cost and embodied carbon of each of the models are stored in a single results matrix. Next, the multi-objective function, J, for each of the models is calculated using Equation 3-7, where W_W, W_C and W_E represent the multi-objective weights for structural weight, cost and embodied carbon, respectively. A multi-objective function assesses optimality accounting for all relevant variables.

$$J = W_W * Weight + W_C * Cost + W_E * Embodied\ Carbon \ldots . (Eq. 3-7)$$

Before calculating J using Equation 3-7, the unnormalized dataset (x) for structural weight, cost and embodied carbon are first normalized to dataset (z) using Equation 3-8.

$$z_i = \frac{x_i - \min(x)}{\max(x) - \min(x)} \ldots \ldots (Eq. 3-8)$$

The normalized dataset is analyzed for 4 different multi-objective weight combinations (MOWC) of W_W, W_C and W_E as shown in Table 3.9.

Table 3.9 – Multi-Objective Weight Combinations (MOWC)

Combination	W_W	W_C	W_E
1	0.33	0.33	0.33
2	0.50	0.25	0.25
3	0.25	0.50	0.25
4	0.25	0.25	0.50

3.6.3 Module 2

Module 2 is used to create a single model, in order to determine the most optimal vertically mixed system for a given layout and configuration. The script iterates through all possible combinations of vertical placement of shear walls, braces and moment frames, and determines the combination that results in the minimum multi-objective function value. Once all possible combinations are modelled and run, gradient plots are constructed to visually represent the effects of the different lateral system on the three output parameters i.e. structural weight, cost and embodied carbon.

4. Results

The results from Module 1 and Module 2 of the script are summarized and discussed in this chapter. The chapter is divided into two sections, which discuss the relevant findings from Module 1 and Module 2, respectively.

4.1 Module 1

The first set of data for Module 1 are graphically represented in Figures 4-1 through 4-4, which display the normalized objective function value for all 6 VMSCs as outlined in Table 3.8 for the 4 MOWCs as outlined in Table 3.9. These figures display the results for 5, 10, 20 and 40 story structures, assuming a constant layout 2 and configuration 3. By analyzing the different VMSCs for a constant layout and configuration, the correlation between building height and type of vertically mixed lateral system is highlighted in the figures.

Next, the correlation between the 4 different configurations and type of vertically mixed lateral system for a given layout and story height is shown in Figure 4-5, by plotting the normalized objective function values for all 6 VMSCs for the different configurations, assuming a 20-story structure for layout 1 and multi-objective weights of $W_W = W_C = W_E = 0.33$.

Figure 4-6 serves a similar purpose to Figure 4-5, but instead displays the correlation between the 2 layouts and the type of vertically mixed lateral system for a given configuration and story height. For this figure, configuration is 3, number of stories is 20, and the multi-objective weights are kept at $W_W = W_C = W_E = 0.33$.

Finally, for Module 1, Figures 4-7 through 4-9 display the contributions of each of the construction materials i.e. steel and concrete towards structural weight, cost and embodied carbon for a given layout and configuration. The structures are analyzed for 5 and 40 stories, in order to display any relevant correlation between story height and the contributions from each of the materials towards the output parameters.

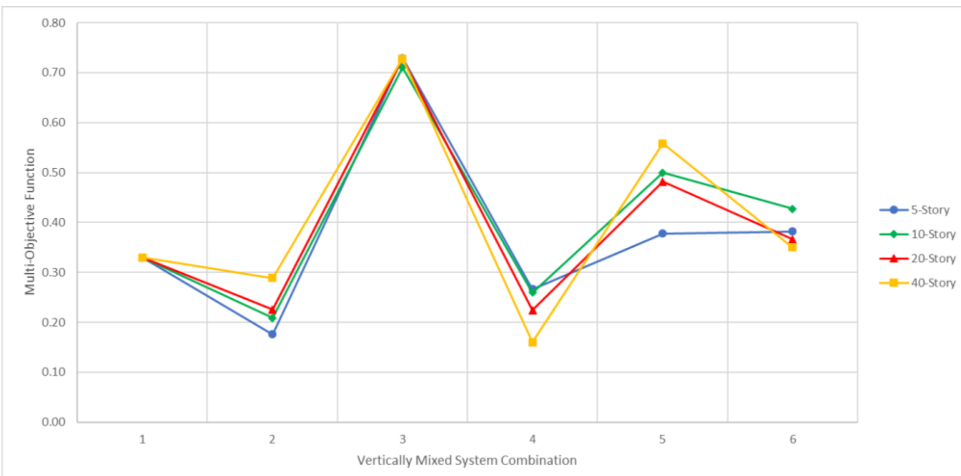


Fig. 4-1 Multi-Objective Function (Layout: 2, Configuration: 3, $W_W = 0.33$, $W_C = 0.33$, $W_E = 0.33$)

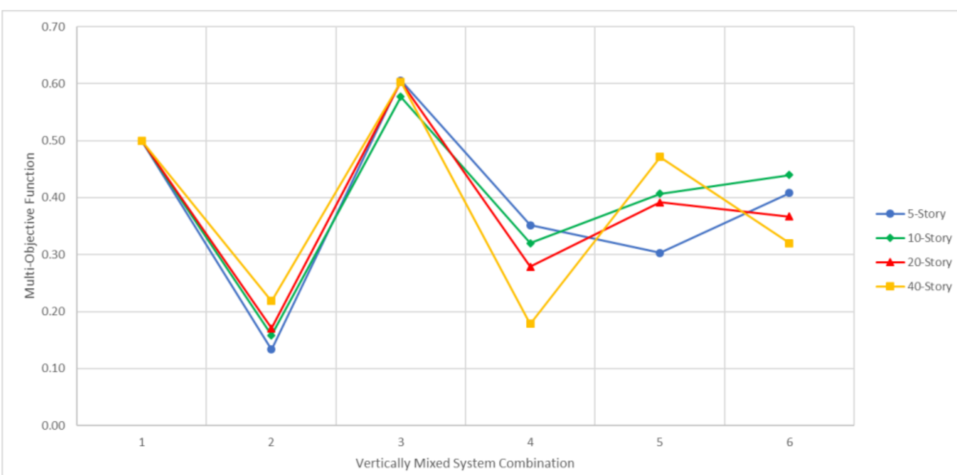


Fig. 4-2 Multi-Objective Function (Layout: 2, Configuration: 3, $W_W = 0.50$, $W_C = 0.25$, $W_E = 0.25$)

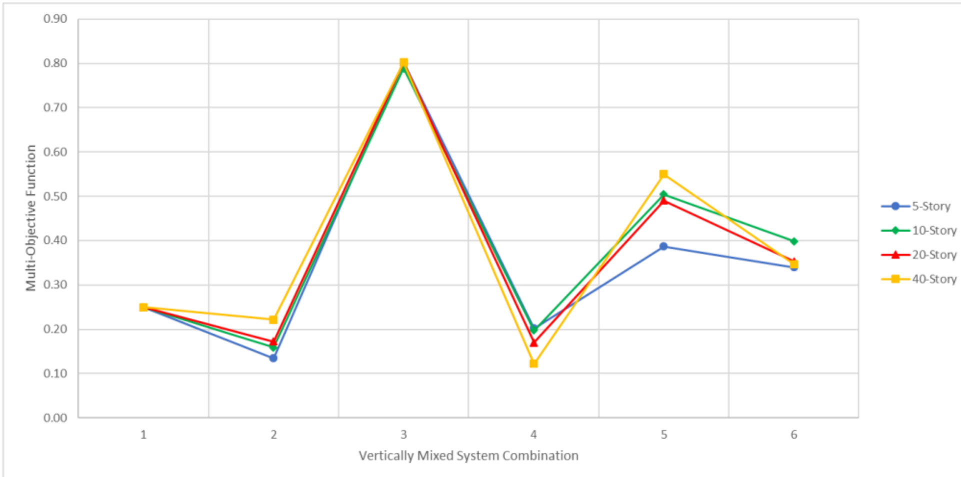


Fig. 4-3 Multi-Objective Function (Layout: 2, Configuration: 3, W_W = 0.25, W_C = 0.50, W_E = 0.25)

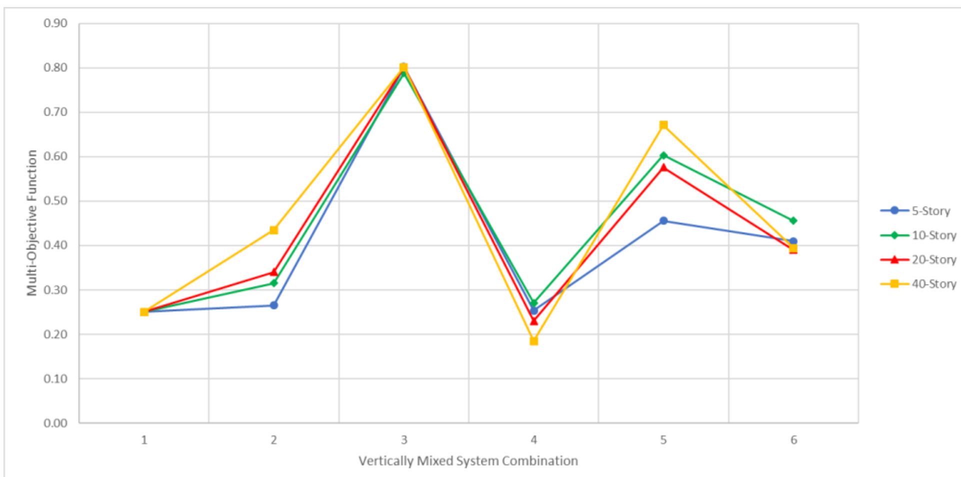


Fig. 4-4 Multi-Objective Function (Layout: 2, Configuration: 3, W_W = 0.25, W_C = 0.25, W_E = 0.50)

Figures 4-1 through 4-4 present the normalized multi-objective function value for all 6 VMSCs and the 4 MOWCs. The results from different building heights are graphed on the same plot to display the correlation between the multi-objective function values and the number of stories for a given data-set. The minima for the multi-objective functions suggest the optimal solution to be either VMSC 2 or 4, which represent a fully braced frame system and a 50% concrete shear wall and 50% braced frame system, respectively. For the 4 MOWCs, the multi-objective function values for a 5-story structure and VMSC 2 are 0.18, 0.13, 0.13 and 0.27, respectively. Similarly, for VMSC 4, the corresponding multi objective function values are 0.27, 0.35, 0.20 and 0.25, respectively. Therefore, using an all braced frame system provides an average 51% improvement of the multi-objective function over using a 50% concrete wall and 50% braced frame system for the 5-story building. The same comparison is performed between

VMSC 2 and 4 for the 40-story building. For the 4 MOWCs, the multi-objective function values for the 40-story structure, for VMSC 2, are 0.29, 0.22, 0.22 and 0.43, respectively. For VMSC 4, the multi objective function values for the same structure are 0.16, 0.18, 0.12 and 0.18, respectively. Therefore, for a 40-story building, a 50% concrete wall and 50% braced frame system becomes the most optimal vertically mixed system, with a 44% optimality over an all braced frame system. Such a result is intuitive and supportive of this paper's initial hypothesis, since a taller structure has higher later loads near the base the structure than a lower structure, and requires lateral load-resisting systems with greater capacities to resist that load.

The multi-objective weight combinations also have a significant impact on the optimality of the structures. For the 5-story structure, VMSC 6 is the most optimal solution for MOWC 3 and 4. For these MOWCs, the multi-objective function values are 0.38 and 0.41, respectively. Similarly, for the 10-story structure, the multi-objective function values are 0.43 and 0.44. However, as MOWC 2 is considered, the multi-objective function values for the 5-story and 10-story structures for VMSC 5 become 0.34 and 0.40, respectively. By assigning a higher multi-objective weight to structural weight, the optimal solution becomes a 50% braced frame and 50% moment frame system over a 33% split of moment frames, braced frames and concrete shear walls.

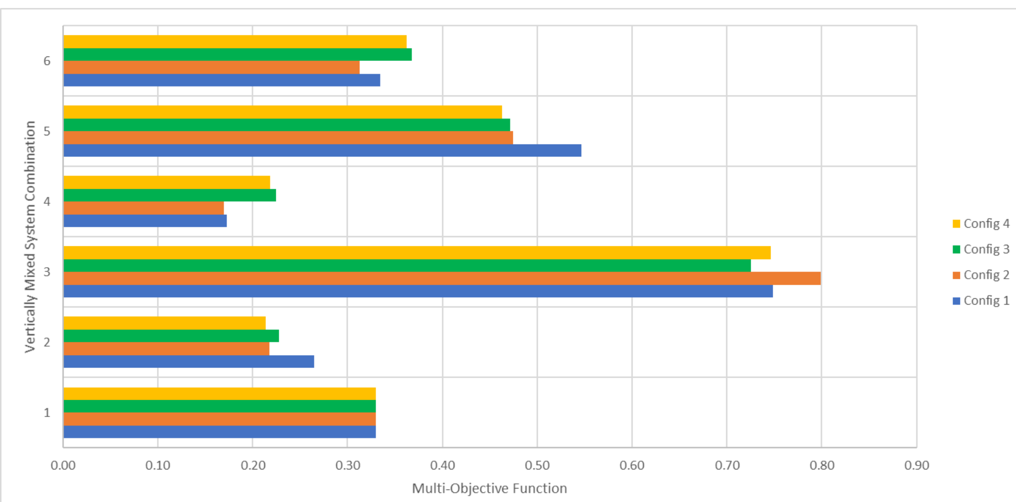


Fig. 4-5 Multi-Objective Function (Layout: 1, Story: 20, W_W = 0.33, W_C = 0.33, W_E = 0.33)

Figure 4-5 displays the normalized objective function values for all 4 configurations for the 6 VMSCs, assuming a 20-story structure with layout 1. The average multi-objective function values for the 4 configurations over the 6 VMSCs are 0.40, 0.38, 0.39 and 0.39, respectively. Despite the difference between the averages of the configurations being not decisive, configuration 2 with a central core is the most optimal solution. Also, configuration 1 with an eccentric core poses to be the least optimal solution. These results indicate that a central configuration of lateral load-resisting bays keeps the center of stiffness of the building close to the center of mass, thus reducing torsional effects from wind loading. In an eccentric system the center of stiffness is further away from the center of mass, thus requiring load-resisting systems with higher capacities, leading to a reduced structural efficiency, as shown the increase in the multi-objective function value.

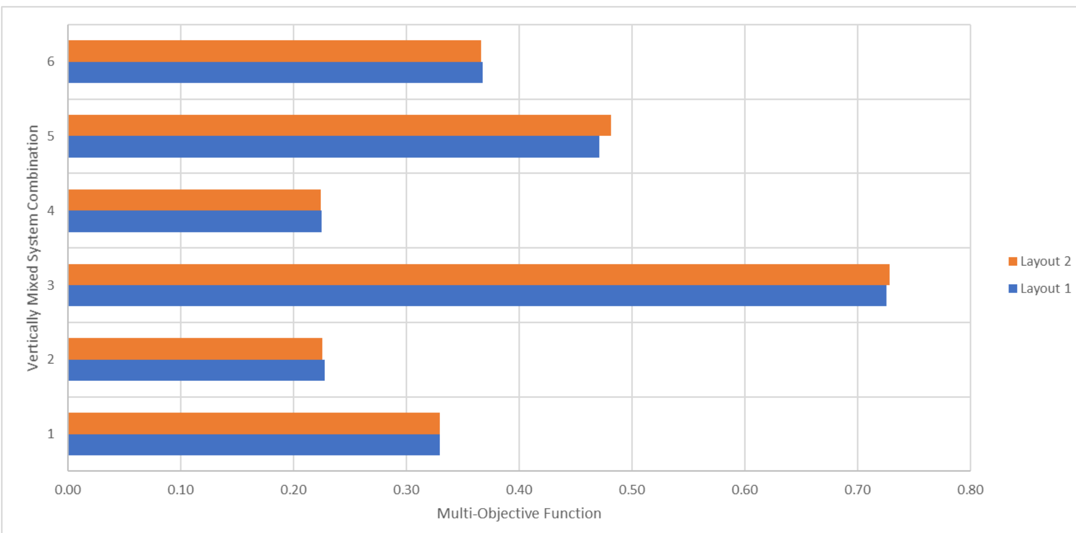


Fig. 4-6 Multi-Objective Function (Configuration: 3, Story: 20, W_W = 0.33, W_C = 0.33, W_E = 0.33)

Figure 4-6 displays the normalized objective function values for all 2 layouts for the 6 VMSCs, assuming a 20-story structure with configuration 3. The average multi-objective function values for the 2 layouts over the 6 VMSCs are 0.40 and 0.41, respectively. Similar to the results of varying configurations, the difference between the averages of the multi-objective function values between the two layouts is not significant. This is due to the fact that the values of the multi-objective function are normalized, and scaled based on the demand and capacity of each model. However, comparatively, Layout 1, which is a square layout, poses a higher optimality over layout 2, which is a rectangular layout for VMSC 3 and 5. A square layout has the same magnitude of loading along each principal axis, and thus does not require additional load-resisting elements along a weaker axis. This advantage may be the principal factor behind a square layout's optimality over a rectangular layout.

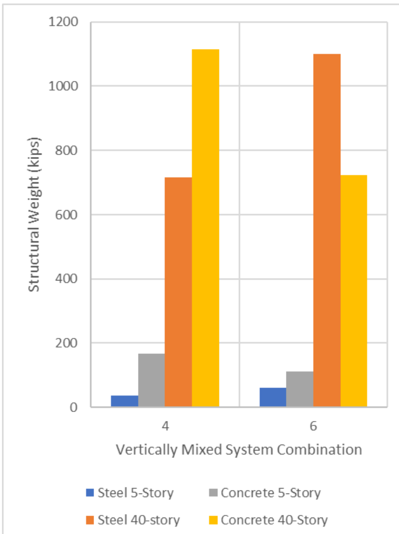


Fig. 4-7 Material Contribution for Structural Weight

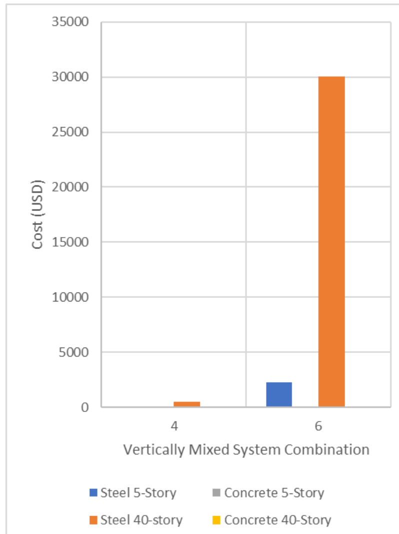


Fig. 4-8 Material Contribution for Cost

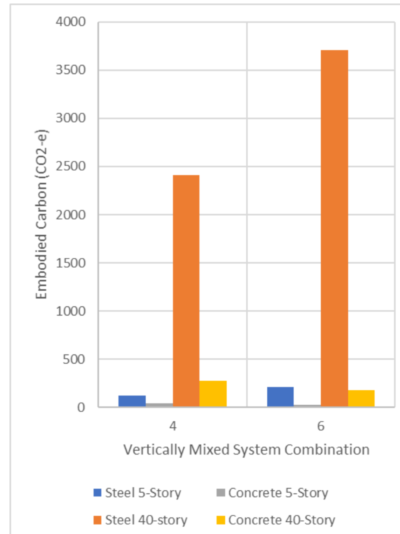


Fig. 4-9 Material Contribution for Embodied Carbon

Figures 4-7 through 4-9 display the contributions of each of the construction materials i.e. steel and concrete towards structural weight, cost and embodied carbon, respectively, for layout 1 and configuration 1 for 5-story and 40-story models. Only VMSC 4 and 6 are considered, since only VMSC 4 and 6 have vertically mixed systems consisting of both steel and concrete. Figure 4-7 indicates that for the 5-story model, the weight of steel used with respect to the weight of concrete is significantly lower than for a 40-story building. For VMSC 4, the ratio of weight of steel per weight of concrete changes from 0.22 to 0.64 between the 5-story and 40-story models, respectively. For VMSC 6, the ratio changes from 0.56 to 1.52, where the weight of steel used in the 40-story model exceeds the weight of concrete. This trend may be due to the discrepancy of density between the two materials. Since steel is heavier than concrete by unit volume, the additional amount of steel used in the taller structure results in significantly higher weights of steel. Figures 4-8 and Figure 4-9 indicate that for both the 5-story and 40-story models, steel contributes remarkably more towards cost and embodied carbon relative to concrete. Although both VMSC 4 and 6 utilize less volume of steel than concrete, steel's high cost and carbon coefficient can be considered the likely cause for this trend.

4.2 Module 2

Using Module 2, a single 5-story structure with layout 1 and configuration 1 is analyzed for all applicable VMSCs. For each applicable VMSC, a separate SAP2000 model is created, and the structural weight, cost and embodied carbon values are recorded. The values for structural weight, cost and embodied carbon of the models are shown as gradient plots in Figures 4-10 through 4-12, respectively, where the color intensity of the point indicates the normalized value of the output parameter.

Using equal multi-objective function weights i.e. $W_W = W_C = W_E = 0.33$, the gradient plot for the multi-objective function value is shown in Figure 4-13. Similar to Figures 4-10 through 4-12, the color intensity of the point indicates the normalized value of the multi-objective function.

