THE SUITABILITY OF DOUBLE-LAYER SPACE STRUCTURES FOR SUPER-TALL BUILDINGS:

A study from Structural and Building Systems Integration Perspectives

by
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Abstract

As buildings rise higher, designers face two major issues. Firstly, how to design efficient structures to resist the lateral loads that impact so greatly on tall buildings. Secondly, how to effectively integrate building systems, which often consume large amounts of space in taller buildings and potentially detract from the building aesthetics. Double-layer space structures have the potential to address these issues due to several beneficial design characteristics. As three-dimensional structures, double-layer space structures are rigid and structurally efficient. They can also integrate with other building systems by using the inherent structural cavities to accommodate services components and contribute a particular architectural aesthetic if their regular pattern is exposed.

Double-layer space structures have been used in long-span structure buildings, but have yet to be applied as vertical structures for super-tall buildings. Only two projects, proposed by Kahn and Tying, and Swenson, have applied double-layer space structures as vertical structures in high-rise buildings. However, they have not yet been executed and no literature has discussed the feasibility of the application of this structural system to super-tall buildings. This situation leads to the research question;

"Are double-layer space structures suitable for super-tall buildings?"

To answer this question, a long-term study with multidisciplinary knowledge, involving surveys of public opinion, and possibly real pilot projects would be required. This research focuses only on structural efficiency and systems integration as the initial step of the study of vertical double-layer space structures in super-tall buildings. The main objective of this research is to analyse the efficiency of this structural system, especially compared to other current tall structural systems. The second objective is to investigate to what extent these structures can integrate with other building systems as well as a discussion on advantages and disadvantages of the integration. The significance of this research is to provide initial scientific information for designers about the possibility of using double-layer space structures as a structural system of super-tall building.

A research methodology including both quantitative and qualitative approaches is employed to measure the structural efficiency of vertical double-layer space structures and to assess their potential to integrate with other building systems. This research covers structural aspects, building services systems including fire safety and approaches to energy efficiency, architectural integration, and construction.

A quantitative approach by structural design and analysis, and comparison of double-layer space structures with other structural systems is used to analyse structural efficiency. Case studies using the structural models of two 100-storey double-layer space structure buildings with different values of slenderness are designed and analysed using the computer software, ETABS. Other currently used structural systems, a bundled-tube, a braced-tube and a diagrid, are also designed using the same configuration and their structural analysis findings are compared to those of double-layer space structures. Services systems, including HVAC, stairs and elevators, are also designed and integrated with the structure.

The systems integration aspect of this research in double-layer space structure buildings is analysed using a qualitative approach in three main steps. The first step is a review of relevant literature covering systems integration and current technologies in tall buildings. Based on this review, systems integration in double-layer space structure buildings in general and the 100-storey case study buildings in particular are explored using computer models. As the final step, the advantages and disadvantages of the systems integration in the designed case studies are discussed.

These case studies are designed in order to represent current super-tall buildings and recent technologies in high-rise buildings. The structural models of 100-storey buildings are relevant for buildings in the approximate range of 75 to 125 storeys or 300 to 500 metres high; the majority of current super-tall buildings have been built in that range of heights. Recent technologies that are commonly used in super-tall buildings, for example Centralised Air Handling and Localised Air Handling for HVAC system, double-decking and sky lobbies for elevator system, and various façade systems, are adopted in these case studies. The aim is

to investigate if double-layer space structures can accommodate building components of current technologies.

The results of this research show that double-layer space structures are efficient where applied in super-tall buildings when compared to other existing structural systems. Double-layer space structures can also integrate with services components. The case study design shows how larger usable floor areas than those in typical tall buildings can be provided by positioning the majority of services and structural components within the space structure on the perimeter of the building. In terms of fire safety, positioning fire safety and egress systems in two different locations far apart, as proposed in this research, increases their reliability. Double-layer space structures are highly redundant structures that enable loads to be transferred through other structural members if several structural members collapse. This advantage minimises the possibility of progressive collapse. The ability of double-layer space structures to visually and physically integrate with architectural components and aspects like façade, interior space and building geometry in various ways is also explored. In terms of construction, simple connections and construction methods can be applied to double-layer space structures leading to competitive construction costs.

The research concludes by discussing the advantages and disadvantages of double-layer space structures for super-tall buildings and concludes that double-layer space structures are indeed suitable for this application within the scope of this research. However