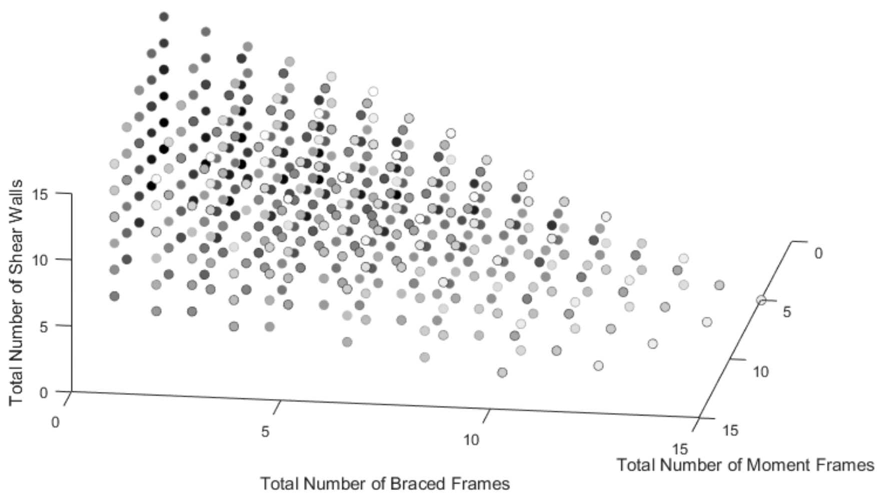


Fig. 4-10 Gradient Plot of Structural Weight (Module 2, Layout 1, Configuration 1, 5-Story)

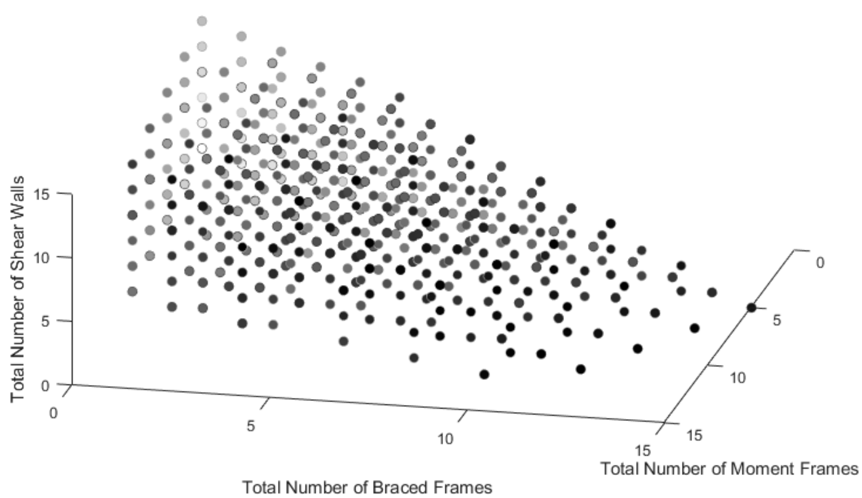


Fig. 4-11 Gradient Plot of Cost (Module 2, Layout 1, Configuration 1, 5-Story)

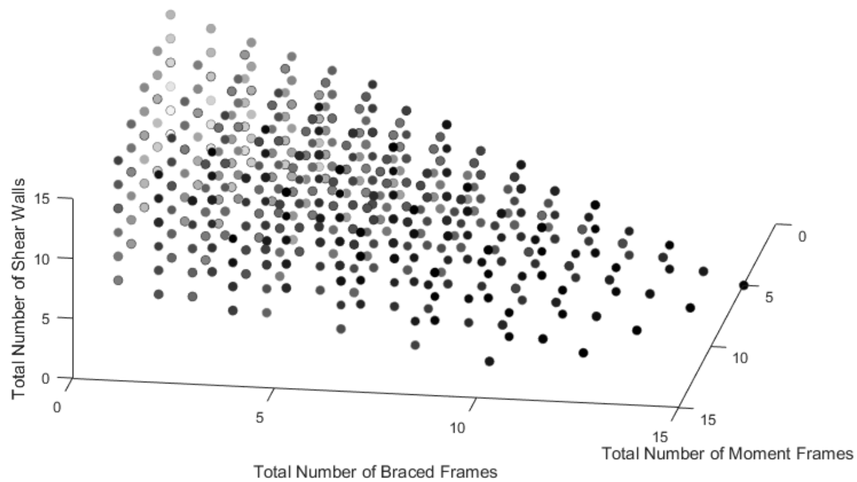


Fig. 4-12 Gradient Plot of Embodied Carbon (Module 2, Layout 1, Configuration 1, 5-Story)

Figures 4-10 through 4-12 display the gradient plots generated using Module 2 for structural weight, cost and embodied carbon, respectively, of a 5-story building with layout 1 and configuration 1. Figures 4-10 and 4-11 indicate that models with concrete shear walls amass the highest structural weights, whereas the models with the highest number of moment connections require the highest costs. Since concrete shear walls are assumed to be cast over the entire length of the lateral load-resisting bay, their weight contribution in a 5-story building is significantly higher than steel. However as shown in Figure 4-7, for a 40-story structure the structural weight contribution of steel surpasses that of concrete. Figure 4-12 provides no clear trend in the distribution of embodied carbon between the different models. The number of data points generated for a 5-story building simply may not be sufficient to identify any such potential trends.

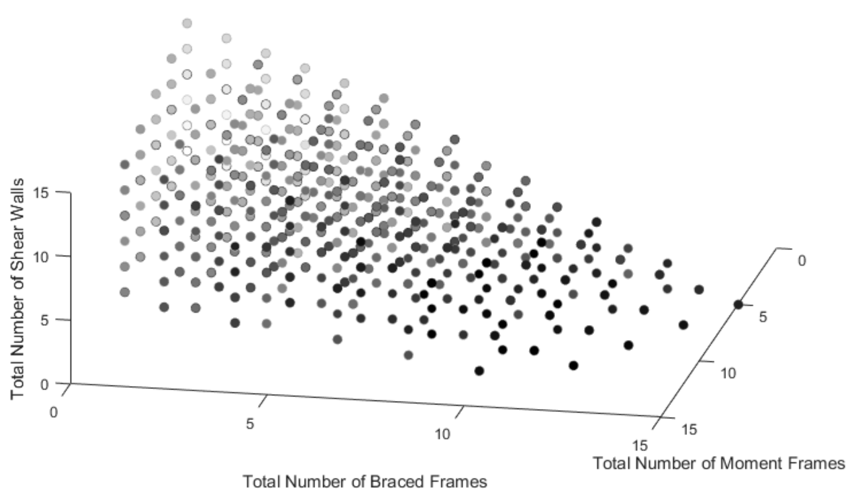


Fig. 4-13 Gradient Plot of Multi-Objective Function (Module 2, Layout 1, Configuration 1, 5-Story)

Figure 4-13 displays the gradient plot of the multi-objective function values generated using Module 2 of a 5-story building with layout 1 and configuration 1. The gradient plot of multi-objective function allows the designer to visually assess the design space, and make an informed decision based on the optimality of viable design options. This plot can be also conveniently used to identify local maxima and minima in the design space, and use that information to choose a final design. For a 5-story building, as seen in Figure 4-13, the optimality of the structures increase as more moment frames and braced frames are used. However for taller buildings, concrete shear walls are expected to contribute more to optimal solutions due to the greater magnitude of lateral loads induced in the lateral load-resisting system. Although Module 2 allows designers to analyze all possible design options for a given building height and lateral load-resisting system layout, Module 1 serves a similar function with a fraction of the computing power.

The differences between the optimal solutions from Module 1 and Module 2 are summarized in Table 4.1. As indicated by Table 4.1, the largest difference in optimality between the two modules is only 12%, suggesting that Module 1 can be used to predict an optimal solution without running an iterative and time consuming Module 2 analysis for each structure. However, if desired by the designer, Module 2 can be implemented to further develop the efficiency and optimality of a design scheme already chosen through using Module 1. For the 5-story building analyzed through Module 2 in chapter 4.2, the most optimal solution for MOWC 3 consisted of 4 floors with braced frames and the top floor with moment frame. In contrast, the most optimal solution obtained through Module 1 for the same structure consisted of 5 floors of braced frames.

Table 4.1 – Module 1 and Module 2 Optimality Difference for Various MOWC

MOWC	Module 1	Module 2	% Difference
1	J = 0.22, VMSC = 2	J = 0.22, Mom = 2, Brace = 3, S.W. = 0	0
2	J = 0.17, VMSC = 2	J = 0.16, Mom = 2, Brace = 3, S.W. = 0	6
3	J = 0.17, VMSC = 2	J = 0.15, Mom = 1, Brace = 4, S.W. = 0	12
4	J = 0.25, VMSC = 1	J = 0.23, Mom = 4, Brace = X, S.W. = 1	8

5. Conclusion

5.1 Summary

This research details and analyzes two methods for optimizing vertically mixed lateral systems in buildings consisting of moment frames, cross braced frames and concrete shear walls. Module 1 allows the designer to assess any predefined rectangular building with equal bay dimensions and lateral load-resisting system for 6 different vertically mixed system combinations. For each of these combinations, the algorithm developed as part of this research retrieves the structural weight, cost and embodied carbon for the model. These values are then analyzed for 4 different multi-objective weight combinations. Using a separate algorithm, Module 2 creates all viable models for any given lateral load-resisting system using incremental changes for the number of stories consisting of moment frames, braced frames and concrete shear walls. Similar to Module 1, the algorithm retrieves the structural weight, cost and embodied carbon for each model. Using these values, gradient plots for each of the output parameters and the multi-objective function value are created. These plots allow the designer to visually assess the design space, and make an informed decision based on the optimality of viable design options. By taking a multi-objective optimization approach to selecting lateral load-resisting systems in buildings, this research proposes a practical tool that can be used by designers to assess the performance of common lateral system layouts based on the optimization criteria.

The results presented in Chapter 4 show that the optimality of buildings, with respect to structural weight, cost and embodied carbon, can be significantly improved using vertically mixed laterally systems. The optimal solution varies depending on the structure's height, lateral load-resisting system and the values of multi-objective weights used. For example, while a fully braced frame system may be the most optimal solution for a 5-story building, the most optimal solution for a 40-story building with the same floor plan and lateral load-resisting system layout can be a 50% braced frame and 50% moment frame system. If a greater multi-objective weight is assigned to a certain variable, the algorithm prioritizes that particular variable over the others. For example, if more multi-objective weight is assigned to structural weight i.e. minimizing structural weight is considered a priority, the optimal solution may change from a 33% split between moment frames, braced frames and shear walls to a 50% braced frame and 50% moment frame system.

The layout and configuration of lateral load-resisting systems also have an influence on the overall optimality of the structure. Highest efficiency in structural design is achieved by using square layouts and centric shear cores, while least effective designs consist of high aspect ratio layout and eccentric lateral load-resisting elements.

5.2 Future Work

Due to the large scope of research involved in the lateral system selection design, there is a variety of ways this research can be expanded upon in future works. Vertically mixed systems are fairly uncommon in today's building industry, and more comprehensive studies need to be conducted to fully identify and analyze all relevant parameters involved in the design and construction process for such systems. Many factors not considered in the scope of this research, for example asymmetrical geometries in buildings, architectural considerations for lateral systems and different building locations, can be analyzed in future studies. Furthermore, a holistic multi-objective optimization can be conducted that will account for indirect parameters, such as manufacturing costs and transportation costs, as part of its analysis. Finally, future studies may be conducted to improve and enhance the designer interaction experience, which will provide the designer with more control over the design process.

5.3 Concluding Remarks

A small number of studies have investigated design procedures for vertically mixed lateral systems. This research reviewed prior research and aims to expand the available data on optimizing such systems using multi-objective optimization. The methods and procedures outlined in this research may be used by potential designers to reaffirm or challenge their preexisting design intuitions regarding the optimized design of lateral systems.

References

American Society of Civil Engineers (ASCE). Minimum Design Loads for Buildings and Other Structures. (2005).

American Society of Civil Engineers (ASCE). Minimum Design Loads for Buildings and Other Structures. (2010).

Brun, J., & Kostem, C. N. (1986*). Lateral Deflection Prediction of Concrete Frame-shear Wall System* (Graduate Thesis, Lehigh University). Retrieved from http://digital.lib.lehigh.edu/fritz/pdf/433_6.

Candiani, E., & Sala, S. (2013). *Optimization of Tied Lateral Systems for Tall Buildings Design* (Graduate Thesis, Politecnico di Milano). Retrieved from https://www.politesi.polimi.it/handle/10589/100521.

Carpinteri, A., Corrado, M., Lacidogna, G., & Cammarano, S. (2012*).* Lateral Load Effects on Tall Shear Wall Structures of Different Height. *Structural Engineering & Mechanics, 41(3), 313-337.*

Case, J. M. (2011). *Effect of Building Geometry on Wind Loads on Lowrise Buildings in a Laboratory-Simulated Tornado with a High Swirl Ratio* (Doctoral dissertation, Iowa State University). Retrieved from Ch http://lib.dr.iastate.edu/etd/10402/001.

Chan, C. Optimal Lateral Stiffness Design of Tall Buildings of Mixed Steel and Concrete Construction. *The Structural Design of Tall Buildings*, 10(3), 155-177.

Chok, K. (2004). *Lateral Systems for Tall Buildings. Department of Civil and Environmental Engineering* (Master's Thesis, Massachusetts Institute of Technology). Retrieved from http://hdl.handle.net/1721.1/30135.

Fatima, T. (2014). *Optimisation of Lateral Load-Resisting Systems in Composite High-rise Buildings* (Master's Thesis, Queensland University of Technology). Retrieved from http://eprints.qut.edu.au/67563.

Griffis, L. G. (1993). Serviceability Limit States Under Wind Load. *Engineering Journal*, Quarter 1, 1-16.

Hajjar, J. (2001). Composite Steel and Concrete Structural Systems for Seismic Engineering. *Journal of Constructional Steel Research*, 703-723.

Khan, F.R. (1972). Influence of design criteria on selection of structural systems for tall buildings, In *Proceedings of the Canadian Structural Engineering Conference*. Toronto: Canadian Steel Industries Construction Council, 1-15.

Khan, F. R. (1965). Design of High-rise Buildings. ASCE AISC Chicago Fabricators, University of Illinois at Chicago Circle.

Maheshwari, M., & Santhakumar, A. (2004). Capacity Design for Tall Buildings with Mixed Systems. *World Conference on Earthquake Engineering*, 1-15.

Nadoushani, Z., & Akbarnezhad, A. (2015). Comparative Analysis of Embodied Carbon Associated with Alternative Structural Systems. *International Association for Automation and Robotics in Construction*.

New York City. New York City Building Code 2014. (2014).

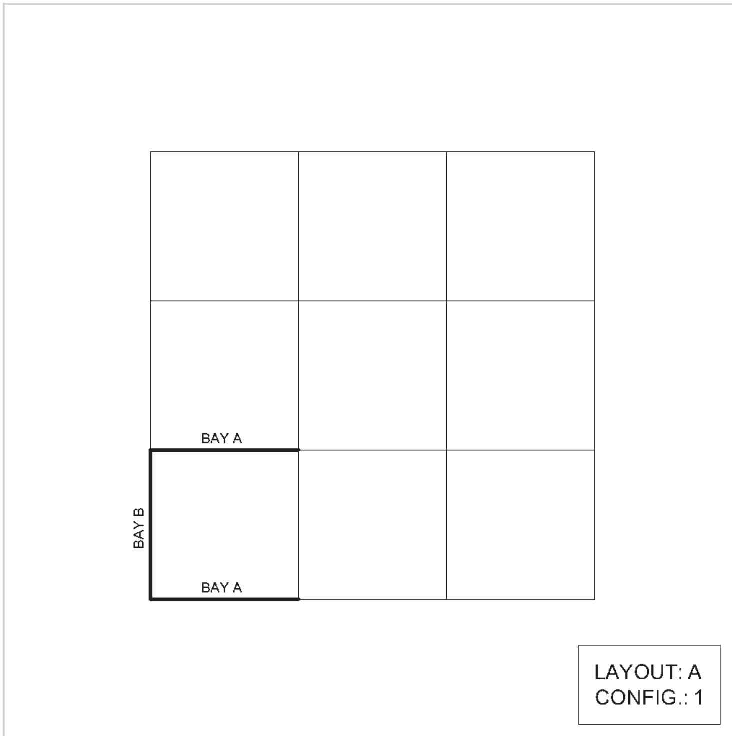
O'Connor, F. (2012). *Effects of Building Plan Configuration on Lateral Load Response* (Master's Thesis, USC School of Architecture University of Southern California). Retrieved from http://digitallibrary.usc.edu/35750.

Sanayei, M., Edgers, L., Alonge, J., & Kirshen, P. (2003). Effects of Increased Wind Loads on Tall Buildings. *Civil Engineering Practice*, Fall, 5-16.

Taranath, Bungale S. (2011). *Structural Analysis and Design of Tall Buildings: Steel and Composite Construction*. Boca Raton: CRC, 2011. Print.

Appendix A – Hand Calculation

Sample Lateral Load Calculation



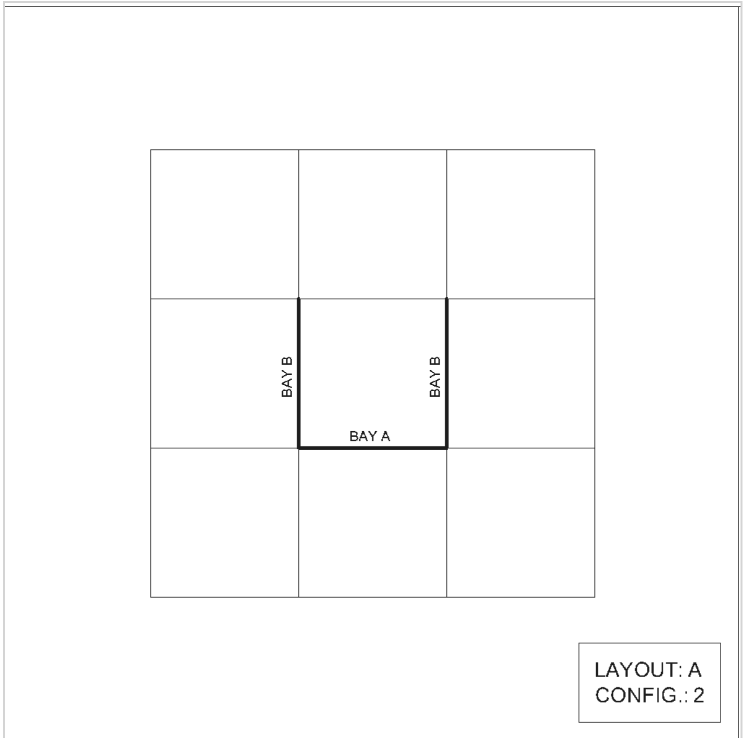
Building Layout:	A	
Lateral Bracing Configuration:	1	
Number of stories:	5	
Bx (ft):	48	
By (ft)	48	
Number of braces || to x-axis (Bay A):	2	
Number of braces || to y-axis (Bay B):	1	
Center of rigidity [x, y]:	0	8
Center of mass [x, y]:	24	24
Load Case	WIND - 1	

Story Forces

Story	Hand Calculation					SAP2000		Δ Change
	P_X (kips)	P_Y (kips)	M_T (k.ft)	Bay A (kips)*	Bay B (kips)*	Bay A (kips)	Bay B (kips)	
5	11.74	0.00	0.00	5.87	0.00	5.00	0.00	1
4	11.69	0.00	0.00	5.85	0.00	6.00	0.00	0
3	11.63	0.00	0.00	5.82	0.00	6.00	0.00	0
2	11.56	0.00	0.00	5.78	0.00	7.00	0.00	1
1	11.44	0.00	0.00	5.72	0.00	7.00	6.00	7
Base Shear X	-	-	-	58.07		65.00		7
Base Shear Y	-	-	-	0.00		0.00		0

* Calculations assume Bay A and B have equal lateral stiffness

Sample Lateral Load Calculation



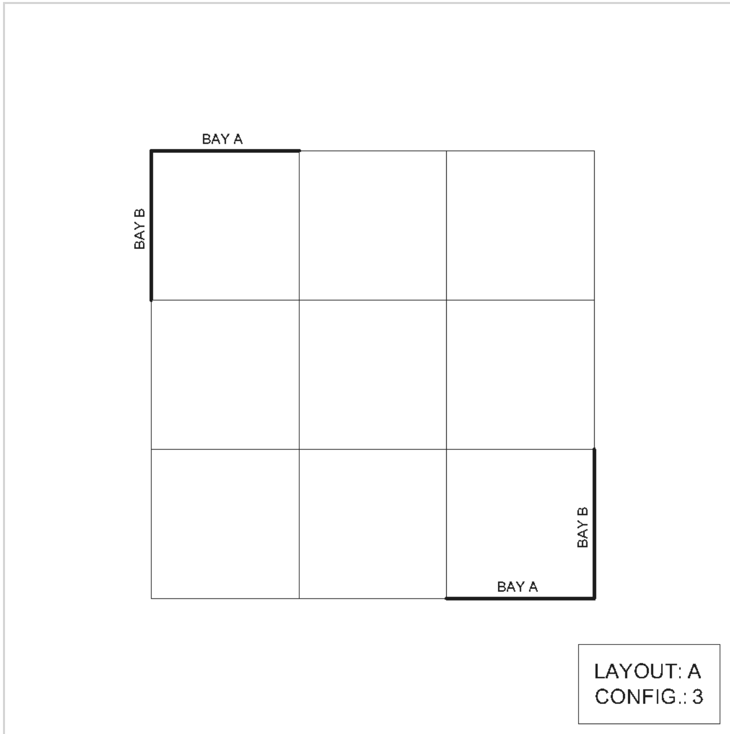
Building Layout:	A	
Lateral Bracing Configuration:	2	
Number of stories:	5	
Bx (ft):	48	
By (ft)	48	
Number of braces || to x-axis (Bay A):	1	
Number of braces || to y-axis (Bay B):	2	
Center of rigidity [x, y]:	24	16
Center of mass [x, y]:	24	24
Load Case	WIND - 2	

Story Forces

Story	Hand Calculation					SAP2000		Δ Change
	P_X (kips)	P_Y (kips)	M_T (k.ft)	Bay A (kips)*	Bay B (kips)*	Bay A (kips)	Bay B (kips)	
5	0.00	11.74	0.00	0.00	11.74	1.00	6.00	5
4	0.00	11.69	0.00	0.00	11.69	0.00	6.00	6
3	0.00	11.63	0.00	0.00	11.63	0.00	6.00	6
2	0.00	11.56	0.00	0.00	11.56	1.00	4.00	7
1	0.00	11.44	0.00	0.00	11.44	1.00	6.00	4
Base Shear X	-	-	-	0.00		0.00		0
Base Shear Y	-	-	-	58.07		65.00		7

* Calculations assume Bay A and B have equal lateral stiffness

Sample Lateral Load Calculation



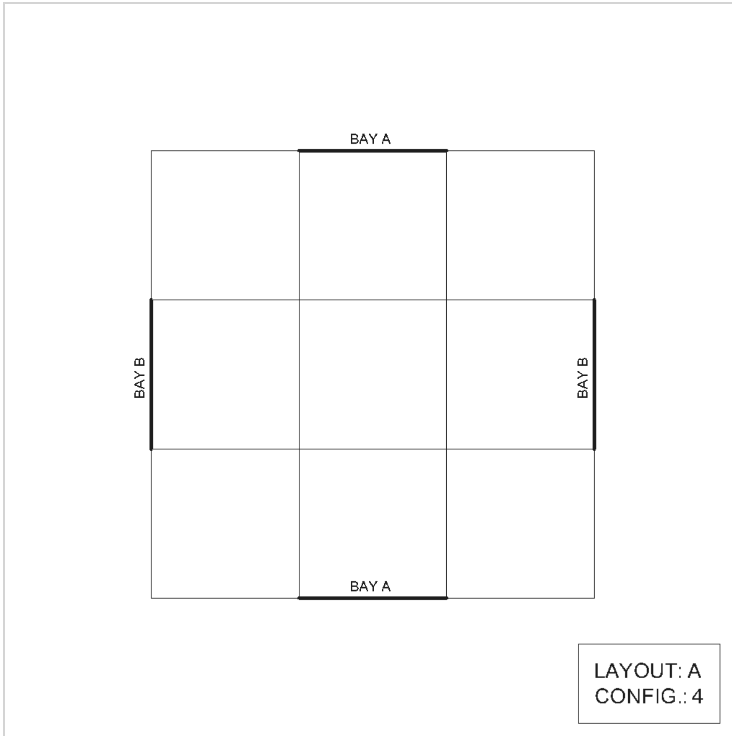
Building Layout:	A	
Lateral Bracing Configuration:	3	
Number of stories:	5	
Bx (ft):	48	
By (ft)	48	
Number of braces | | to x-axis (Bay A):	2	
Number of braces | | to y-axis (Bay B):	2	
Center of rigidity [x, y]:	24	24
Center of mass [x, y]:	24	24
Load Case	WIND - 3	

Story Forces

Story	Hand Calculation					SAP2000		Δ Change
	P_X (kips)	P_Y (kips)	M_T (k.ft)	Bay A (kips)*	Bay B (kips)*	Bay A (kips)	Bay B (kips)	
5	8.80	0.00	63.39	5.06	0.66	4.50	1.00	0
4	8.77	0.00	63.13	5.04	0.66	6.50	1.00	2
3	8.73	0.00	62.82	5.02	0.65	8.00	2.00	4
2	8.67	0.00	62.42	4.98	0.65	8.50	2.00	5
1	8.58	0.00	61.80	4.94	0.64	9.00	3.00	6
Base Shear X	-	-	-	43.55		52.00		8
Base Shear Y	-	-	-	0.00		0.00		0

* Calculations assume Bay A and B have equal lateral stiffness

Sample Lateral Load Calculation		



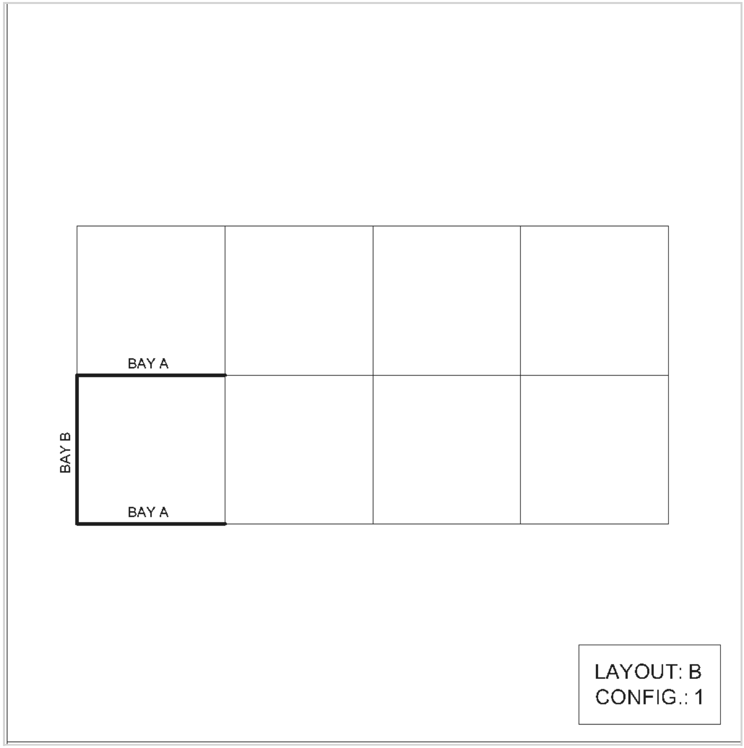
Building Layout:	A	
Lateral Bracing Configuration:	4	
Number of stories:	5	
Bx (ft):	48	
By (ft)	48	
Number of braces | | to x-axis (Bay A):	2	
Number of braces | | to y-axis (Bay B):	2	
Center of rigidity [x, y]:	24	24
Center of mass [x, y]:	24	24
Load Case	WIND - 4	

Story Forces

Story	Hand Calculation					SAP2000		Δ Change
	P_X (kips)	P_Y (kips)	M_T (k.ft)	Bay A (kips)*	Bay B (kips)*	Bay A (kips)	Bay B (kips)	
5	8.80	0.00	-63.39	3.74	-0.66	1.00	0.50	2
4	8.77	0.00	-63.13	3.73	-0.66	0.50	0.50	2
3	8.73	0.00	-62.82	3.71	-0.65	0.50	0.50	2
2	8.67	0.00	-62.42	3.68	-0.65	1.00	0.50	2
1	8.58	0.00	-61.80	3.65	-0.64	0.50	0.50	2
Base Shear X	-	-	-	43.55		52.00		8
Base Shear Y	-	-	-	0.00		0.00		0

* Calculations assume Bay A and B have equal lateral stiffness

Sample Lateral Load Calculation



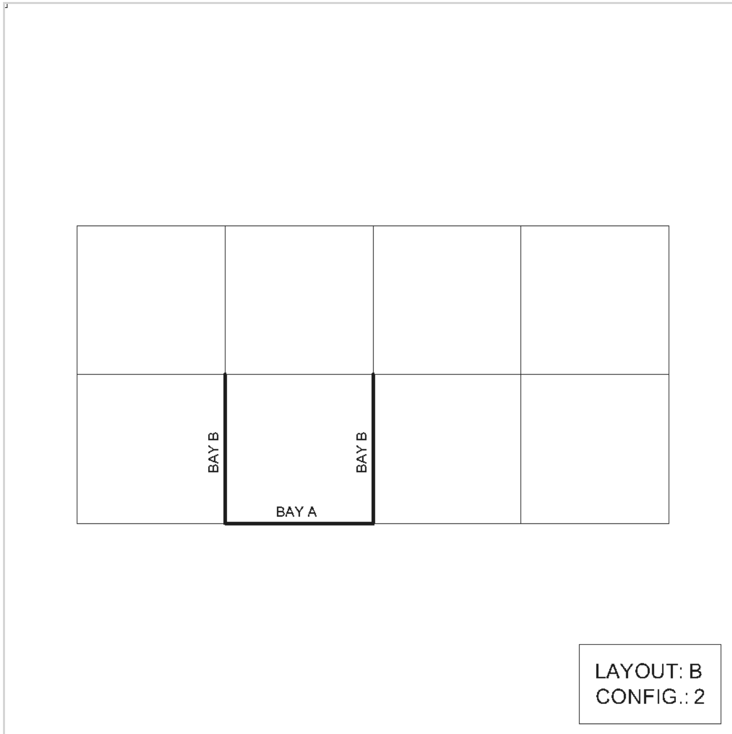
Building Layout:	B	
Lateral Bracing Configuration:	1	
Number of stories:	5	
Bx (ft):	64	
By (ft)	32	
Number of braces | | to x-axis (Bay A):	2	
Number of braces | | to y-axis (Bay B):	1	
Center of rigidity [x, y]:	0	8
Center of mass [x, y]:	32	16
Load Case	WIND - 5	

Story Forces

Story	Hand Calculation					SAP2000		Δ Change
	P_X (kips)	P_Y (kips)	M_T (k.ft)	Bay A (kips)*	Bay B (kips)*	Bay A (kips)	Bay B (kips)	
5	0.00	11.74	488.31	30.52	11.74	19.00	11.00	12
4	0.00	11.69	486.36	30.40	11.69	24.00	8.00	10
3	0.00	11.63	483.98	30.25	11.63	25.00	17.00	0
2	0.00	11.56	480.86	30.05	11.56	28.00	20.00	6
1	0.00	11.44	476.09	29.76	11.44	32.00	15.00	6
Base Shear X	-	-	-	0.00		0.00		0
Base Shear Y	-	-	-	58.07		69.00		11

* Calculations assume Bay A and B have equal lateral stiffness

Sample Lateral Load Calculation



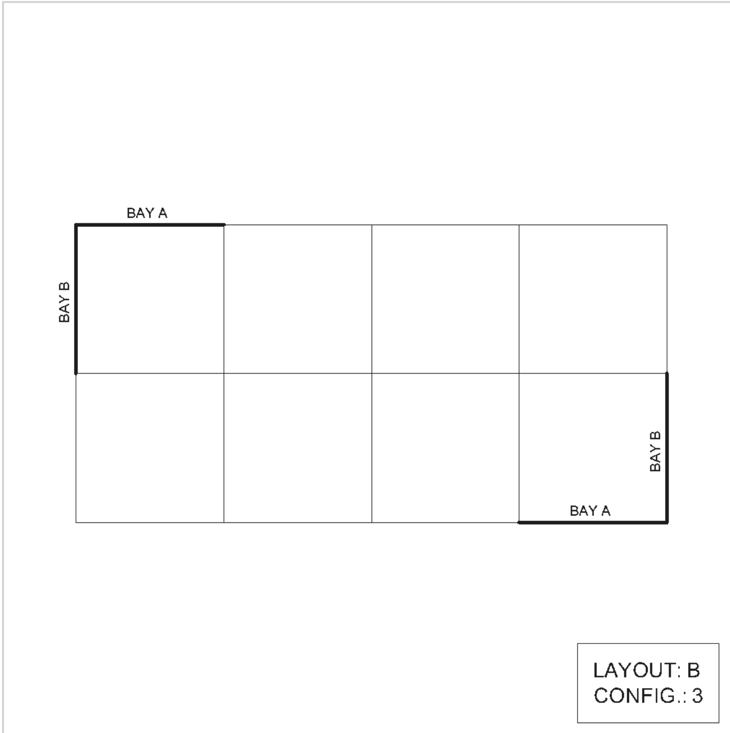
Building Layout:	B	
Lateral Bracing Configuration:	2	
Number of stories:	5	
Bx (ft):	64	
By (ft)	32	
Number of braces | | to x-axis (Bay A):	1	
Number of braces | | to y-axis (Bay B):	2	
Center of rigidity [x, y]:	24	0
Center of mass [x, y]:	32	16
Load Case	WIND - 6	

Story Forces

Story	Hand Calculation					SAP2000		Δ Change
	P_X (kips)	P_Y (kips)	M_T (k.ft)	Bay A (kips)*	Bay B (kips)*	Bay A (kips)	Bay B (kips)	
5	0.00	11.74	-18.78	0.00	10.56	0.00	0.00	11
4	0.00	11.69	-18.71	0.00	10.52	0.00	1.00	10
3	0.00	11.63	-18.61	0.00	10.47	0.00	4.00	6
2	0.00	11.56	-18.49	0.00	10.40	0.00	6.00	4
1	0.00	11.44	-18.31	0.00	10.30	0.00	10.00	0
Base Shear X	-	-	-	0.00		0.00		0
Base Shear Y	-	-	-	58.07		69.00		11

* Calculations assume Bay A and B have equal lateral stiffness

Sample Lateral Load Calculation



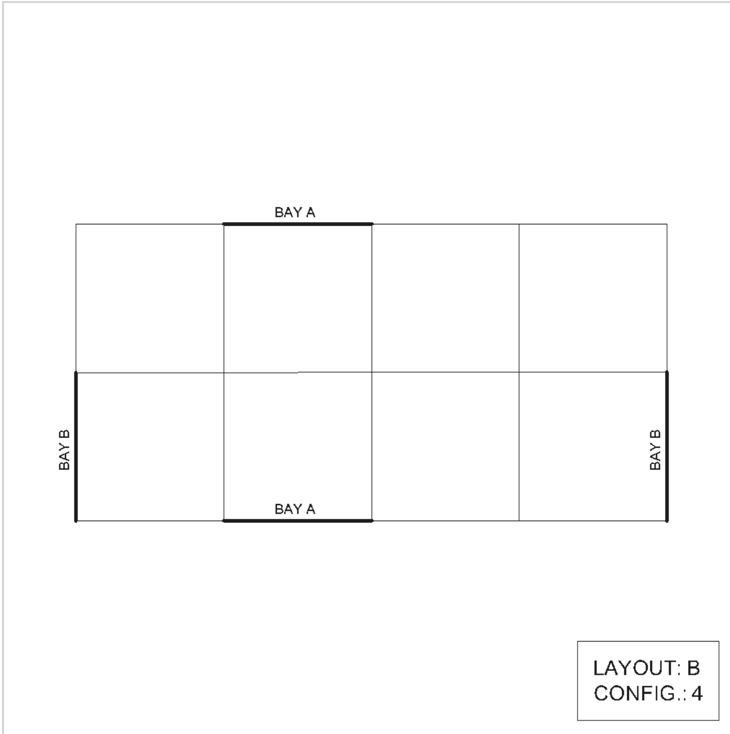
Building Layout:	B	
Lateral Bracing Configuration:	3	
Number of stories:	5	
Bx (ft):	64	
By (ft)	32	
Number of braces | | to x-axis (Bay A):	2	
Number of braces | | to y-axis (Bay B):	2	
Center of rigidity [x, y]:	32	16
Center of mass [x, y]:	32	16
Load Case	QUAKE - X	

Story Forces

Story	Hand Calculation					SAP2000		Δ Change
	P_X (kips)	P_Y (kips)	M_T (k.ft)	Bay A (kips)*	Bay B (kips)*	Bay A (kips)	Bay B (kips)	
5	9.64	0.00	0.00	4.82	0.00	6.00	0.00	1
4	9.64	0.00	0.00	4.82	0.00	6.00	0.00	1
3	9.64	0.00	0.00	4.82	0.00	13.00	0.00	8
2	9.64	0.00	0.00	4.82	0.00	12.00	0.00	7
1	9.64	0.00	0.00	4.82	0.00	6.00	0.00	1
Base Shear X	-	-	-	48.19		52.00		4
Base Shear Y	-	-	-	0.00		0.00		0

* Calculations assume Bay A and B have equal lateral stiffness

Sample Lateral Load Calculation



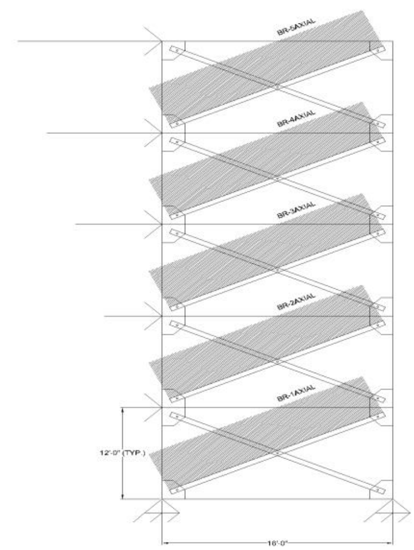
Building Layout:	B	
Lateral Bracing Configuration:	4	
Number of stories:	5	
Bx (ft):	64	
By (ft)	32	
Number of braces || to x-axis (Bay A):	2	
Number of braces || to y-axis (Bay B):	2	
Center of rigidity [x, y]:	32	16
Center of mass [x, y]:	32	16
Load Case	QUAKE - Y	

Story Forces

Story	Hand Calculation					SAP2000		Δ Change
	P_X (kips)	P_Y (kips)	M_T (k.ft)	Bay A (kips)*	Bay B (kips)*	Bay A (kips)	Bay B (kips)	
5	0.00	9.64	0.00	0.00	9.64	0.00	6.00	4
4	0.00	9.64	0.00	0.00	9.64	0.00	6.00	4
3	0.00	9.64	0.00	0.00	9.64	0.00	13.00	3
2	0.00	9.64	0.00	0.00	9.64	0.00	12.00	2
1	0.00	9.64	0.00	0.00	9.64	0.00	13.00	3
Base Shear X	-	-	-	0.00		0.00		0
Base Shear Y	-	-	-	48.19		53.00		5

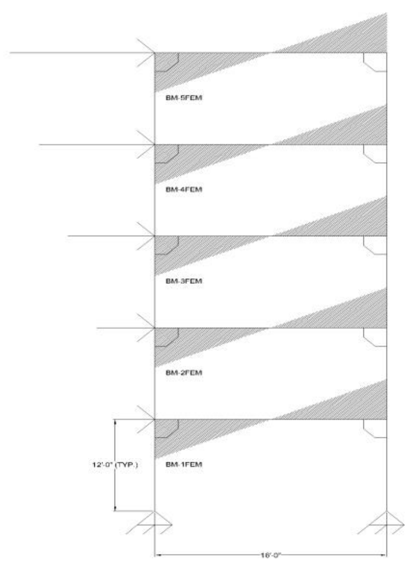
* Calculations assume Bay A and B have equal lateral stiffness

Sample Brace Calculation



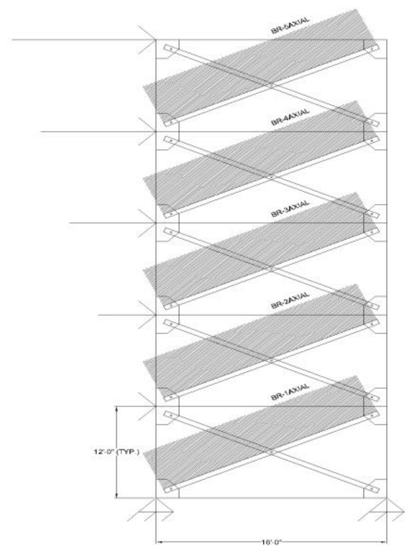
Building Geometry		Element	Hand Calculation	SAP2000	% Difference
Layout:	B	$BR\text{-}5_{axial}$ (kips)	22.54	23.44	4
Configuration:	3	$BR\text{-}4_{axial}$ (kips)	42.45	42.77	1
Stories:	5	$BR\text{-}3_{axial}$ (kips)	59.98	62.79	5
Bay Width (ft):	16	$BR\text{-}2_{axial}$ (kips)	74.91	77.87	4
Load Case:	QUAKE - X	$BR\text{-}1_{axial}$ (kips)	87.63	92.67	6

Sample Moment Frame Calculation



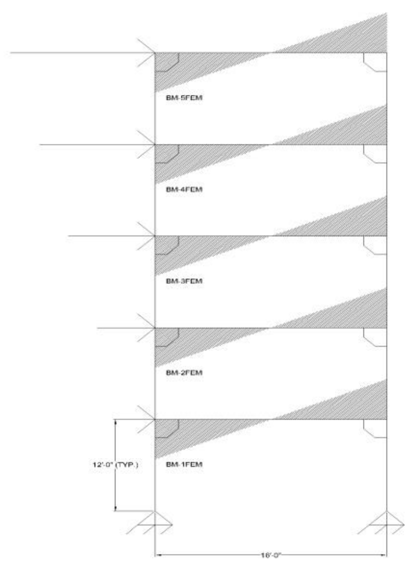
Building Geometry		Element	Hand Calculation	SAP2000	% Difference
Layout:	B	$BM\text{-}5_{FEMmax}$ (kip.ft)	174	177	2
Configuration:	3	$BM\text{-}4_{FEMmax}$ (kip.ft)	324	328	1
Stories:	5	$BM\text{-}3_{FEMmax}$ (kip.ft)	503	522	4
Bay Width (ft):	16	$BM\text{-}2_{FEMmax}$ (kip.ft)	708	737	4
Load Case:	QUAKE - X	$BM\text{-}1_{FEMmax}$ (kip.ft)	1048	1090	4

Sample Brace Calculation



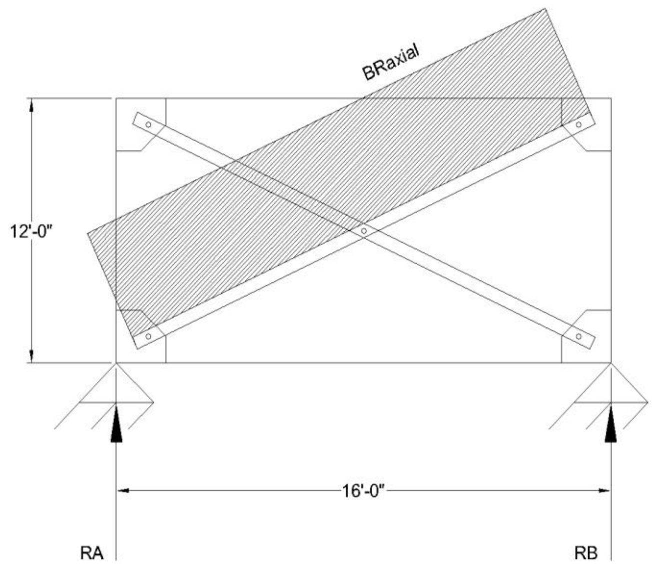
Building Geometry		Element	Hand Calculation	SAP2000	% Difference
Layout:	A	BR-5$_{axial}$ (kips)	27.55	28.45	3
Configuration:	2	BR-4$_{axial}$ (kips)	51.19	54.09	6
Stories:	5	BR-3$_{axial}$ (kips)	71.22	73.78	4
Bay Width (ft):	16	BR-2$_{axial}$ (kips)	87.39	91.66	5
Load Case:	WIND - 2	BR-1$_{axial}$ (kips)	100.15	106.99	7

Sample Moment Frame Calculation



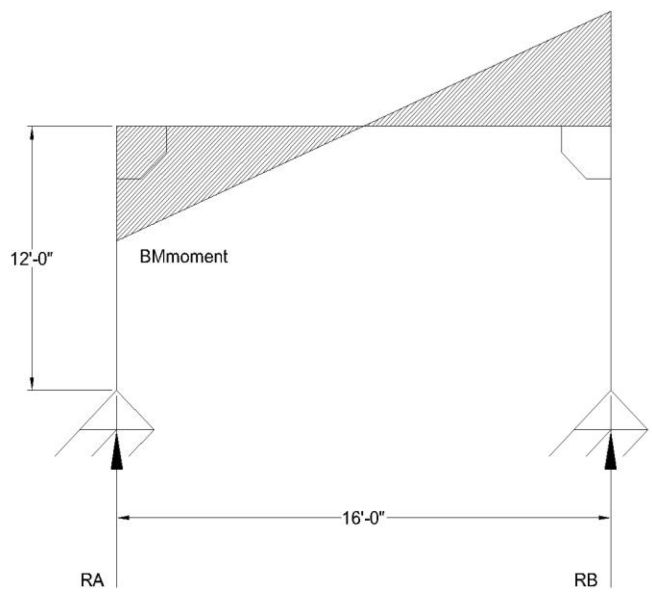
Building Geometry		Element	Hand Calculation	SAP2000	% Difference
Layout:	A	BM-5$_{FEMmax}$ (kip.ft)	211	217	3
Configuration:	2	BM-4$_{FEMmax}$ (kip.ft)	390	410	5
Stories:	5	BM-3$_{FEMmax}$ (kip.ft)	598	615	3
Bay Width (ft):	16	BM-2$_{FEMmax}$ (kip.ft)	828	858	4
Load Case:	WIND - 2	BM-1$_{FEMmax}$ (kip.ft)	1210	1312	8

Sample Unit Brace Calculation



Force/Moment	Hand Calculation	SAP2000	% Difference
R_A (kips):	-0.75	-0.75	0
R_B (kips):	0.75	0.75	0
Brace Axial Force (kips):	1.25	1.25	0

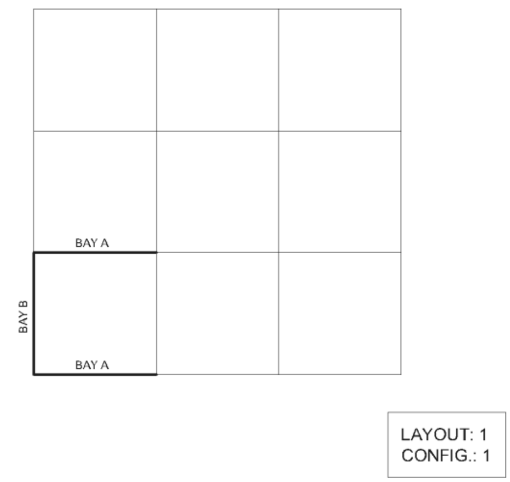
Sample Unit Moment Frame Calculation



Force/Moment	Hand Calculation	SAP2000	% Difference
R_A (kips):	-0.75	-0.75	0
R_B (kips):	0.75	0.75	0
Beam End Moment (kip.ft):	5.99	6.05	1

Appendix B - Results

Output Results



Layout:	1
Configuration:	1
Story:	5

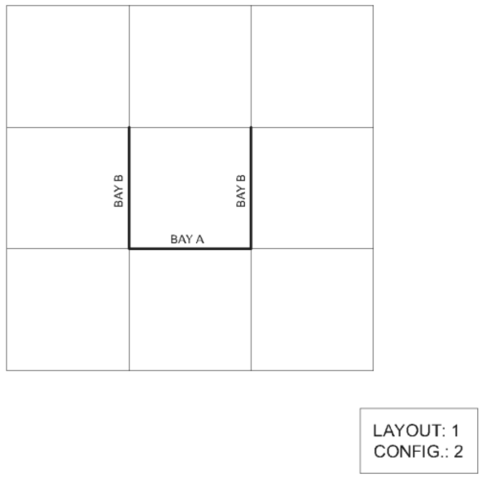
Result Parameters

Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	9.60	278.40	0	288.00	13.32	101.95
100% Bracing	82.77	0.00	0	82.77	62.08	278.93
100% Moment Frames	109.62	0.00	15	109.62	11332.21	369.42
~50% Concrete Shear Wall, ~50% Bracing	36.80	167.04	0	203.84	31.28	165.79
~50% Bracing, ~50% Moment Frames	91.26	0.00	6	91.26	4568.45	307.56
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	61.67	111.36	3	173.03	2298.71	235.68

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33, W_C = 0.33, W_E = 0.34$	$W_W = 0.50, W_C = 0.25, W_E = 0.25$	$W_W = 0.25, W_C = 0.50, W_E = 0.25$	$W_W = 0.25, W_C = 0.25, W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.22	0.17	0.17	0.33
100% Moment Frames	0.70	0.57	0.78	0.78
~50% Concrete Shear Wall, ~50% Bracing	0.27	0.36	0.21	0.27
~50% Bracing, ~50% Moment Frames	0.40	0.31	0.40	0.50
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.38	0.40	0.34	0.41
J_{min}	0.22	0.17	0.17	0.25

Output Results



Layout:	1
Configuration:	2
Story:	5

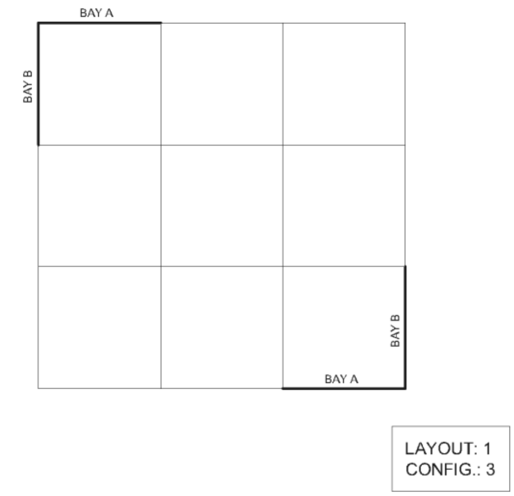
Result Parameters

Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	9.60	278.40	0	288.00	13.32	101.95
100% Bracing	78.69	0.00	0	78.69	59.02	265.19
100% Moment Frames	135.72	0.00	15	135.72	11351.79	457.38
~50% Concrete Shear Wall, ~50% Bracing	36.36	167.04	0	203.40	30.95	164.29
~50% Bracing, ~50% Moment Frames	96.80	0.00	6	96.80	4572.60	326.21
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	71.41	111.36	3	182.77	2306.01	268.49

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33, W_C = 0.33, W_E = 0.34$	$W_W = 0.50, W_C = 0.25, W_E = 0.25$	$W_W = 0.25, W_C = 0.50, W_E = 0.25$	$W_W = 0.25, W_C = 0.25, W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.15	0.12	0.12	0.23
100% Moment Frames	0.75	0.64	0.82	0.82
~50% Concrete Shear Wall, ~50% Bracing	0.26	0.34	0.19	0.24
~50% Bracing, ~50% Moment Frames	0.37	0.30	0.38	0.44
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.39	0.42	0.34	0.41
J_{min}	0.15	0.12	0.12	0.23

Output Results



Layout:	1
Configuration:	3
Story:	5

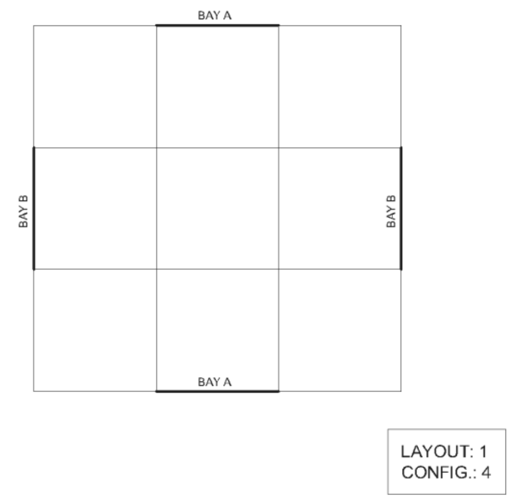
Result Parameters

Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	12.80	371.20	0	384.00	17.77	135.94
100% Bracing	105.97	0.00	0	105.97	79.47	357.10
100% Moment Frames	162.94	0.00	20	162.94	15122.20	549.09
~50% Concrete Shear Wall, ~50% Bracing	49.71	222.72	0	272.43	42.18	223.21
~50% Bracing, ~50% Moment Frames	124.07	0.00	8	124.07	6093.05	418.11
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	89.38	148.48	4	237.86	3070.30	338.32

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33, W_C = 0.33, W_E = 0.34$	$W_W = 0.50, W_C = 0.25, W_E = 0.25$	$W_W = 0.25, W_C = 0.50, W_E = 0.25$	$W_W = 0.25, W_C = 0.25, W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.18	0.13	0.14	0.27
100% Moment Frames	0.73	0.60	0.80	0.80
~50% Concrete Shear Wall, ~50% Bracing	0.27	0.35	0.20	0.26
~50% Bracing, ~50% Moment Frames	0.38	0.30	0.39	0.46
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.38	0.41	0.34	0.41
J_{min}	0.18	0.13	0.14	0.25

Output Results



Layout:	1
Configuration:	4
Story:	5

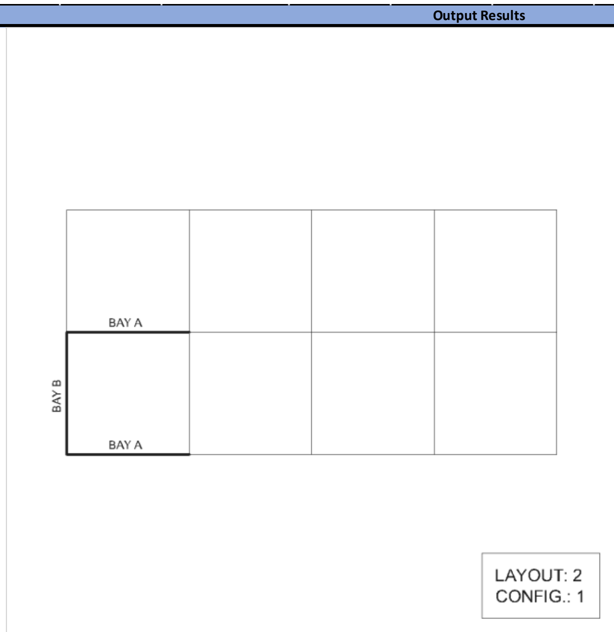
Result Parameters

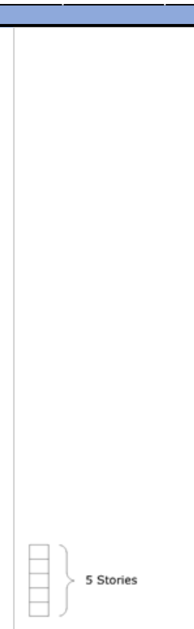
Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	12.80	371.20	0	384.00	17.77	135.94
100% Bracing	115.19	0.00	0	115.19	86.40	388.20
100% Moment Frames	176.82	0.00	20	176.82	15132.61	595.88
~50% Concrete Shear Wall, ~50% Bracing	53.40	222.72	0	276.12	44.95	235.65
~50% Bracing, ~50% Moment Frames	134.85	0.00	8	134.85	6101.14	454.44
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	96.47	148.48	4	244.95	3075.62	362.21

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33, W_C = 0.33, W_E = 0.34$	$W_W = 0.50, W_C = 0.25, W_E = 0.25$	$W_W = 0.25, W_C = 0.50, W_E = 0.25$	$W_W = 0.25, W_C = 0.25, W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.18	0.14	0.14	0.28
100% Moment Frames	0.74	0.61	0.81	0.81
~50% Concrete Shear Wall, ~50% Bracing	0.27	0.35	0.20	0.26
~50% Bracing, ~50% Moment Frames	0.39	0.31	0.39	0.47
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.39	0.41	0.34	0.42
J_{min}	0.18	0.14	0.14	0.25

Output Results





Layout:	2
Configuration:	1
Story:	5

Result Parameters

Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	9.60	278.40	0	288.00	13.32	101.95
100% Bracing	86.41	0.00	0	86.41	64.81	291.22
100% Moment Frames	114.74	0.00	15	114.74	11336.06	386.68
~50% Concrete Shear Wall, ~50% Bracing	36.93	167.04	0	203.97	31.37	166.20
~50% Bracing, ~50% Moment Frames	98.05	0.00	6	98.05	4573.54	330.44
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	62.81	111.36	3	174.17	2299.56	239.52

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33$, $W_C = 0.33$, $W_E = 0.34$	$W_W = 0.50$, $W_C = 0.25$, $W_E = 0.25$	$W_W = 0.25$, $W_C = 0.50$, $W_E = 0.25$	$W_W = 0.25$, $W_C = 0.25$, $W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.22	0.17	0.17	0.33
100% Moment Frames	0.71	0.57	0.79	0.79
~50% Concrete Shear Wall, ~50% Bracing	0.27	0.35	0.20	0.26
~50% Bracing, ~50% Moment Frames	0.42	0.33	0.42	0.52
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.37	0.39	0.33	0.40
J_{min}	0.22	0.17	0.17	0.25

Output Results

Layout:	2
Configuration:	2
Story:	5

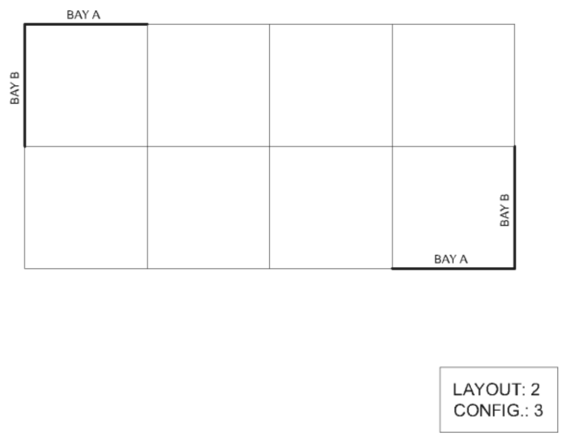
Result Parameters

Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	9.60	278.40	0	288.00	13.32	101.95
100% Bracing	79.73	0.00	0	79.73	59.80	268.70
100% Moment Frames	130.26	0.00	15	130.26	11347.69	438.97
~50% Concrete Shear Wall, ~50% Bracing	36.58	167.04	0	203.62	31.11	165.04
~50% Bracing, ~50% Moment Frames	98.99	0.00	6	98.99	4574.24	333.59
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	71.09	111.36	3	182.45	2305.77	267.41

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33$, $W_C = 0.33$, $W_E = 0.34$	$W_W = 0.50$, $W_C = 0.25$, $W_E = 0.25$	$W_W = 0.25$, $W_C = 0.50$, $W_E = 0.25$	$W_W = 0.25$, $W_C = 0.25$, $W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.16	0.12	0.13	0.25
100% Moment Frames	0.74	0.62	0.81	0.81
~50% Concrete Shear Wall, ~50% Bracing	0.26	0.34	0.20	0.24
~50% Bracing, ~50% Moment Frames	0.39	0.32	0.40	0.47
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.39	0.42	0.35	0.42
J_{min}	0.16	0.12	0.13	0.24

Output Results



Layout:	2
Configuration:	3
Story:	5

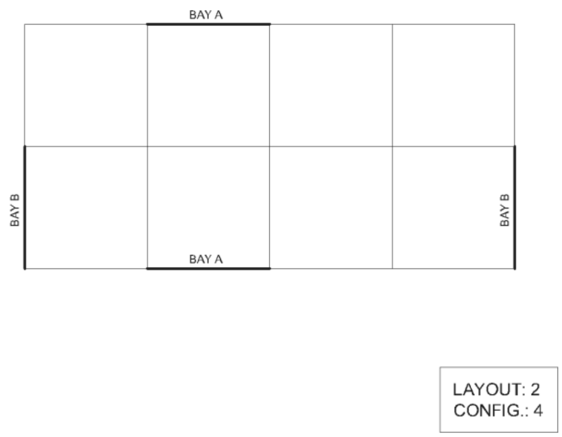
Result Parameters

Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	12.80	371.20	0	384.00	17.77	135.94
100% Bracing	106.31	0.00	0	106.31	79.73	358.26
100% Moment Frames	165.04	0.00	20	165.04	15123.78	556.19
~50% Concrete Shear Wall, ~50% Bracing	49.71	222.72	0	272.43	42.18	223.21
~50% Bracing, ~50% Moment Frames	124.76	0.00	8	124.76	6093.57	420.43
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	89.38	148.48	4	237.86	3070.30	338.32

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33$, $W_C = 0.33$, $W_E = 0.34$	$W_W = 0.50$, $W_C = 0.25$, $W_E = 0.25$	$W_W = 0.25$, $W_C = 0.50$, $W_E = 0.25$	$W_W = 0.25$, $W_C = 0.25$, $W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.18	0.13	0.13	0.27
100% Moment Frames	0.73	0.61	0.80	0.80
~50% Concrete Shear Wall, ~50% Bracing	0.27	0.35	0.20	0.25
~50% Bracing, ~50% Moment Frames	0.38	0.30	0.39	0.46
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.38	0.41	0.34	0.41
J_{min}	0.18	0.13	0.13	0.25

Output Results



Layout:	2
Configuration:	4
Story:	5

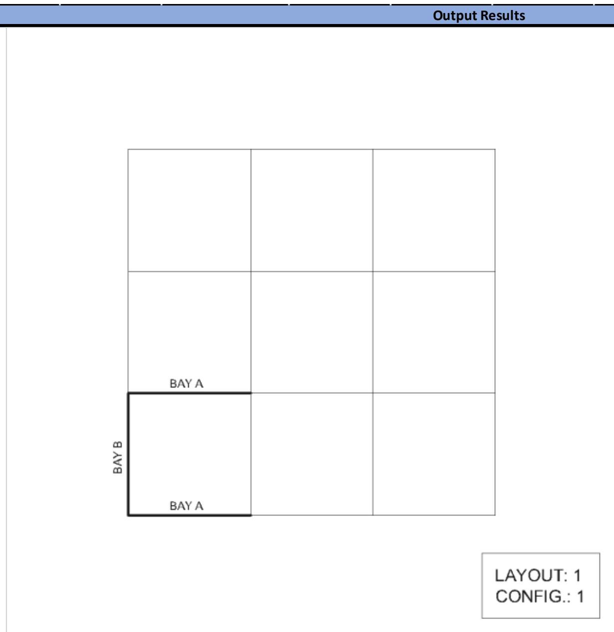
Result Parameters

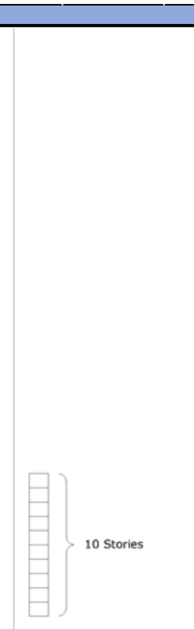
Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	12.80	371.20	0	384.00	17.77	135.94
100% Bracing	115.19	0.00	0	115.19	86.40	388.20
100% Moment Frames	178.93	0.00	20	178.93	15134.19	602.98
~50% Concrete Shear Wall, ~50% Bracing	53.40	222.72	0	276.12	44.95	235.65
~50% Bracing, ~50% Moment Frames	135.29	0.00	8	135.29	6101.47	455.93
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	96.47	148.48	4	244.95	3075.62	362.21

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33$, $W_C = 0.33$, $W_E = 0.34$	$W_W = 0.50$, $W_C = 0.25$, $W_E = 0.25$	$W_W = 0.25$, $W_C = 0.50$, $W_E = 0.25$	$W_W = 0.25$, $W_C = 0.25$, $W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.18	0.14	0.14	0.27
100% Moment Frames	0.74	0.62	0.81	0.81
~50% Concrete Shear Wall, ~50% Bracing	0.27	0.35	0.20	0.26
~50% Bracing, ~50% Moment Frames	0.38	0.31	0.39	0.46
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.39	0.41	0.34	0.41
J_{min}	0.18	0.14	0.14	0.25

Output Results





Layout:	1
Configuration:	1
Story:	10

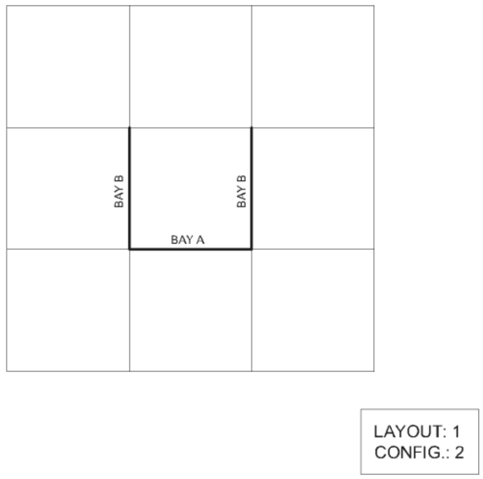
Result Parameters

Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	19.20	556.80	0	576.00	26.65	203.90
100% Bracing	205.62	0.00	0	205.62	154.21	692.93
100% Moment Frames	281.25	0.00	30	281.25	22710.94	947.82
~50% Concrete Shear Wall, ~50% Bracing	93.40	278.40	0	371.80	76.17	384.35
~50% Bracing, ~50% Moment Frames	236.89	0.00	15	236.89	11427.67	798.32
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	134.66	222.72	9	357.38	6855.89	509.47

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33, W_C = 0.33, W_E = 0.34$	$W_W = 0.50, W_C = 0.25, W_E = 0.25$	$W_W = 0.25, W_C = 0.50, W_E = 0.25$	$W_W = 0.25, W_C = 0.25, W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.22	0.17	0.17	0.33
100% Moment Frames	0.73	0.60	0.80	0.80
~50% Concrete Shear Wall, ~50% Bracing	0.23	0.29	0.17	0.23
~50% Bracing, ~50% Moment Frames	0.46	0.37	0.47	0.55
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.37	0.38	0.36	0.38
J_{min}	0.22	0.17	0.17	0.23

Output Results



Layout:	1
Configuration:	2
Story:	10

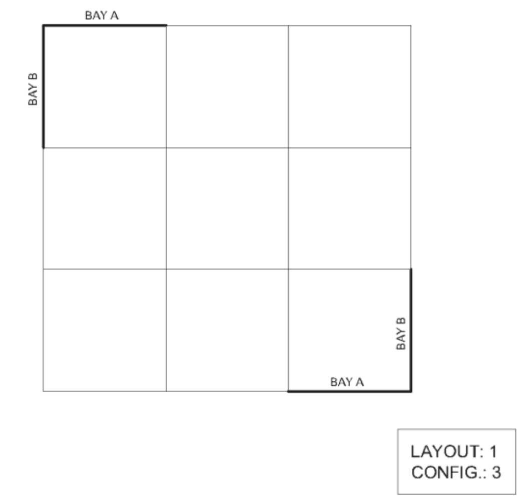
Result Parameters

Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	19.20	556.80	0	576.00	26.65	203.90
100% Bracing	181.59	0.00	0	181.59	136.19	611.96
100% Moment Frames	287.32	0.00	30	287.32	22715.49	968.27
~50% Concrete Shear Wall, ~50% Bracing	88.41	278.40	0	366.81	72.44	367.55
~50% Bracing, ~50% Moment Frames	244.32	0.00	15	244.32	11433.24	823.36
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	147.18	222.72	9	369.90	6865.28	551.67

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33, W_C = 0.33, W_E = 0.34$	$W_W = 0.50, W_C = 0.25, W_E = 0.25$	$W_W = 0.25, W_C = 0.50, W_E = 0.25$	$W_W = 0.25, W_C = 0.25, W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.18	0.13	0.14	0.27
100% Moment Frames	0.75	0.63	0.82	0.82
~50% Concrete Shear Wall, ~50% Bracing	0.23	0.29	0.17	0.22
~50% Bracing, ~50% Moment Frames	0.49	0.41	0.49	0.57
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.41	0.43	0.38	0.42
J_{min}	0.18	0.13	0.14	0.22

Output Results



Layout:	1
Configuration:	3
Story:	10

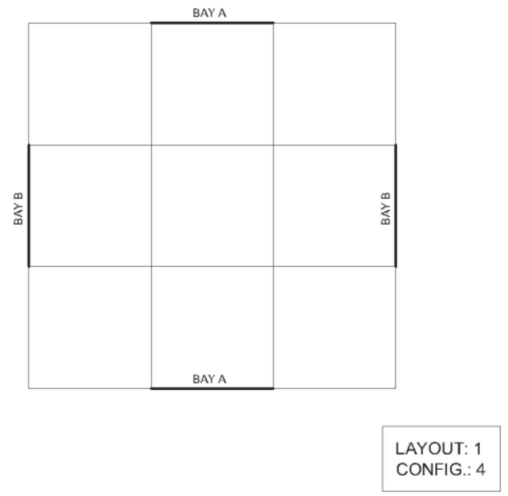
Result Parameters

Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	25.60	742.40	0	768.00	35.53	271.87
100% Bracing	221.49	0.00	0	221.49	166.12	746.43
100% Moment Frames	302.91	0.00	40	302.91	30227.18	1020.80
~50% Concrete Shear Wall, ~50% Bracing	119.45	371.20	0	490.65	97.76	495.36
~50% Bracing, ~50% Moment Frames	280.54	0.00	20	280.54	15210.41	945.43
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	178.31	296.96	12	475.27	9140.27	675.14

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33, W_C = 0.33, W_E = 0.34$	$W_W = 0.50, W_C = 0.25, W_E = 0.25$	$W_W = 0.25, W_C = 0.50, W_E = 0.25$	$W_W = 0.25, W_C = 0.25, W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.21	0.16	0.16	0.32
100% Moment Frames	0.71	0.57	0.79	0.79
~50% Concrete Shear Wall, ~50% Bracing	0.26	0.32	0.20	0.27
~50% Bracing, ~50% Moment Frames	0.50	0.40	0.50	0.60
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.43	0.44	0.40	0.46
J_{min}	0.21	0.16	0.16	0.25

Output Results



Layout:	1
Configuration:	4
Story:	10

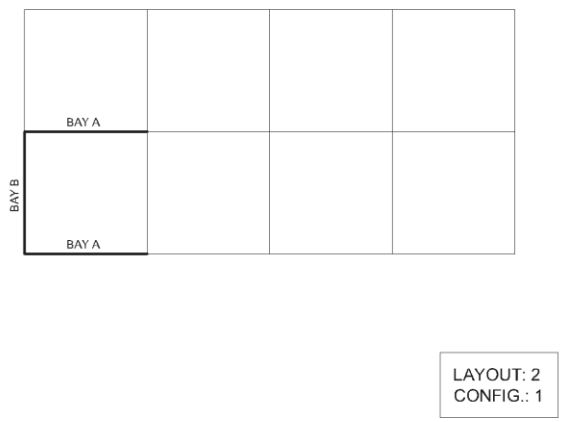
Result Parameters

Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	25.60	742.40	0	768.00	35.53	271.87
100% Bracing	234.81	0.00	0	234.81	176.11	791.32
100% Moment Frames	327.90	0.00	40	327.90	30245.92	1105.01
~50% Concrete Shear Wall, ~50% Bracing	128.88	371.20	0	500.08	104.83	527.13
~50% Bracing, ~50% Moment Frames	298.06	0.00	20	298.06	15223.54	1004.45
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	192.49	296.96	12	489.45	9150.90	722.92

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33, W_C = 0.33, W_E = 0.34$	$W_W = 0.50, W_C = 0.25, W_E = 0.25$	$W_W = 0.25, W_C = 0.50, W_E = 0.25$	$W_W = 0.25, W_C = 0.25, W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.21	0.16	0.16	0.31
100% Moment Frames	0.72	0.59	0.79	0.79
~50% Concrete Shear Wall, ~50% Bracing	0.27	0.33	0.20	0.28
~50% Bracing, ~50% Moment Frames	0.50	0.40	0.50	0.59
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.44	0.45	0.41	0.47
J_{min}	0.21	0.16	0.16	0.25

Output Results



Layout:	2
Configuration:	1
Story:	10

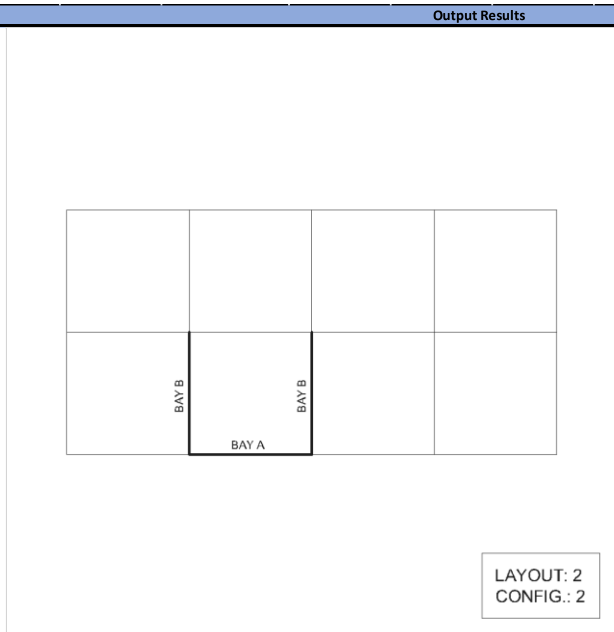
Result Parameters

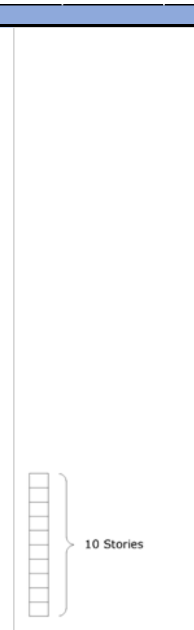
Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	19.20	556.80	0	576.00	26.65	203.90
100% Bracing	226.24	0.00	0	226.24	169.68	762.42
100% Moment Frames	327.54	0.00	30	327.54	22745.66	1103.81
~50% Concrete Shear Wall, ~50% Bracing	98.22	278.40	0	376.62	79.79	400.61
~50% Bracing, ~50% Moment Frames	266.14	0.00	15	266.14	11449.61	896.89
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	139.08	222.72	9	361.80	6859.21	524.37

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33, W_C = 0.33, W_E = 0.34$	$W_W = 0.50, W_C = 0.25, W_E = 0.25$	$W_W = 0.25, W_C = 0.50, W_E = 0.25$	$W_W = 0.25, W_C = 0.25, W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.21	0.16	0.16	0.31
100% Moment Frames	0.76	0.64	0.82	0.82
~50% Concrete Shear Wall, ~50% Bracing	0.21	0.27	0.16	0.22
~50% Bracing, ~50% Moment Frames	0.46	0.38	0.47	0.54
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.34	0.36	0.34	0.35
J_{min}	0.21	0.16	0.16	0.22

Output Results





Layout:	2
Configuration:	2
Story:	10

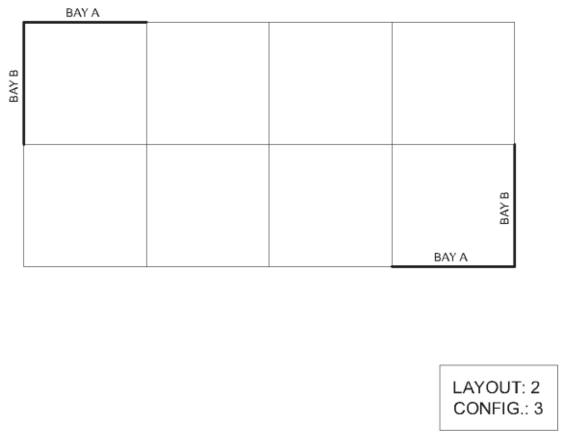
Result Parameters

Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	19.20	556.80	0	576.00	26.65	203.90
100% Bracing	186.53	0.00	0	186.53	139.90	628.60
100% Moment Frames	306.61	0.00	30	306.61	22729.96	1033.27
~50% Concrete Shear Wall, ~50% Bracing	90.55	278.40	0	368.95	74.03	374.74
~50% Bracing, ~50% Moment Frames	246.54	0.00	15	246.54	11434.90	830.82
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	148.96	222.72	9	371.68	6866.62	557.68

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33, W_C = 0.33, W_E = 0.34$	$W_W = 0.50, W_C = 0.25, W_E = 0.25$	$W_W = 0.25, W_C = 0.50, W_E = 0.25$	$W_W = 0.25, W_C = 0.25, W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.17	0.13	0.13	0.26
100% Moment Frames	0.76	0.65	0.83	0.83
~50% Concrete Shear Wall, ~50% Bracing	0.22	0.29	0.17	0.22
~50% Bracing, ~50% Moment Frames	0.47	0.39	0.48	0.54
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.40	0.42	0.38	0.41
J_{min}	0.17	0.13	0.13	0.22

Output Results



Layout:	2
Configuration:	3
Story:	10

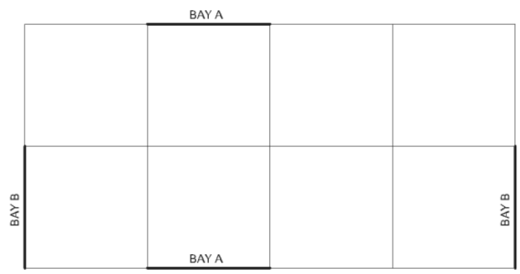
Result Parameters

Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	25.60	742.40	0	768.00	35.53	271.87
100% Bracing	222.44	0.00	0	222.44	166.83	749.62
100% Moment Frames	306.39	0.00	40	306.39	30229.79	1032.52
~50% Concrete Shear Wall, ~50% Bracing	119.45	371.20	0	490.65	97.76	495.36
~50% Bracing, ~50% Moment Frames	283.76	0.00	20	283.76	15212.82	956.28
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	178.21	296.96	12	475.17	9140.19	674.81

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33, W_C = 0.33, W_E = 0.34$	$W_W = 0.50, W_C = 0.25, W_E = 0.25$	$W_W = 0.25, W_C = 0.50, W_E = 0.25$	$W_W = 0.25, W_C = 0.25, W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.21	0.16	0.16	0.32
100% Moment Frames	0.71	0.58	0.79	0.79
~50% Concrete Shear Wall, ~50% Bracing	0.26	0.32	0.20	0.27
~50% Bracing, ~50% Moment Frames	0.50	0.41	0.50	0.60
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.43	0.44	0.40	0.46
J_{min}	0.21	0.16	0.16	0.25

Output Results



Layout:	2
Configuration:	4
Story:	10

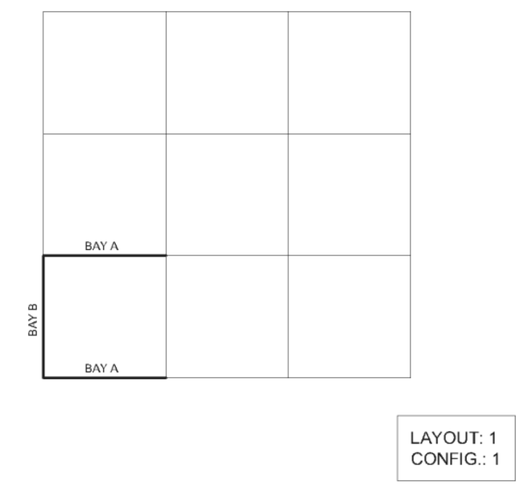
Result Parameters

Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	25.60	742.40	0	768.00	35.53	271.87
100% Bracing	237.23	0.00	0	237.23	177.92	799.47
100% Moment Frames	331.10	0.00	40	331.10	30248.32	1115.80
~50% Concrete Shear Wall, ~50% Bracing	128.24	371.20	0	499.44	104.35	524.96
~50% Bracing, ~50% Moment Frames	303.65	0.00	20	303.65	15227.74	1023.31
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	192.04	296.96	12	489.00	9150.57	721.43

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33, W_C = 0.33, W_E = 0.34$	$W_W = 0.50, W_C = 0.25, W_E = 0.25$	$W_W = 0.25, W_C = 0.50, W_E = 0.25$	$W_W = 0.25, W_C = 0.25, W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.21	0.16	0.16	0.31
100% Moment Frames	0.72	0.59	0.79	0.79
~50% Concrete Shear Wall, ~50% Bracing	0.26	0.32	0.20	0.27
~50% Bracing, ~50% Moment Frames	0.50	0.41	0.51	0.60
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.43	0.45	0.40	0.46
J_{min}	0.21	0.16	0.16	0.25

Output Results



Layout:	1
Configuration:	1
Story:	20

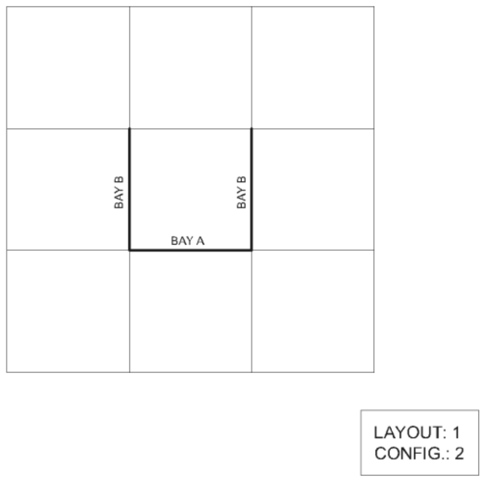
Result Parameters

Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	38.40	1113.60	0	1152.00	53.30	407.81
100% Bracing	645.88	0.00	0	645.88	484.41	2176.62
100% Moment Frames	782.29	0.00	60	782.29	45586.72	2636.32
~50% Concrete Shear Wall, ~50% Bracing	234.01	556.80	0	790.81	187.76	927.82
~50% Bracing, ~50% Moment Frames	748.63	0.00	30	748.63	23061.47	2522.88
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	389.36	389.76	18	779.12	13800.59	1409.58

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33, W_C = 0.33, W_E = 0.34$	$W_W = 0.50, W_C = 0.25, W_E = 0.25$	$W_W = 0.25, W_C = 0.50, W_E = 0.25$	$W_W = 0.25, W_C = 0.25, W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.27	0.20	0.20	0.40
100% Moment Frames	0.75	0.63	0.82	0.82
~50% Concrete Shear Wall, ~50% Bracing	0.17	0.20	0.13	0.19
~50% Bracing, ~50% Moment Frames	0.55	0.47	0.54	0.65
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.33	0.32	0.33	0.37
J_{min}	0.17	0.20	0.13	0.19

Output Results



Layout:	1
Configuration:	2
Story:	20

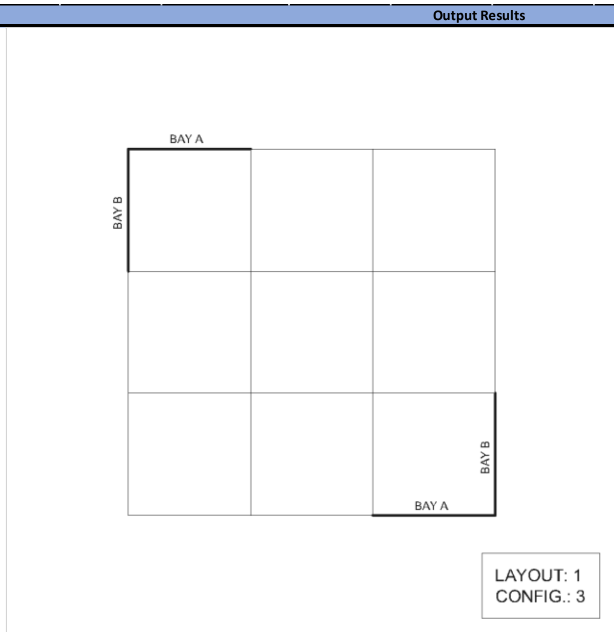
Result Parameters

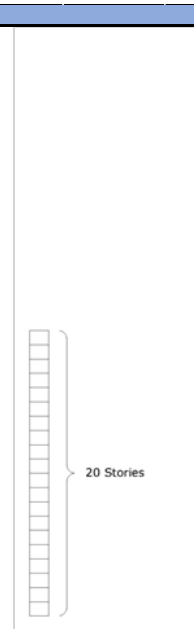
Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	38.40	1113.60	0	1152.00	53.30	407.81
100% Bracing	574.27	0.00	0	574.27	430.70	1935.29
100% Moment Frames	817.00	0.00	60	817.00	45612.75	2753.28
~50% Concrete Shear Wall, ~50% Bracing	207.56	556.80	0	764.36	167.92	838.67
~50% Bracing, ~50% Moment Frames	663.56	0.00	30	663.56	22997.67	2236.20
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	346.92	389.76	18	736.68	13768.77	1266.56

Objective Functions

Lateral Load-Resisting System	W_W = 0.33, W_C = 0.33, W_E = 0.34	W_W = 0.50, W_C = 0.25, W_E = 0.25	W_W = 0.25, W_C = 0.50, W_E = 0.25	W_W = 0.25, W_C = 0.25, W_E = 0.50
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.22	0.16	0.17	0.33
100% Moment Frames	0.80	0.71	0.86	0.86
~50% Concrete Shear Wall, ~50% Bracing	0.17	0.21	0.13	0.17
~50% Bracing, ~50% Moment Frames	0.47	0.40	0.49	0.55
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.31	0.31	0.31	0.33
J_{min}	0.17	0.16	0.13	0.17

Output Results





Layout:	1
Configuration:	3
Story:	20

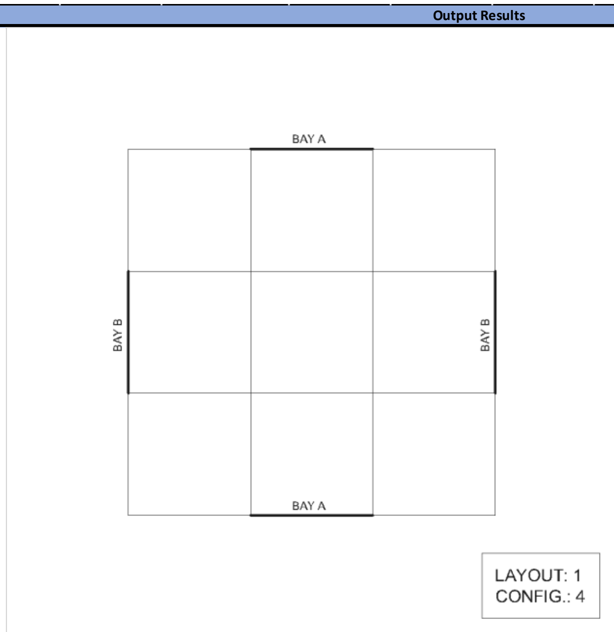
Result Parameters

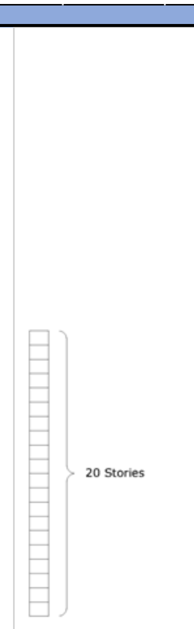
Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	51.20	1484.80	0	1536.00	71.07	543.74
100% Bracing	576.16	0.00	0	576.16	432.12	1941.67
100% Moment Frames	767.50	0.00	80	767.50	60575.62	2586.47
~50% Concrete Shear Wall, ~50% Bracing	253.12	742.40	0	995.52	206.17	1038.61
~50% Bracing, ~50% Moment Frames	665.62	0.00	40	665.62	30499.22	2243.15
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	399.11	519.68	24	918.79	18310.77	1474.93

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33$, $W_C = 0.33$, $W_E = 0.34$	$W_W = 0.50$, $W_C = 0.25$, $W_E = 0.25$	$W_W = 0.25$, $W_C = 0.50$, $W_E = 0.25$	$W_W = 0.25$, $W_C = 0.25$, $W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.23	0.17	0.17	0.34
100% Moment Frames	0.73	0.60	0.80	0.80
~50% Concrete Shear Wall, ~50% Bracing	0.22	0.28	0.17	0.23
~50% Bracing, ~50% Moment Frames	0.47	0.38	0.48	0.56
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.37	0.37	0.35	0.39
J_{min}	0.22	0.17	0.17	0.23

Output Results





Layout:	1
Configuration:	4
Story:	20

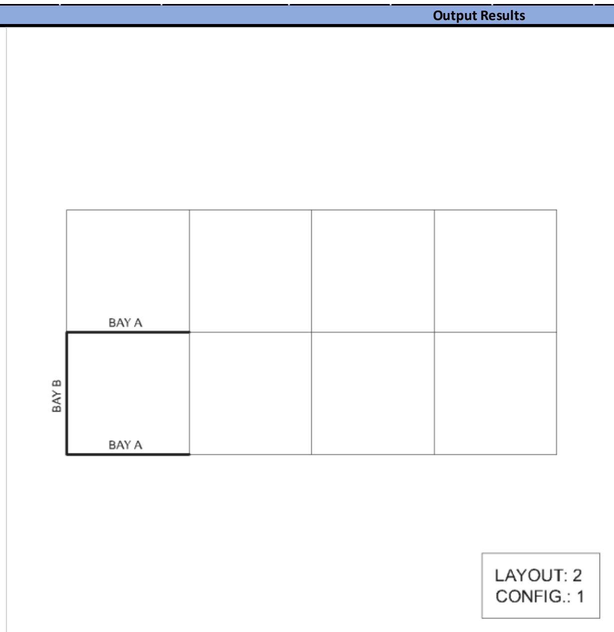
Result Parameters

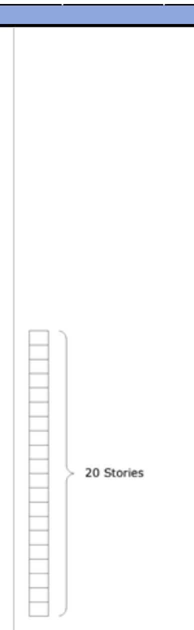
Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	51.20	1484.80	0	1536.00	71.07	543.74
100% Bracing	599.98	0.00	0	599.98	449.98	2021.93
100% Moment Frames	844.22	0.00	80	844.22	60633.17	2845.03
~50% Concrete Shear Wall, ~50% Bracing	261.97	742.40	0	1004.37	212.81	1068.44
~50% Bracing, ~50% Moment Frames	701.44	0.00	40	701.44	30526.08	2363.85
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	419.74	519.68	24	939.42	18326.24	1544.45

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33, W_C = 0.33, W_E = 0.34$	$W_W = 0.50, W_C = 0.25, W_E = 0.25$	$W_W = 0.25, W_C = 0.50, W_E = 0.25$	$W_W = 0.25, W_C = 0.25, W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.21	0.16	0.16	0.32
100% Moment Frames	0.75	0.63	0.82	0.82
~50% Concrete Shear Wall, ~50% Bracing	0.22	0.27	0.17	0.22
~50% Bracing, ~50% Moment Frames	0.46	0.38	0.48	0.55
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.36	0.37	0.35	0.38
J_{min}	0.21	0.16	0.16	0.22

Output Results





Layout:	2
Configuration:	1
Story:	20

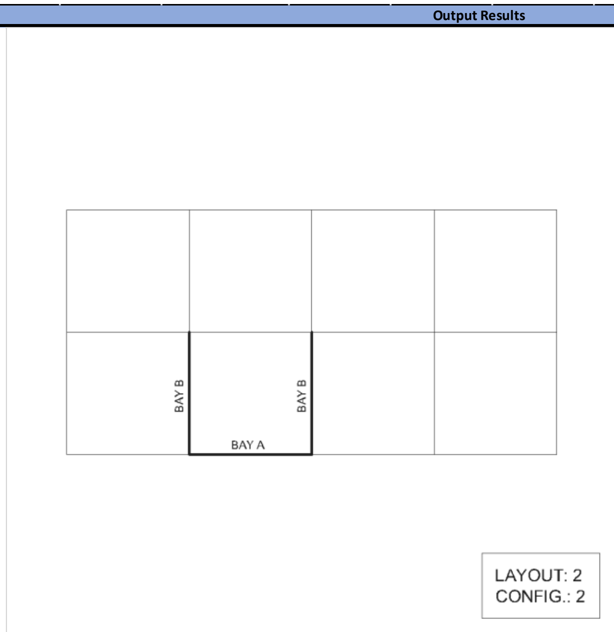
Result Parameters

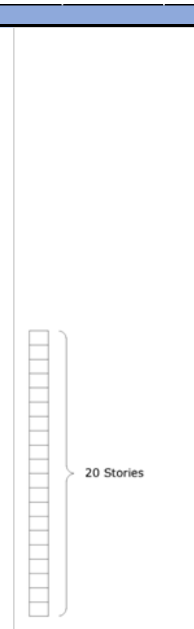
Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	38.40	1113.60	0	1152.00	53.30	407.81
100% Bracing	701.46	0.00	0	701.46	526.10	2363.92
100% Moment Frames	831.36	0.00	60	831.36	45623.52	2801.70
~50% Concrete Shear Wall, ~50% Bracing	260.64	556.80	0	817.44	207.73	1017.55
~50% Bracing, ~50% Moment Frames	798.74	0.00	30	798.74	23099.05	2691.75
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	446.63	389.76	18	836.39	13843.55	1602.57

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33, W_C = 0.33, W_E = 0.34$	$W_W = 0.50, W_C = 0.25, W_E = 0.25$	$W_W = 0.25, W_C = 0.50, W_E = 0.25$	$W_W = 0.25, W_C = 0.25, W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.27	0.21	0.21	0.41
100% Moment Frames	0.76	0.64	0.82	0.82
~50% Concrete Shear Wall, ~50% Bracing	0.17	0.19	0.13	0.19
~50% Bracing, ~50% Moment Frames	0.55	0.47	0.55	0.66
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.36	0.35	0.35	0.40
J_{min}	0.17	0.19	0.13	0.19

Output Results





Layout:	2
Configuration:	2
Story:	20

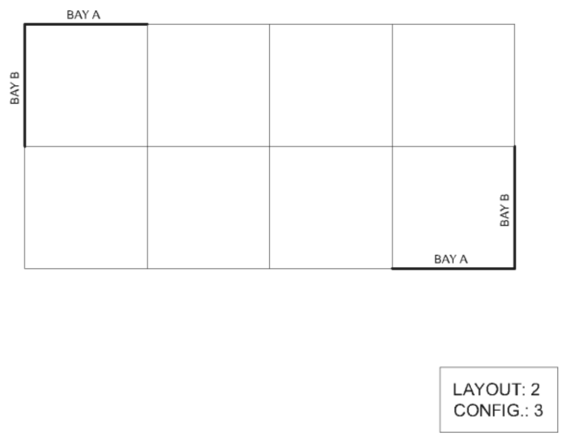
Result Parameters

Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	38.40	1113.60	0	1152.00	53.30	407.81
100% Bracing	585.64	0.00	0	585.64	439.23	1973.59
100% Moment Frames	815.74	0.00	60	815.74	45611.80	2749.03
~50% Concrete Shear Wall, ~50% Bracing	214.12	556.80	0	770.92	172.84	860.79
~50% Bracing, ~50% Moment Frames	706.81	0.00	30	706.81	23030.11	2381.95
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	360.05	389.76	18	749.81	13778.61	1310.80

Objective Functions

Lateral Load-Resisting System	W_W = 0.33, W_C = 0.33, W_E = 0.34	W_W = 0.50, W_C = 0.25, W_E = 0.25	W_W = 0.25, W_C = 0.50, W_E = 0.25	W_W = 0.25, W_C = 0.25, W_E = 0.50
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.22	0.17	0.17	0.34
100% Moment Frames	0.79	0.70	0.85	0.85
~50% Concrete Shear Wall, ~50% Bracing	0.17	0.21	0.13	0.18
~50% Bracing, ~50% Moment Frames	0.52	0.44	0.52	0.60
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.32	0.32	0.32	0.34
J_{min}	0.17	0.17	0.13	0.18

Output Results



Layout:	2
Configuration:	3
Story:	20

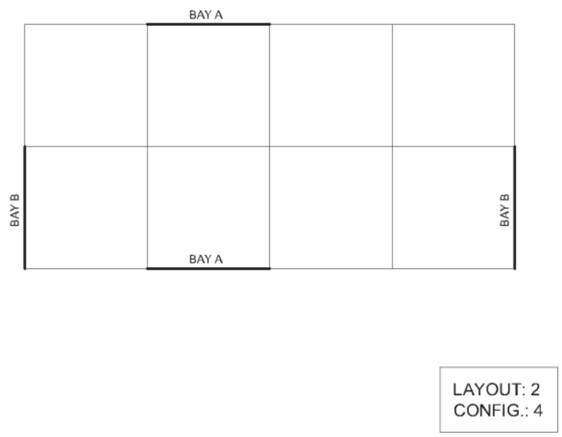
Result Parameters

Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	51.20	1484.80	0	1536.00	71.07	543.74
100% Bracing	577.47	0.00	0	577.47	433.10	1946.08
100% Moment Frames	775.94	0.00	80	775.94	60581.95	2614.90
~50% Concrete Shear Wall, ~50% Bracing	253.78	742.40	0	996.18	206.67	1040.83
~50% Bracing, ~50% Moment Frames	681.75	0.00	40	681.75	30511.31	2297.48
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	400.31	519.68	24	919.99	18311.67	1478.97

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33, W_C = 0.33, W_E = 0.34$	$W_W = 0.50, W_C = 0.25, W_E = 0.25$	$W_W = 0.25, W_C = 0.50, W_E = 0.25$	$W_W = 0.25, W_C = 0.25, W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.23	0.17	0.17	0.34
100% Moment Frames	0.73	0.60	0.80	0.80
~50% Concrete Shear Wall, ~50% Bracing	0.22	0.28	0.17	0.23
~50% Bracing, ~50% Moment Frames	0.48	0.39	0.49	0.58
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.37	0.37	0.35	0.39
J_{min}	0.22	0.17	0.17	0.23

Output Results



Layout:	2
Configuration:	4
Story:	20

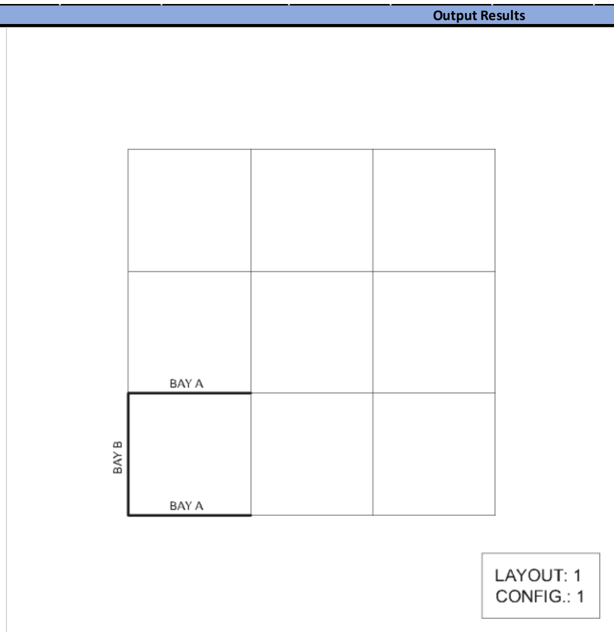
Result Parameters

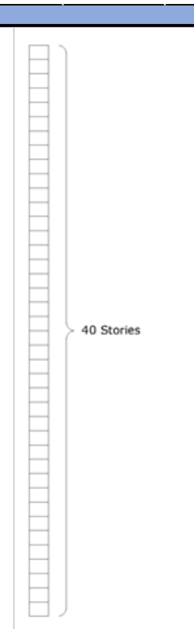
Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	51.20	1484.80	0	1536.00	71.07	543.74
100% Bracing	594.87	0.00	0	594.87	446.15	2004.71
100% Moment Frames	847.29	0.00	80	847.29	60635.47	2855.37
~50% Concrete Shear Wall, ~50% Bracing	268.08	742.40	0	1010.48	217.39	1089.03
~50% Bracing, ~50% Moment Frames	708.78	0.00	40	708.78	30531.59	2388.61
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	413.26	519.68	24	932.94	18321.38	1522.60

Objective Functions

Lateral Load-Resisting System	W_W = 0.33, W_C = 0.33, W_E = 0.34	W_W = 0.50, W_C = 0.25, W_E = 0.25	W_W = 0.25, W_C = 0.50, W_E = 0.25	W_W = 0.25, W_C = 0.25, W_E = 0.50
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.21	0.16	0.16	0.32
100% Moment Frames	0.75	0.63	0.82	0.82
~50% Concrete Shear Wall, ~50% Bracing	0.22	0.28	0.17	0.23
~50% Bracing, ~50% Moment Frames	0.47	0.39	0.48	0.56
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.36	0.36	0.35	0.38
J_{min}	0.21	0.16	0.16	0.23

Output Results





Layout:	1
Configuration:	1
Story:	40

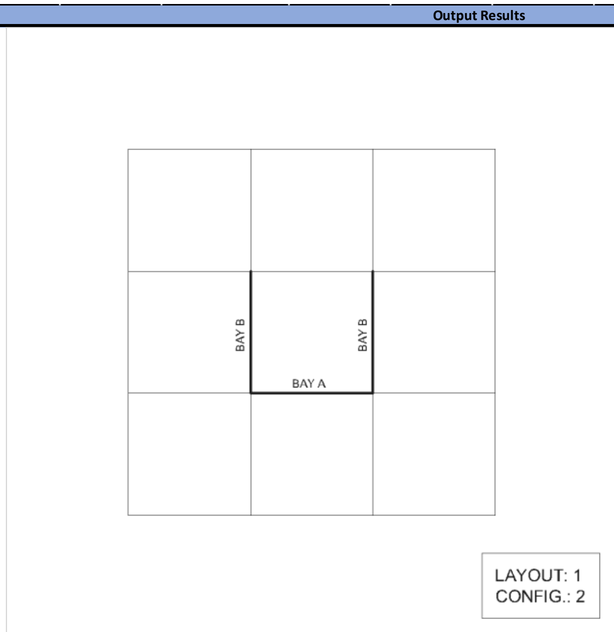
Result Parameters

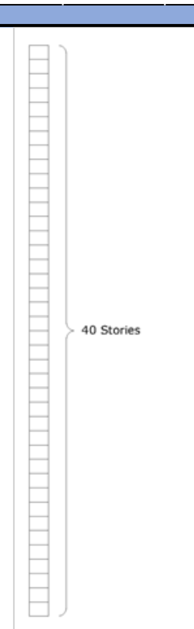
Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	76.80	2227.20	0	2304.00	106.60	815.62
100% Bracing	1597.06	0.00	0	1597.06	1197.79	5382.08
100% Moment Frames	1821.44	0.00	120	1821.44	91366.08	6138.25
~50% Concrete Shear Wall, ~50% Bracing	715.02	1113.60	0	1828.62	560.77	2688.03
~50% Bracing, ~50% Moment Frames	1724.96	0.00	60	1724.96	46293.72	5813.11
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	1100.83	723.84	39	1824.67	30091.54	3890.75

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33, W_C = 0.33, W_E = 0.34$	$W_W = 0.50, W_C = 0.25, W_E = 0.25$	$W_W = 0.25, W_C = 0.50, W_E = 0.25$	$W_W = 0.25, W_C = 0.25, W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.29	0.22	0.22	0.43
100% Moment Frames	0.76	0.66	0.83	0.83
~50% Concrete Shear Wall, ~50% Bracing	0.23	0.25	0.17	0.26
~50% Bracing, ~50% Moment Frames	0.54	0.45	0.53	0.64
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.41	0.39	0.39	0.45
J_{min}	0.23	0.22	0.17	0.25

Output Results





Layout:	1
Configuration:	2
Story:	40

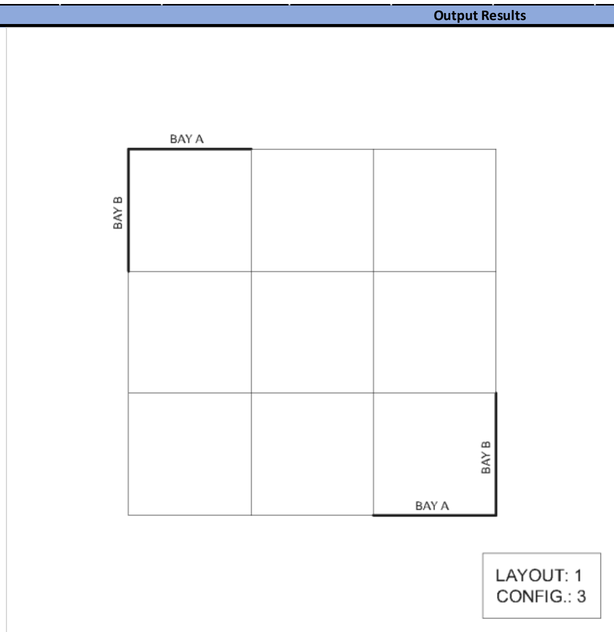
Result Parameters

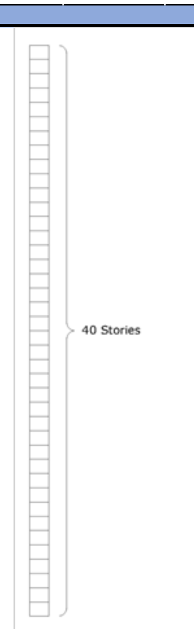
Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	76.80	2227.20	0	2304.00	106.60	815.62
100% Bracing	1660.99	0.00	0	1660.99	1245.74	5597.53
100% Moment Frames	2018.11	0.00	120	2018.11	91513.58	6801.03
~50% Concrete Shear Wall, ~50% Bracing	650.81	1113.60	0	1764.41	512.61	2471.63
~50% Bracing, ~50% Moment Frames	1845.40	0.00	60	1845.40	46384.05	6219.00
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	1127.55	723.84	39	1851.39	30111.58	3980.79

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33, W_C = 0.33, W_E = 0.34$	$W_W = 0.50, W_C = 0.25, W_E = 0.25$	$W_W = 0.25, W_C = 0.50, W_E = 0.25$	$W_W = 0.25, W_C = 0.25, W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.27	0.20	0.21	0.40
100% Moment Frames	0.84	0.78	0.89	0.89
~50% Concrete Shear Wall, ~50% Bracing	0.15	0.15	0.11	0.18
~50% Bracing, ~50% Moment Frames	0.56	0.50	0.55	0.65
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.38	0.36	0.37	0.42
J_{min}	0.15	0.15	0.11	0.18

Output Results





Layout:	1
Configuration:	3
Story:	40

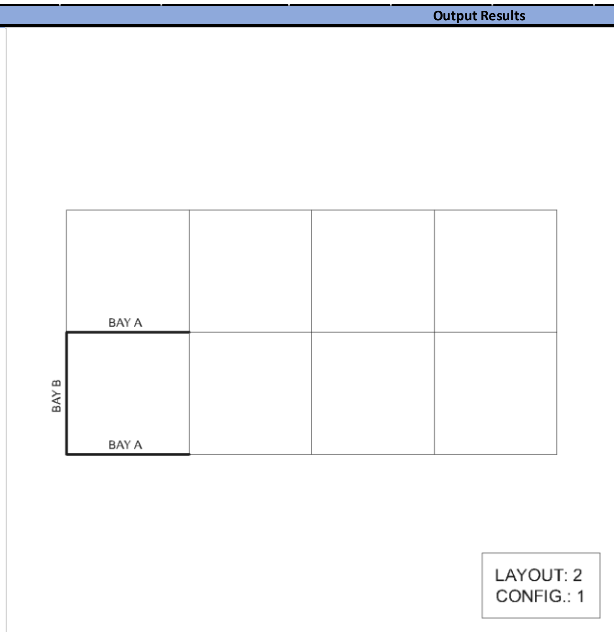
Result Parameters

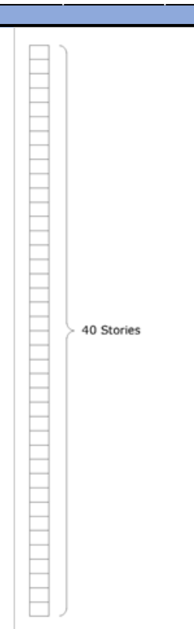
Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	102.40	2969.60	0	3072.00	142.13	1087.49
100% Bracing	1906.98	0.00	0	1906.98	1430.23	6426.52
100% Moment Frames	2183.08	0.00	160	2183.08	121637.31	7356.99
~50% Concrete Shear Wall, ~50% Bracing	667.29	1484.80	0	2152.09	533.13	2619.95
~50% Bracing, ~50% Moment Frames	2138.12	0.00	80	2138.12	61603.59	7205.48
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	1156.18	965.12	52	2121.30	39888.37	4137.61

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33, W_C = 0.33, W_E = 0.34$	$W_W = 0.50, W_C = 0.25, W_E = 0.25$	$W_W = 0.25, W_C = 0.50, W_E = 0.25$	$W_W = 0.25, W_C = 0.25, W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.28	0.22	0.22	0.43
100% Moment Frames	0.74	0.62	0.81	0.81
~50% Concrete Shear Wall, ~50% Bracing	0.15	0.17	0.12	0.18
~50% Bracing, ~50% Moment Frames	0.55	0.47	0.55	0.66
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.33	0.30	0.33	0.37
J_{min}	0.15	0.17	0.12	0.18

Output Results





Layout:	2
Configuration:	1
Story:	40

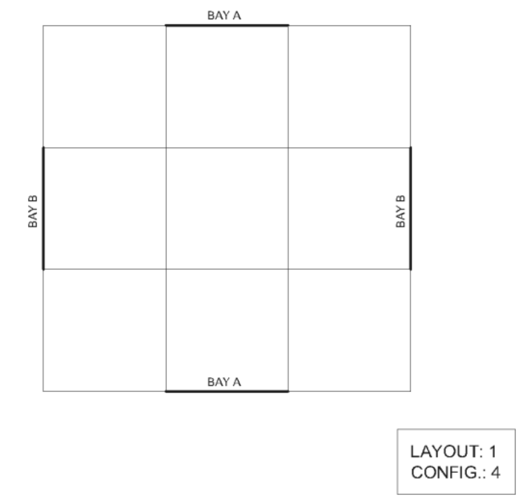
Result Parameters

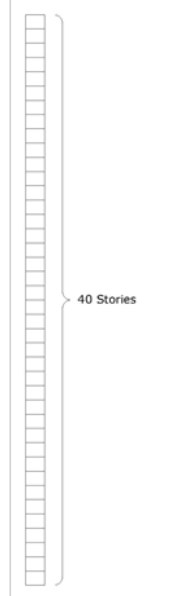
Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	76.80	2227.20	0	2304.00	106.60	815.62
100% Bracing	1622.95	0.00	0	1622.95	1217.21	5469.35
100% Moment Frames	1781.29	0.00	120	1781.29	91335.97	6002.96
~50% Concrete Shear Wall, ~50% Bracing	754.14	1113.60	0	1867.74	590.11	2819.86
~50% Bracing, ~50% Moment Frames	1688.35	0.00	60	1688.35	46266.26	5689.75
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	1123.16	723.84	39	1847.00	30108.29	3966.01

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33, W_C = 0.33, W_E = 0.34$	$W_W = 0.50, W_C = 0.25, W_E = 0.25$	$W_W = 0.25, W_C = 0.50, W_E = 0.25$	$W_W = 0.25, W_C = 0.25, W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.30	0.23	0.23	0.45
100% Moment Frames	0.74	0.62	0.81	0.81
~50% Concrete Shear Wall, ~50% Bracing	0.25	0.28	0.19	0.28
~50% Bracing, ~50% Moment Frames	0.51	0.41	0.51	0.62
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.42	0.40	0.40	0.47
J_{min}	0.25	0.23	0.19	0.25

Output Results





Layout:	1
Configuration:	4
Story:	40

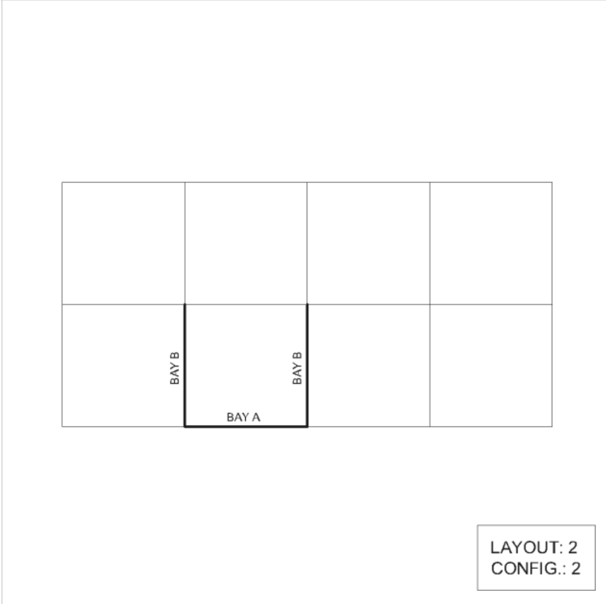
Result Parameters

Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	102.40	2969.60	0	3072.00	142.13	1087.49
100% Bracing	2106.51	0.00	0	2106.51	1579.88	7098.94
100% Moment Frames	2532.15	0.00	160	2532.15	121899.12	8533.36
~50% Concrete Shear Wall, ~50% Bracing	685.28	1484.80	0	2170.08	546.63	2680.60
~50% Bracing, ~50% Moment Frames	2421.75	0.00	80	2421.75	61816.32	8161.31
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	1193.61	965.12	52	2158.73	39916.44	4263.75

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33, W_C = 0.33, W_E = 0.34$	$W_W = 0.50, W_C = 0.25, W_E = 0.25$	$W_W = 0.25, W_C = 0.50, W_E = 0.25$	$W_W = 0.25, W_C = 0.25, W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.27	0.20	0.21	0.41
100% Moment Frames	0.81	0.72	0.86	0.86
~50% Concrete Shear Wall, ~50% Bracing	0.09	0.09	0.07	0.12
~50% Bracing, ~50% Moment Frames	0.59	0.53	0.57	0.68
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.27	0.22	0.28	0.31
J_{min}	0.09	0.09	0.07	0.12

Output Results



Layout:	2
Configuration:	2
Story:	40

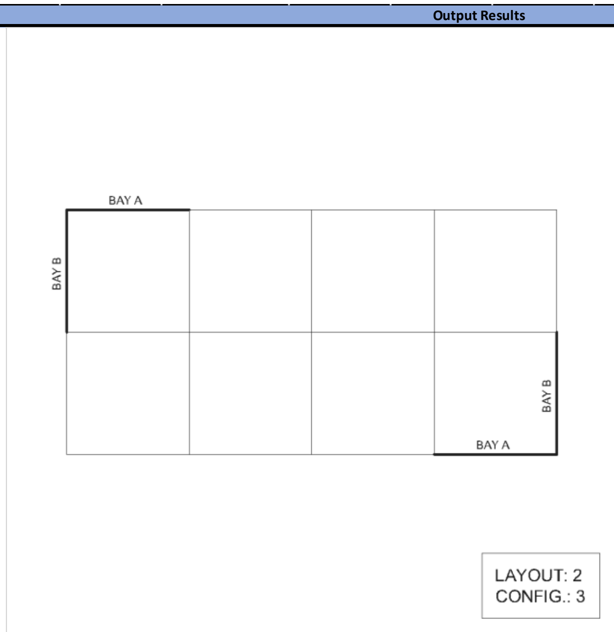
Result Parameters

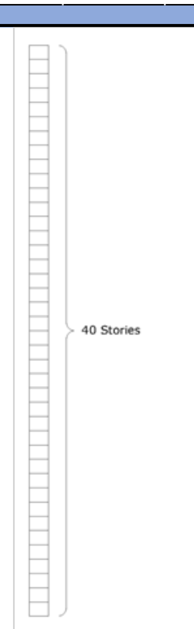
Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	76.80	2227.20	0	2304.00	106.60	815.62
100% Bracing	1601.71	0.00	0	1601.71	1201.28	5397.76
100% Moment Frames	2102.15	0.00	120	2102.15	91576.62	7084.26
~50% Concrete Shear Wall, ~50% Bracing	658.97	1113.60	0	1772.57	518.73	2499.13
~50% Bracing, ~50% Moment Frames	1864.99	0.00	60	1864.99	46398.74	6285.01
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	1137.83	723.84	39	1861.67	30119.30	4015.46

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33, W_C = 0.33, W_E = 0.34$	$W_W = 0.50, W_C = 0.25, W_E = 0.25$	$W_W = 0.25, W_C = 0.50, W_E = 0.25$	$W_W = 0.25, W_C = 0.25, W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.25	0.19	0.19	0.37
100% Moment Frames	0.90	0.86	0.93	0.93
~50% Concrete Shear Wall, ~50% Bracing	0.17	0.19	0.13	0.20
~50% Bracing, ~50% Moment Frames	0.58	0.53	0.56	0.66
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.40	0.39	0.38	0.43
J_{min}	0.17	0.19	0.13	0.20

Output Results





Layout:	2
Configuration:	3
Story:	40

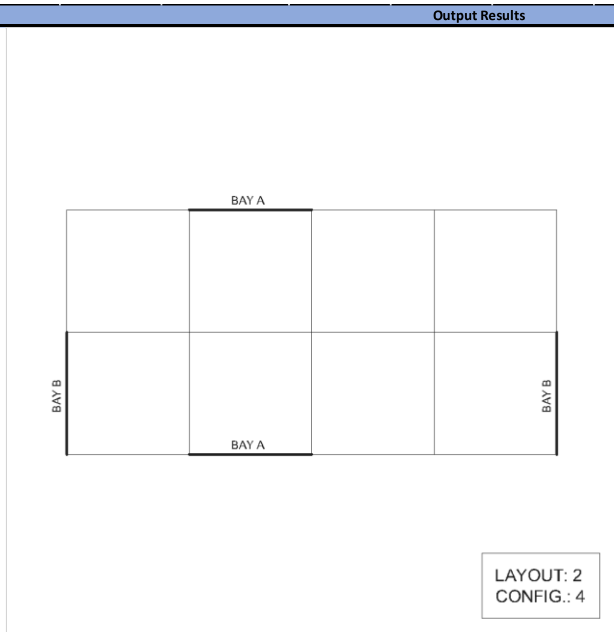
Result Parameters

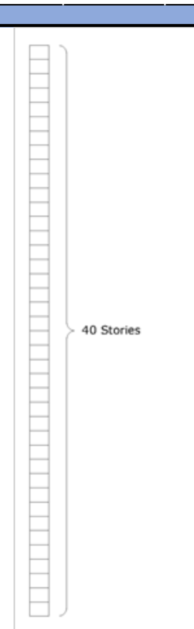
Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	102.40	2969.60	0	3072.00	142.13	1087.49
100% Bracing	1883.52	0.00	0	1883.52	1412.64	6347.45
100% Moment Frames	2128.86	0.00	160	2128.86	121596.64	7174.25
~50% Concrete Shear Wall, ~50% Bracing	670.03	1484.80	0	2154.83	535.19	2629.22
~50% Bracing, ~50% Moment Frames	2114.27	0.00	80	2114.27	61585.70	7125.08
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	1179.39	965.12	52	2144.51	39905.78	4215.83

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33$, $W_C = 0.33$, $W_E = 0.34$	$W_W = 0.50$, $W_C = 0.25$, $W_E = 0.25$	$W_W = 0.25$, $W_C = 0.50$, $W_E = 0.25$	$W_W = 0.25$, $W_C = 0.25$, $W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.29	0.22	0.22	0.43
100% Moment Frames	0.73	0.60	0.80	0.80
~50% Concrete Shear Wall, ~50% Bracing	0.16	0.18	0.12	0.18
~50% Bracing, ~50% Moment Frames	0.56	0.47	0.55	0.67
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.35	0.32	0.35	0.39
J_{min}	0.16	0.18	0.12	0.18

Output Results





Layout:	2
Configuration:	4
Story:	40

Result Parameters

Lateral Load-Resisting System	W_S (kips)	W_C (kips)	# Mom	W_{Total} (kips)	Cost ($)	Emb. Carbon
100% Concrete Shear Wall	102.40	2969.60	0	3072.00	142.13	1087.49
100% Bracing	2041.25	0.00	0	2041.25	1530.94	6879.01
100% Moment Frames	2428.22	0.00	160	2428.22	121821.16	8183.09
~50% Concrete Shear Wall, ~50% Bracing	684.09	1484.80	0	2168.89	545.73	2676.58
~50% Bracing, ~50% Moment Frames	2340.16	0.00	80	2340.16	61755.12	7886.33
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	1238.41	965.12	52	2203.53	39950.04	4414.71

Objective Functions

Lateral Load-Resisting System	$W_W = 0.33, W_C = 0.33, W_E = 0.34$	$W_W = 0.50, W_C = 0.25, W_E = 0.25$	$W_W = 0.25, W_C = 0.50, W_E = 0.25$	$W_W = 0.25, W_C = 0.25, W_E = 0.50$
100% Concrete Shear Wall	0.33	0.50	0.25	0.25
100% Bracing	0.27	0.21	0.21	0.41
100% Moment Frames	0.78	0.69	0.84	0.84
~50% Concrete Shear Wall, ~50% Bracing	0.12	0.12	0.09	0.14
~50% Bracing, ~50% Moment Frames	0.58	0.51	0.57	0.68
~33% Concrete Shear Wall, ~33% Bracing, ~33% Moment Frames	0.31	0.28	0.32	0.36
J_{min}	0.12	0.12	0.09	0.14

Appendix C – MATLAB Code

Main Script

```
%% User Input Override
clear;
clc;
clf;

Layout = 1;
Configs = 1;
s = 5;
Sys = 2;

h = 12;
wall_thickness = 8;
fc = 4000;
fy = 50;
Module = 1;

if Layout == 1
   Bx = 48;
   By = 48;
   dx = 16;
   dy = 16;
end
if Layout == 2
   Bx = 64;
   By = 32;
   dx = 16;
   dy = 16;
end

%% Error Messages
if rem((Bx/dx),1) ~= 0
   error('Please enter a bay width along x that divides building width along x in an integer value');
   return
end
if rem((By/dy),1) ~= 0
   error('Please enter a bay width along y that divides building width along y in an integer value');
   return
end

%% Material Definition
Es = 29000000; % Modulus of elasticity for steel in psi
Ec = 57000*(fc^0.5); % Modulus of elasticity for concrete in psi

%% Module 1

if Module == 1
   [bayX, bayY, FloorCoord, bayx_num, bayy_num, nx, ny, columnLine] = GeometricSetup(s, h, Bx, By, dx, dy); % Initiating global
geometric setup

   if Configs == 1 && Layout == 1
      bayx_info = [1,mommom,bracebrace,wallwall; 4,mommom,bracebrace,wallwall];
      bayy_info = [1,mommom,bracebrace,wallwall];
      totalmom = 3*mommom;
   end
```

```
  if Configs == 1 && Layout == 2
    bayx_info = [1,mommom,bracebrace,wallwall; 5,mommom,bracebrace,wallwall];
    bayy_info = [1,mommom,bracebrace,wallwall];
    totalmom = 3*mommom;
  end
  if Configs == 2 && Layout == 1
    bayx_info = [5,mommom,bracebrace,wallwall];
    bayy_info = [5,mommom,bracebrace,wallwall; 8,mommom,bracebrace,wallwall];
    totalmom = 3*mommom;
  end
  if Configs == 2 && Layout == 2
    bayx_info = [2,mommom,bracebrace,wallwall];
    bayy_info = [3,mommom,bracebrace,wallwall; 5,mommom,bracebrace,wallwall];
    totalmom = 3*mommom;
  end
  if Configs == 3 && Layout == 1
    bayx_info = [3,mommom,bracebrace,wallwall; 10,mommom,bracebrace,wallwall];
    bayy_info = [3,mommom,bracebrace,wallwall; 10,mommom,bracebrace,wallwall];
    totalmom = 4*mommom;
  end
  if Configs == 3 && Layout == 2
    bayx_info = [4,mommom,bracebrace,wallwall; 9,mommom,bracebrace,wallwall];
    bayy_info = [2,mommom,bracebrace,wallwall; 9,mommom,bracebrace,wallwall];
    totalmom = 4*mommom;
  end
  if Configs == 4 && Layout == 1
    bayx_info = [2,mommom,bracebrace,wallwall; 11,mommom,bracebrace,wallwall];
    bayy_info = [2,mommom,bracebrace,wallwall; 11,mommom,bracebrace,wallwall];
    totalmom = 4*mommom;
  end
  if Configs == 4 && Layout == 2
    bayx_info = [2,mommom,bracebrace,wallwall; 10,mommom,bracebrace,wallwall];
    bayy_info = [1,mommom,bracebrace,wallwall; 9,mommom,bracebrace,wallwall];
    totalmom = 4*mommom;
  end

  [w_conc, w_steel] = sapapi(FloorCoord, bayX, bayY, s, h, bayx_num, bayy_num, bayx_info, bayy_info, wall_thickness, nx, ny,
columnLine, Bx, By);
  sol = [w_steel, w_conc, totalmom];
end

%% Module 2

if Module == 2
  [bayX, bayY, FloorCoord, bayx_num, bayy_num, nx, ny, columnLine] = GeometricSetup(s, h, Bx, By, dx, dy); % Initiating global
geometric setup

  % 1 = Corner (2X, 1Y), 2 = Middle (1X,2Y), 3 = Diagonal (2X,2Y), 4 = Orthogonal (2X,2Y)
  Config = input('Enter the lateral bracing configuration you want to analyze (1, 2, 3, 4): ');
  if Config == 1
  q = 0;
  for m1 = 0:s
    for b1 = 0:s
      for c1 = 0:s
        for m2 = 0:s
          for b2 = 0:s
            for c2 = 0:s
              if (m1 + b1 + c1 == s) && (m2 + b2 + c2 == s)
```

```
                    q = q + 1;
                  end
                end
              end
            end
          end
        end
      end
      ui = input(['There are ' num2str(q) ' solutions. Do you want to proceed? enter 1 for yes, 0 for no: ']);
      sol = zeros(q,9);
      if ui == 1
        if Config == 1
          q = 1;
          for m1 = 0:s
            for b1 = 0:s
              for c1 = 0:s
                for m2 = 0:s
                  for b2 = 0:s
                    for c2 = 0:s
                      if (m1 + b1 + c1 == s) && (m2 + b2 + c2 == s)
                        bayx_info = [bx1,m1,b1,c1; bx2,m1,b1,c1];
                        bayy_info = [by1,m2,b2,c2];
                        [w_conc, w_steel] = sapapi(FloorCoord, bayX, bayY, s, h, bayx_num, bayy_num, bayx_info, bayy_info,
wall_thickness, nx, ny, columnLine, Bx, By);
                        sol(q,1) = m1;
                        sol(q,2) = b1;
                        sol(q,3) = c1;
                        sol(q,4) = m2;
                        sol(q,5) = b2;
                        sol(q,6) = c2;
                        sol(q,7) = w_conc;
                        sol(q,8) = w_steel;
                        sol(q,9) = (2*m1) + m2;
                        q = q + 1
                      end
                    end
                  end
                end
              end
            end
          end
        end
        str1 = 'Module2_Mode';
        str2 = num2str(Config);
        str3 = '_Bx';
        str4 = num2str(Bx);
        str5 = '_By';
        str6 = num2str(By);
        str7 = '_Story';
        str8 = num2str(s);
        str_all = strcat(str1,str2,str3,str4,str5,str6,str7,str8);
        csvwrite(str_all,sol);

        if Config == 2
          q = 1;
          for m1 = 0:s
            for b1 = 0:s
              for c1 = 0:s
```

```
                for m2 = 0:s
                    for b2 = 0:s
                        for c2 = 0:s
                            if (m1 + b1 + c1 == s) && (m2 + b2 + c2 == s)
                                bayx_info = [bx1,m1,b1,c1];
                                bayy_info = [by1,m2,b2,c2; by2,m2,b2,c2];
                                [w_conc, w_steel] = sapapi(FloorCoord, bayX, bayY, s, h, bayx_num, bayy_num, bayx_info, bayy_info,
wall_thickness, nx, ny, columnLine, Bx, By);
                                sol(q,1) = m1;
                                sol(q,2) = b1;
                                sol(q,3) = c1;
                                sol(q,4) = m2;
                                sol(q,5) = b2;
                                sol(q,6) = c2;
                                sol(q,7) = w_conc;
                                sol(q,8) = w_steel;
                                sol(q,9) = m1 + (2*m2);
                                q = q + 1
                            end
                        end
                    end
                end
            end
        end
    end
end
str1 = 'Module2_Mode';
str2 = num2str(Config);
str3 = '_Bx';
str4 = num2str(Bx);
str5 = '_By';
str6 = num2str(By);
str7 = '_Story';
str8 = num2str(s);
str_all = strcat(str1,str2,str3,str4,str5,str6,str7,str8);
csvwrite(str_all,sol);

if Config == 3 || Config == 4
    q = 1;
    for m1 = 0:s
        for b1 = 0:s
            for c1 = 0:s
                for m2 = 0:s
                    for b2 = 0:s
                        for c2 = 0:s
                            if (m1 + b1 + c1 == s) && (m2 + b2 + c2 == s)
                                bayx_info = [bx1,m1,b1,c1; bx2,m1,b1,c1];
                                bayy_info = [by1,m2,b2,c2; by2,m2,b2,c2];
                                [w_conc, w_steel] = sapapi(FloorCoord, bayX, bayY, s, h, bayx_num, bayy_num, bayx_info, bayy_info,
wall_thickness, nx, ny, columnLine, Bx, By);
                                sol(q,1) = m1;
                                sol(q,2) = b1;
                                sol(q,3) = c1;
                                sol(q,4) = m2;
                                sol(q,5) = b2;
                                sol(q,6) = c2;
                                sol(q,7) = w_conc;
                                sol(q,8) = w_steel;
```

```
                        sol(q,9) = (2*m1) + (2*m2);
                        q = q + 1
                      end
                    end
                  end
                end
              end
            end
          end
        end
        str1 = 'Module2_Layout';
        str2 = num2str(Layout);
        str3 = '_Config';
        str4 = num2str(Config);
        str5 = '_Story';
        str6 = num2str(s);
        str_all = strcat(str1,str2,str3,str4,str5,str6);
        csvwrite(str_all,sol);
    end
end
```

BuildingGeometry

```
function [bayX, bayY, FloorCoord, bayx_num, bayy_num, nx, ny, columnLine] = GeometricSetup(s, h, Bx, By, dx, dy)

%% Setting up BayXMain, BayYMain and FloorCoord
nx = (Bx/dx); % Number of bays along x direction on one gridline
ny = (By/dy); % Number of bays along y direction on one gridline
bayx_num = nx*(ny + 1); % Total number of bays along x direction
bayy_num = ny*(nx + 1); % Total number of bays along y direction
columnLine = cell(((nx + 1)*(ny + 1)),(s + 1)); % Cell array number of column lines by number of stories + 1.
                                    % Each cell element to contain coordinate of point at that
                                    % column-line and story as [x,y,z]
% Populating columnLine cell
for story_count = 0:s
  counter = 1;
  for i1 = 1:(ny + 1)
    for i2 = counter:(counter + nx)
      if i2 > (nx + 1)
        if rem(i2,(nx + 1)) == 0
          columnLine{i2,story_count + 1}(1) = nx*dx;
          columnLine{i2,story_count + 1}(2) = ((i2/(nx + 1)) - 1)*dy;
        else
          columnLine{i2,story_count + 1}(1) = ((rem(i2,(nx + 1))) - 1)*dx;
          columnLine{i2,story_count + 1}(2) = ((i2 - (rem(i2,(nx + 1))))/(nx + 1))*dy;
        end
        columnLine{i2,story_count + 1}(3) = story_count*h;
      end
      if i2 <= (nx + 1)
        columnLine{i2,story_count + 1}(1) = (i2 - 1)*dx;
        columnLine{i2,story_count + 1}(2) = 0;
        columnLine{i2,story_count + 1}(3) = story_count*h;
      end
    end
    counter = counter + (nx + 1);
  end
```

```
end

bayX_columnLine = zeros(bayx_num,2);
bayY_columnLine = zeros(bayy_num,2);

% Assigning bays along x-direction to appropriate column lines (1 = left, 2 = right)
for i = 1:bayx_num
  if i <= nx
    bayX_columnLine(i,1) = i;
    bayX_columnLine(i,2) = i + 1;
  else
    if rem(i,nx) == 0
      bayX_columnLine(i,1) = ((i/nx)*(nx + 1)) - 1;
      bayX_columnLine(i,2) = ((i/nx)*(nx + 1));
    else
      bayX_columnLine(i,1) = (1 + (nx + 1)*((i - (rem(i,nx)))/nx)) + (rem(i,nx)) - 1;
      bayX_columnLine(i,2) = (1 + (nx + 1)*((i - (rem(i,nx)))/nx)) + (rem(i,nx));
    end
  end
end

% Assigning bays along x-direction to appropriate column lines (1 = bottom, 2 = top)
for i = 1:bayy_num
  if i <= ny
      bayY_columnLine(i,1) = (i*(nx + 1)) + 1 - (nx + 1);
      bayY_columnLine(i,2) = (i*(nx + 1)) + 1;
  else
    if rem(i,ny) == 0
      bayY_columnLine(i,1) = (i/ny) + (nx + 1)*(ny - 1);
      bayY_columnLine(i,2) = (i/ny) + (nx + 1)*ny;
    else
      bayY_columnLine(i,1) = (((i - (rem(i,ny)))/ny) + 1) + (rem(i,ny))*(nx + 1) - (nx + 1);
      bayY_columnLine(i,2) = (((i - (rem(i,ny)))/ny) + 1) + (rem(i,ny))*(nx + 1);
    end
  end
end

bayX = cell(bayx_num,s,4);
bayY = cell(bayy_num,s,4);

for i = 1:bayx_num
  for j = 1:s
    bayX{i,j,1}(1) = columnLine{(bayX_columnLine(i,1)),j}(1); % x coord. of bottom-left point
    bayX{i,j,1}(2) = columnLine{(bayX_columnLine(i,1)),j}(2); % y coord. of bottom-left point
    bayX{i,j,1}(3) = columnLine{(bayX_columnLine(i,1)),j}(3); % z coord. of bottom-left point

    bayX{i,j,2}(1) = columnLine{(bayX_columnLine(i,2)),j}(1); % x coord. of bottom-right point
    bayX{i,j,2}(2) = columnLine{(bayX_columnLine(i,2)),j}(2); % y coord. of bottom-right point
    bayX{i,j,2}(3) = columnLine{(bayX_columnLine(i,2)),j}(3); % z coord. of bottom-right point

    bayX{i,j,3}(1) = bayX{i,j,2}(1); % x coord. of top-right point
    bayX{i,j,3}(2) = bayX{i,j,2}(2); % y coord. of top-right point
    bayX{i,j,3}(3) = bayX{i,j,2}(3) + h; % z coord. of top-right point
```

```
      bayX{i,j,4}(1) = bayX{i,j,1}(1); % x coord. of top-left point
      bayX{i,j,4}(2) = bayX{i,j,1}(2); % y coord. of top-left point
      bayX{i,j,4}(3) = bayX{i,j,1}(3) + h; % z coord. of top-left point
   end
end

for i = 1:bayy_num
   for j = 1:s
      bayY{i,j,1}(1) = columnLine{(bayY_columnLine(i,1)),j}(1); % x coord. of bottom-left point
      bayY{i,j,1}(2) = columnLine{(bayY_columnLine(i,1)),j}(2); % y coord. of bottom-left point
      bayY{i,j,1}(3) = columnLine{(bayY_columnLine(i,1)),j}(3); % z coord. of bottom-left point

      bayY{i,j,2}(1) = columnLine{(bayY_columnLine(i,2)),j}(1); % x coord. of bottom-right point
      bayY{i,j,2}(2) = columnLine{(bayY_columnLine(i,2)),j}(2); % y coord. of bottom-right point
      bayY{i,j,2}(3) = columnLine{(bayY_columnLine(i,2)),j}(3); % z coord. of bottom-right point

      bayY{i,j,3}(1) = bayY{i,j,2}(1); % x coord. of top-right point
      bayY{i,j,3}(2) = bayY{i,j,2}(2); % y coord. of top-right point
      bayY{i,j,3}(3) = bayY{i,j,2}(3) + h; % z coord. of top-right point

      bayY{i,j,4}(1) = bayY{i,j,1}(1); % x coord. of top-left point
      bayY{i,j,4}(2) = bayY{i,j,1}(2); % y coord. of top-left point
      bayY{i,j,4}(3) = bayY{i,j,1}(3) + h; % z coord. of top-left point
   end
end

FloorCoord = cell(s,3); % Matrix containing corner points of each floor

% Populating floorCoord matrix
for i = 1:s
   FloorCoord{i,1}(1) = 0;
   FloorCoord{i,1}(2) = Bx;
   FloorCoord{i,1}(3) = Bx;
   FloorCoord{i,1}(4) = 0;

   FloorCoord{i,2}(1) = 0;
   FloorCoord{i,2}(2) = 0;
   FloorCoord{i,2}(3) = By;
   FloorCoord{i,2}(4) = By;

   FloorCoord{i,3}(1) = i*h;
   FloorCoord{i,3}(2) = i*h;
   FloorCoord{i,3}(3) = i*h;
   FloorCoord{i,3}(4) = i*h;
end

end
```

SAPAPI

```
function [w_conc, w_steel] = sapapi(FloorCoord, bayX, bayY, s, h, bayx_num, bayy_num, bayx_info, bayy_info, wall_thickness,
        nx, ny, columnLine, Bx, By)

fc = 5; %ksi (concrete)
fy = 50; %ksi (steel)
floor_thickness = 10; % Floor thickness in inches

%% SAP2000 API Initialization
feature('COM_SafeArraySingleDim', 1); % Pass data to Sap2000 as one-dimensional arrays
feature('COM_PassSafeArrayByRef', 1); % Pass non-scalar arrays to Sap2000 API by reference
SapObject = actxserver('sap2000v15.SapObject'); % Create SAP2000 object
SapObject.ApplicationStart; % Start SAP2000 application
ret = SapObject.Hide; % Hide SAP from displaying on screen
%ret = SapObject.Unhide; % Unhide SAP from displaying on screen
SapModel = SapObject.SapModel; % Create SapModel object
ret = SapModel.InitializeNewModel; % Initialize model
ret = SapModel.File.NewBlank; % Create new blank model

%% Material Definition
ret = SapModel.PropMaterial.Delete('4000Psi');
ret = SapModel.PropMaterial.Delete('A992fy50');

ret = SapModel.PropMaterial.SetMaterial('Mat_steel', 1, -1);
ret = SapModel.PropMaterial.SetMaterial('Mat_floor', 2, -1);
ret = SapModel.PropMaterial.SetMaterial('Mat_wall', 2, -1);

ret = SapModel.SetPresentUnits(3);
ret = SapModel.PropMaterial.SetOSteel_1('Mat_steel', fy, 68, 60, 70, 1, 0, 0.02, 0.1, 0.2, -0.1);
ret = SapModel.PropMaterial.SetONoDesign('Mat_floor');
ret = SapModel.PropMaterial.SetOConcrete_1('Mat_wall', fc, false, 0, 1, 0, 0.0022, 0.0052, -0.1);
ret = SapModel.SetPresentUnits(4);

%% Setting Groups
ret = SapModel.GroupDef.SetGroup('Group_steelcol');
ret = SapModel.GroupDef.SetGroup('Group_beam_mom');
ret = SapModel.GroupDef.SetGroup('Group_beam_pin');
ret = SapModel.GroupDef.SetGroup('Group_brace');
ret = SapModel.GroupDef.SetGroup('Group_gravitycol');
ret = SapModel.GroupDef.SetGroup('Group_floor');
ret = SapModel.GroupDef.SetGroup('Group_wall');
for i = 1:(s+1)
  str1 = 'Group_level_';
  str2 = num2str(i-1);
  str = strcat(str1,str2);
  ret = SapModel.GroupDef.SetGroup(str);
end

%% Property Definition
ret = SapModel.PropArea.SetShell_1('Prop_floor', 5, true, 'Mat_floor', 0, (floor_thickness/12), (floor_thickness/12), -1);%
        Defining floor area property
ret = SapModel.PropArea.SetShell_1('Prop_wall', 1, true, 'Mat_wall', 0, (wall_thickness/12), (wall_thickness/12), -1);% Defining
        wall area property
```

```
ret = SapModel.PropArea.SetShellDesign('Prop_wall', 'Mat_wall', 2, (1.5/12), (2.5/12), (1.5/12), (2.5/12)); % Assigning design
        parameters for walls

%Defining Auto-select list for Steel I shapes
SteelI = {'W36X441'; 'W36X302'; 'W36X231'; 'W36X194'; 'W36X150'; 'W33X318'; 'W33X221'; 'W33X141'; 'W30X357'; 'W30X235';
        'W30X148'; 'W30X108'; 'W27X368'; 'W27X258'; 'W27X178'; 'W27X114'; 'W24X370'; 'W24X250'; 'W24X176';
        'W24X117'; 'W24X84'; 'W24X55'; 'W21X147'; 'W21X101'; 'W21X68'; 'W21X57'; 'W18X283'; 'W18X192'; 'W18X130';
        'W18X86'; 'W18X60'; 'W18X40'; 'W16X77'; 'W16X45'; 'W16X26'; 'W14X550'; 'W14X398'; 'W14X283'; 'W14X193';
        'W14X132'; 'W14X90'; 'W14X61'; 'W14X38'; 'W14X22'};
[n, temp] = size(SteelI);
for i =1:n
  ret = SapModel.PropFrame.ImportProp(SteelI{i}, 'Mat_steel', 'AISC13.pro', SteelI{i});
end
ret = SapModel.PropFrame.SetAutoSelectSteel('Auto_SteelI', n, SteelI, 'W14X22');

%Defining Auto-select list for Steel double angles
Steel2L = {'2L3X3X1/2'; '2L3X3X3/8'; '2L4X4X1/2'; '2L4X4X3/8'; '2L4X4X7/16'; '2L6X6X1';...
     '2L6X6X3/8'; '2L6X6X5/16'; '2L6X6X7/8'; '2L8X8X1/2'; '2L8X8X7/8'; '2L8X8X9/16';};
[n, temp] = size(Steel2L);
for i =1:n
  ret = SapModel.PropFrame.ImportProp(Steel2L{i}, 'Mat_steel', 'AISC13.pro', Steel2L{i});
end
ret = SapModel.PropFrame.SetAutoSelectSteel('Auto_Steel2L', n, Steel2L, '2L3X3X1/2');

%% Modelling Floors
% Creating area objects to define floors
for i = 1:s
  x = transpose(FloorCoord{i,1});
  y = transpose(FloorCoord{i,2});
  z = transpose(FloorCoord{i,3});
  ret = SapModel.AreaObj.AddByCoord(4, x, y, z, num2str(i));
  ret = SapModel.AreaObj.SetGroupAssign(num2str(i), 'Group_floor'); % Assigning floor plane to 'Group_floor'
end

%% Creating bayxmain and bayymain Matrices
[bayx_num_temp, temp] = size(bayx_info);
[bayy_num_temp, temp] = size(bayy_info);
bayxmain = cell(bayx_num_temp,s,4); % bayX reformatted to omit unused bays
bayymain = cell(bayy_num_temp,s,4); % bayY reformatted to omit unused bays

counter = 1;
counter2 = 0;
columnLine_temp = zeros((bayx_num_temp*2)+(bayy_num_temp*2),2);
for i = 1:bayx_num_temp
  for j = 1:bayx_num
    if j == bayx_info(i,1)
      for k = 1:s
        bayxmain(counter,k,1) = bayX(j,k,1);
        bayxmain(counter,k,2) = bayX(j,k,2);
        bayxmain(counter,k,3) = bayX(j,k,3);
        bayxmain(counter,k,4) = bayX(j,k,4);
        columnLine_temp(counter2+1,1) = bayxmain{counter,k,1}(1);
        columnLine_temp(counter2+1,2) = bayxmain{counter,k,1}(2);
        columnLine_temp(counter2+2,1) = bayxmain{counter,k,2}(1);
```

```
            columnLine_temp(counter2+2,2) = bayxmain{counter,k,2}(2);
          end
          counter = counter + 1;
          counter2 = counter2 + 2;
      end
   end
end
counter = 1;
for i = 1:bayy_num_temp
   for j = 1:bayy_num
      if j == bayy_info(i,1)
          for k = 1:s
            bayymain(counter,k,1) = bayY(j,k,1);
            bayymain(counter,k,2) = bayY(j,k,2);
            bayymain(counter,k,3) = bayY(j,k,3);
            bayymain(counter,k,4) = bayY(j,k,4);
            columnLine_temp(counter2+1,1) = bayymain{counter,k,1}(1);
            columnLine_temp(counter2+1,2) = bayymain{counter,k,1}(2);
            columnLine_temp(counter2+2,1) = bayymain{counter,k,2}(1);
            columnLine_temp(counter2+2,2) = bayymain{counter,k,2}(2);
          end
          counter = counter + 1;
          counter2 = counter2 + 2;
      end
   end
end

%% Modelling Lateral Elements
Surf_wall = 0;
counter_elem_p = s;
counter_elem_f = 0;
for i = 1:bayx_num_temp
   for j = 1:s
      c_b = 0;
      c_t = c_b + bayx_info(i,4);
      b_b = c_t;
      b_t = b_b + bayx_info(i,3);
      m_b = b_t;
      m_t = m_b + bayx_info(i,2);

      if j <= c_t
          x = [(bayxmain{i,j,1}(1));(bayxmain{i,j,2}(1));(bayxmain{i,j,3}(1));(bayxmain{i,j,4}(1))];
          y = [(bayxmain{i,j,1}(2));(bayxmain{i,j,2}(2));(bayxmain{i,j,3}(2));(bayxmain{i,j,4}(2))];
          z = [(bayxmain{i,j,1}(3));(bayxmain{i,j,2}(3));(bayxmain{i,j,3}(3));(bayxmain{i,j,4}(3))];
          ret = SapModel.AreaObj.AddByCoord(4, x, y, z, num2str(counter_elem_p + 1), 'Prop_wall', num2str(counter_elem_p + 1));
              % Shear wall
          ret = SapModel.AreaObj.SetGroupAssign(num2str(counter_elem_p + 1), 'Group_wall');
          Surf_wall_temp = ((bayxmain{i,j,2}(1)) - (bayxmain{i,j,1}(1)))*h;
          Surf_wall = Surf_wall + Surf_wall_temp;
          counter_elem_p = counter_elem_p + 1;
      end

      if j <= b_t && j > c_t
```

```
            ret = SapModel.FrameObj.AddByCoord((bayxmain{i,j,1}(1)), (bayxmain{i,j,1}(2)), (bayxmain{i,j,1}(3)), (bayxmain{i,j,4}(1)),
                (bayxmain{i,j,4}(2)), (bayxmain{i,j,4}(3)), num2str(counter_elem_f + 1), 'Auto_SteelI', num2str(counter_elem_f + 1)); %
                Left Column
            ret = SapModel.FrameObj.AddByCoord((bayxmain{i,j,2}(1)), (bayxmain{i,j,2}(2)), (bayxmain{i,j,2}(3)), (bayxmain{i,j,3}(1)),
                (bayxmain{i,j,3}(2)), (bayxmain{i,j,3}(3)), num2str(counter_elem_f + 2), 'Auto_SteelI', num2str(counter_elem_f + 2)); %
                Right Column
            ret = SapModel.FrameObj.AddByCoord((bayxmain{i,j,1}(1)), (bayxmain{i,j,1}(2)), (bayxmain{i,j,1}(3)), (bayxmain{i,j,3}(1)),
                (bayxmain{i,j,3}(2)), (bayxmain{i,j,3}(3)), num2str(counter_elem_f + 3), 'Auto_Steel2L', num2str(counter_elem_f + 3));
                % Brace #1
            ret = SapModel.FrameObj.AddByCoord((bayxmain{i,j,2}(1)), (bayxmain{i,j,2}(2)), (bayxmain{i,j,2}(3)), (bayxmain{i,j,4}(1)),
                (bayxmain{i,j,4}(2)), (bayxmain{i,j,4}(3)), num2str(counter_elem_f + 4), 'Auto_Steel2L', num2str(counter_elem_f + 4));
                % Brace #2
            ret = SapModel.FrameObj.AddByCoord((bayxmain{i,j,3}(1)), (bayxmain{i,j,3}(2)), (bayxmain{i,j,3}(3)), (bayxmain{i,j,4}(1)),
                (bayxmain{i,j,4}(2)), (bayxmain{i,j,4}(3)), num2str(counter_elem_f + 5), 'Auto_SteelI', num2str(counter_elem_f + 5)); %
                Beam
            ret = SapModel.FrameObj.SetGroupAssign(num2str(counter_elem_f + 1), 'Group_steelcol');
            ret = SapModel.FrameObj.SetGroupAssign(num2str(counter_elem_f + 2), 'Group_steelcol');
            ret = SapModel.FrameObj.SetGroupAssign(num2str(counter_elem_f + 3), 'Group_brace');
            ret = SapModel.FrameObj.SetGroupAssign(num2str(counter_elem_f + 4), 'Group_brace');
            ret = SapModel.FrameObj.SetGroupAssign(num2str(counter_elem_f + 5), 'Group_beam_pin');
            counter_elem_f = counter_elem_f + 5;
        end

        if j <= m_t && j > b_t
            ret = SapModel.FrameObj.AddByCoord((bayxmain{i,j,1}(1)), (bayxmain{i,j,1}(2)), (bayxmain{i,j,1}(3)), (bayxmain{i,j,4}(1)),
                (bayxmain{i,j,4}(2)), (bayxmain{i,j,4}(3)), num2str(counter_elem_f + 1), 'Auto_SteelI', num2str(counter_elem_f + 1)); %
                Left Column
            ret = SapModel.FrameObj.AddByCoord((bayxmain{i,j,2}(1)), (bayxmain{i,j,2}(2)), (bayxmain{i,j,2}(3)), (bayxmain{i,j,3}(1)),
                (bayxmain{i,j,3}(2)), (bayxmain{i,j,3}(3)), num2str(counter_elem_f + 2), 'Auto_SteelI', num2str(counter_elem_f + 2)); %
                Right Column
            ret = SapModel.FrameObj.AddByCoord((bayxmain{i,j,3}(1)), (bayxmain{i,j,3}(2)), (bayxmain{i,j,3}(3)), (bayxmain{i,j,4}(1)),
                (bayxmain{i,j,4}(2)), (bayxmain{i,j,4}(3)), num2str(counter_elem_f + 3), 'Auto_SteelI', num2str(counter_elem_f + 3)); %
                Beam
            ret = SapModel.FrameObj.SetGroupAssign(num2str(counter_elem_f + 1), 'Group_steelcol');
            ret = SapModel.FrameObj.SetGroupAssign(num2str(counter_elem_f + 2), 'Group_steelcol');
            ret = SapModel.FrameObj.SetGroupAssign(num2str(counter_elem_f + 3), 'Group_beam_mom');
            counter_elem_f = counter_elem_f + 3;
        end
    end
end

for i = 1:bayy_num_temp
    for j = 1:s
        c_b = 0;
        c_t = c_b + bayy_info(i,4);
        b_b = c_t;
        b_t = b_b + bayy_info(i,3);
        m_b = b_t;
        m_t = m_b + bayy_info(i,2);

        if j <= c_t
            x = [(bayymain{i,j,1}(1));(bayymain{i,j,2}(1));(bayymain{i,j,3}(1));(bayymain{i,j,4}(1))];
            y = [(bayymain{i,j,1}(2));(bayymain{i,j,2}(2));(bayymain{i,j,3}(2));(bayymain{i,j,4}(2))];
            z = [(bayymain{i,j,1}(3));(bayymain{i,j,2}(3));(bayymain{i,j,3}(3));(bayymain{i,j,4}(3))];
```

```
            ret = SapModel.AreaObj.AddByCoord(4, x, y, z, num2str(counter_elem_p + 1), 'Prop_wall', num2str(counter_elem_p + 1));
                % Shear wall
            ret = SapModel.AreaObj.SetGroupAssign(num2str(counter_elem_p + 1), 'Group_wall');
            Surf_wall_temp = ((bayymain{i,j,2}(2)) - (bayymain{i,j,1}(2)))*h;
            Surf_wall = Surf_wall + Surf_wall_temp;
            counter_elem_p = counter_elem_p + 1;
        end

        if j <= b_t && j > c_t
            ret = SapModel.FrameObj.AddByCoord((bayymain{i,j,1}(1)), (bayymain{i,j,1}(2)), (bayymain{i,j,1}(3)), (bayymain{i,j,4}(1)),
                (bayymain{i,j,4}(2)), (bayymain{i,j,4}(3)), num2str(counter_elem_f + 1), 'Auto_SteelI', num2str(counter_elem_f + 1)); %
                Left Column
            ret = SapModel.FrameObj.AddByCoord((bayymain{i,j,2}(1)), (bayymain{i,j,2}(2)), (bayymain{i,j,2}(3)), (bayymain{i,j,3}(1)),
                (bayymain{i,j,3}(2)), (bayymain{i,j,3}(3)), num2str(counter_elem_f + 2), 'Auto_SteelI', num2str(counter_elem_f + 2)); %
                Right Column
            ret = SapModel.FrameObj.AddByCoord((bayymain{i,j,1}(1)), (bayymain{i,j,1}(2)), (bayymain{i,j,1}(3)), (bayymain{i,j,3}(1)),
                (bayymain{i,j,3}(2)), (bayymain{i,j,3}(3)), num2str(counter_elem_f + 3), 'Auto_Steel2L', num2str(counter_elem_f + 3));
                % Brace #1
            ret = SapModel.FrameObj.AddByCoord((bayymain{i,j,2}(1)), (bayymain{i,j,2}(2)), (bayymain{i,j,2}(3)), (bayymain{i,j,4}(1)),
                (bayymain{i,j,4}(2)), (bayymain{i,j,4}(3)), num2str(counter_elem_f + 4), 'Auto_Steel2L', num2str(counter_elem_f + 4));
                % Brace #2
            ret = SapModel.FrameObj.AddByCoord((bayymain{i,j,3}(1)), (bayymain{i,j,3}(2)), (bayymain{i,j,3}(3)), (bayymain{i,j,4}(1)),
                (bayymain{i,j,4}(2)), (bayymain{i,j,4}(3)), num2str(counter_elem_f + 5), 'Auto_SteelI', num2str(counter_elem_f + 5)); %
                Beam
            ret = SapModel.FrameObj.SetGroupAssign(num2str(counter_elem_f + 1), 'Group_steelcol');
            ret = SapModel.FrameObj.SetGroupAssign(num2str(counter_elem_f + 2), 'Group_steelcol');
            ret = SapModel.FrameObj.SetGroupAssign(num2str(counter_elem_f + 3), 'Group_brace');
            ret = SapModel.FrameObj.SetGroupAssign(num2str(counter_elem_f + 4), 'Group_brace');
            ret = SapModel.FrameObj.SetGroupAssign(num2str(counter_elem_f + 5), 'Group_beam_pin');
            counter_elem_f = counter_elem_f + 5;
        end

        if j <= m_t && j > b_t
            ret = SapModel.FrameObj.AddByCoord((bayymain{i,j,1}(1)), (bayymain{i,j,1}(2)), (bayymain{i,j,1}(3)), (bayymain{i,j,4}(1)),
                (bayymain{i,j,4}(2)), (bayymain{i,j,4}(3)), num2str(counter_elem_f + 1), 'Auto_SteelI', num2str(counter_elem_f + 1)); %
                Left Column
            ret = SapModel.FrameObj.AddByCoord((bayymain{i,j,2}(1)), (bayymain{i,j,2}(2)), (bayymain{i,j,2}(3)), (bayymain{i,j,3}(1)),
                (bayymain{i,j,3}(2)), (bayymain{i,j,3}(3)), num2str(counter_elem_f + 2), 'Auto_SteelI', num2str(counter_elem_f + 2)); %
                Right Column
            ret = SapModel.FrameObj.AddByCoord((bayymain{i,j,3}(1)), (bayymain{i,j,3}(2)), (bayymain{i,j,3}(3)), (bayymain{i,j,4}(1)),
                (bayymain{i,j,4}(2)), (bayymain{i,j,4}(3)), num2str(counter_elem_f + 3), 'Auto_SteelI', num2str(counter_elem_f + 3)); %
                Beam
            ret = SapModel.FrameObj.SetGroupAssign(num2str(counter_elem_f + 1), 'Group_steelcol');
            ret = SapModel.FrameObj.SetGroupAssign(num2str(counter_elem_f + 2), 'Group_steelcol');
            ret = SapModel.FrameObj.SetGroupAssign(num2str(counter_elem_f + 3), 'Group_beam_mom');
            counter_elem_f = counter_elem_f + 3;
        end
    end
end

%% Adding Rigid Diaphragm constraints
for i = 1:(nx + 1)*(ny + 1)
    for j = 1:(s+1)
```

```
      ret = SapModel.PointObj.AddCartesian(columnLine{i,j}(1), columnLine{i,j}(2), columnLine{i,j}(3), num2str(i + (j*1000)),
            num2str(i + (j*1000)));
      str1 = 'Group_level_';
      str2 = num2str(j-1);
      str = strcat(str1,str2);
      ret = SapModel.PointObj.SetGroupAssign(num2str(i + (j*1000)), str);
   end
end

for i = 1:s
   str1 = 'const_';
   str2 = num2str(i);
   str = strcat(str1,str2);
   ret = SapModel.ConstraintDef.SetDiaphragm(str, 3);
end

for i = 1:s
   str1 = 'Group_level_';
   str2 = num2str(i);
   str3 = 'const_';
   str4 = strcat(str1,str2);
   str5 = strcat(str3,str2);
   ret = SapModel.PointObj.SetConstraint(str4, str5, 1);
end

%% Modifying Groups
% Assigning Properties
ret = SapModel.AreaObj.SetAutoMesh('Group_floor', 1, nx, ny, 0, 0, 0, 0, 0, 0, 0, true, true, false, false, 'Group_floor', false, 0, 1);
            % Meshing floors
ret = SapModel.AreaObj.SetAutoMesh('Group_wall', 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, true, true, false, false, 'Group_wall', false, 0, 1); %
            Meshing walls
modifiers = [10000000; 10000000; 10000000; 10000000; 10000000; 10000000; 1; 1; 1; 0]; % Property modifiers for floor elements
ret = SapModel.AreaObj.SetModifiers('Group_floor', modifiers, 1); % Modelling floors as infinitely stiff members

% Setting restraint at foundation level
Restraint = logical(zeros(6,1));
     for i = 1:4
        Restraint(i,1) = true();
     end
     for i = 5:6
        Restraint(i,1) = false();
     end
ret = SapModel.PointObj.SetRestraint('Group_level_0', Restraint, 1);

% Setting restraint at for pin-pin frame objects
Restraint = logical(zeros(6,1));
for i = 1:4
   Restraint(i,1) = false();
end
for i = 5:6
   Restraint(i,1) = true();
end
StartEndValue = [0;0;0;0;0;0];
ret = SapModel.FrameObj.SetReleases('Group_brace', Restraint, Restraint, StartEndValue, StartEndValue, 1);
```

```
ret = SapModel.FrameObj.SetReleases('Group_beam_pin', Restraint, Restraint, StartEndValue, StartEndValue, 1);
ret = SapObject.SapModel.FrameObj.SetTCLimits('Group_brace', true, 0, false, 1, 1); % Modelling braces as tension only

%% Defining Load Patterns and Cases
ret = SapModel.LoadPatterns.Add('WIND1', 6, 0, true);
ret = SapModel.LoadPatterns.Add('WIND2', 6, 0, true);
ret = SapModel.LoadPatterns.Add('WIND3', 6, 0, true);
ret = SapModel.LoadPatterns.Add('WIND4', 6, 0, true);
ret = SapModel.LoadPatterns.Add('WIND5', 6, 0, true);
ret = SapModel.LoadPatterns.Add('WIND6', 6, 0, true);
ret = SapModel.LoadPatterns.Add('WIND7', 6, 0, true);
ret = SapModel.LoadPatterns.Add('WIND8', 6, 0, true);
ret = SapModel.LoadPatterns.Add('WIND9', 6, 0, true);
ret = SapModel.LoadPatterns.Add('WIND10', 6, 0, true);
ret = SapModel.LoadPatterns.Add('WIND11', 6, 0, true);
ret = SapModel.LoadPatterns.Add('WIND12', 6, 0, true);
ret = SapModel.LoadPatterns.Add('QuakeX', 5, 0, true);
ret = SapModel.LoadPatterns.Add('QuakeY', 5, 0, true);

% Lateral Load Patterns
ret = SapModel.LoadPatterns.AutoWind.SetASCE705('WIND1', 1,  0, 0.8, 0.5, 1,     0,     0, false, 0, 0, 98, 2, 1.15, 1, 0.85, 0.85);
ret = SapModel.LoadPatterns.AutoWind.SetASCE705('WIND2', 1, 90, 0.8, 0.5, 1,     0,     0, false, 0, 0, 98, 2, 1.15, 1, 0.85, 0.85);
ret = SapModel.LoadPatterns.AutoWind.SetASCE705('WIND3', 1,  0, 0.8, 0.5, 2,  0.15,     0, false, 0, 0, 98, 2, 1.15, 1, 0.85, 0.85);
ret = SapModel.LoadPatterns.AutoWind.SetASCE705('WIND4', 1,  0, 0.8, 0.5, 2, -0.15,     0, false, 0, 0, 98, 2, 1.15, 1, 0.85, 0.85);
ret = SapModel.LoadPatterns.AutoWind.SetASCE705('WIND5', 1, 90, 0.8, 0.5, 2,  0.15,     0, false, 0, 0, 98, 2, 1.15, 1, 0.85, 0.85);
ret = SapModel.LoadPatterns.AutoWind.SetASCE705('WIND6', 1, 90, 0.8, 0.5, 2, -0.15,     0, false, 0, 0, 98, 2, 1.15, 1, 0.85, 0.85);
ret = SapModel.LoadPatterns.AutoWind.SetASCE705('WIND7', 1,  0, 0.8, 0.5, 3,     0,     0, false, 0, 0, 98, 2, 1.15, 1, 0.85, 0.85);
ret = SapModel.LoadPatterns.AutoWind.SetASCE705('WIND8', 1, 90, 0.8, 0.5, 3,     0,     0, false, 0, 0, 98, 2, 1.15, 1, 0.85, 0.85);
ret = SapModel.LoadPatterns.AutoWind.SetASCE705('WIND9', 1,  0, 0.8, 0.5, 4,  0.15,  0.15, false, 0, 0, 98, 2, 1.15, 1, 0.85, 0.85);
ret = SapModel.LoadPatterns.AutoWind.SetASCE705('WIND10', 1, 0, 0.8, 0.5, 4, -0.15, -0.15, false, 0, 0, 98, 2, 1.15, 1, 0.85, 0.85);
ret = SapModel.LoadPatterns.AutoWind.SetASCE705('WIND11', 1,90, 0.8, 0.5, 4,  0.15,  0.15, false, 0, 0, 98, 2, 1.15, 1, 0.85, 0.85);
ret = SapModel.LoadPatterns.AutoWind.SetASCE705('WIND12', 1,90, 0.8, 0.5, 4, -0.15, -0.15, false, 0, 0, 98, 2, 1.15, 1, 0.85, 0.85);
ret = SapModel.LoadPatterns.AutoSeismic.SetIBC2006('QuakeX', 1, 0.05, 1, 1, 0, false, 0, 0, 6, 2.5, 5, 1.25, 2, 0, 0, '', 0.28, 0.072,
        6, 4, 1.58, 2.40);
ret = SapModel.LoadPatterns.AutoSeismic.SetIBC2006('QuakeY', 2, 0.05, 1, 1, 0, false, 0, 0, 6, 2.5, 5, 1.25, 2, 0, 0, '', 0.28, 0.072,
        6, 4, 1.58, 2.40);

%% Defining Load Combos
ret = SapModel.RespCombo.AddDesignDefaultCombos(true, false, false, false); % Defining auto load combos for steel

%% Deleting Groups
ret = SapModel.GroupDef.Delete('Group_brace');
ret = SapModel.GroupDef.Delete('Group_beam_pin');
ret = SapModel.GroupDef.Delete('Group_beam_mom');

%% Steel and Concrete Design Parameters
ret = SapModel.DesignSteel.SetCode('AISC360-05/IBC2006'); % Setting steel design code
ret = SapModel.DesignConcrete.SetCode('ACI 318-05/IBC2003'); % Setting concrete design code

%% Saving and Running Model
ret = SapModel.View.RefreshView(0, false()); % Refresh view, update (initialize) zoom
ret = SapModel.File.Save('C:\API\API1.sdb'); % Save model
ret = SapModel.Analyze.RunAnalysis(); % run model (this will create the analysis model)
```

```
%% Running Steel Design
ret = SapModel.DesignSteel.AISC360_05_IBC2006.SetPreference(2, 2); % Setting seismic design category
ret = SapModel.DesignSteel.AISC360_05_IBC2006.SetPreference(13, 1); % Ignore seismic code
ret = SapModel.DesignSteel.AISC360_05_IBC2006.SetPreference(14, 1); % Ignore special seismic load
ret = SapModel.DesignSteel.AISC360_05_IBC2006.SetPreference(18, 1); % Consider deflections

%% Closing Model
ret = SapObject.ApplicationExit(false()); % Closing SAP2000
SapModel = 0; % Closing SAP2000
SapObject = 0; % Closing SAP2000

%% Reopening Model and Running Analysis
feature('COM_SafeArraySingleDim', 1); % Pass data to Sap2000 as one-dimensional arrays
feature('COM_PassSafeArrayByRef', 1); % Pass non-scalar arrays to Sap2000 API by reference
SapObject = actxserver('sap2000v15.SapObject'); % Create SAP2000 object
SapObject.ApplicationStart; % Start SAP2000 application
%ret = SapObject.Hide; % Hide SAP from displaying on screen
ret = SapObject.Unhide; % Unhide SAP from displaying on screen
SapModel = SapObject.SapModel; % Create SapModel object
FileName = 'C:\API\API1.sdb';
ret = SapModel.File.OpenFile(FileName);
ret = SapModel.DesignSteel.StartDesign;
ret = SapModel.Analyze.RunAnalysis(); % rerunning analysis

%% Calculating Output Variables
w_conc = Surf_wall*(wall_thickness/12)*0.145; % Weight of concrete in kips
w_steel = Surf_wall*(wall_thickness/12)*0.005; % Weight of steel rebars in kips

ret = SapModel.Results.Setup.DeselectAllCasesAndCombosForOutput;
ret = SapModel.Results.Setup.SetCaseSelectedForOutput('DEAD');
NumberResults = 0;
LoadCase = cellstr(' ');
StepType = cellstr(' ');
StepNum = zeros(1,1,'double');
Fx = zeros(1,1,'double');
Fy = zeros(1,1,'double');
Fz = zeros(1,1,'double');
Mx = zeros(1,1,'double');
My = zeros(1,1,'double');
Mz = zeros(1,1,'double');
gx = zeros(1,1,'double');
gy = zeros(1,1,'double');
gz = zeros(1,1,'double');
[ret, NumberResults, LoadCase, StepType, StepNum, Fx, Fy, Fz, Mx, My, Mz, gx, gy, gz] =
        SapModel.Results.BaseReact(NumberResults, LoadCase, StepType, StepNum, Fx, Fy, Fz, Mx, My, Mz, gx, gy, gz);
w_steel = (Fz - (Surf_wall*(wall_thickness/12)*0.150)) + w_steel;

%% Closing Model
ret = SapObject.ApplicationExit(false()); % Closing SAP2000
SapModel = 0; % Closing SAP2000
SapObject = 0; % Closing SAP2000

end
```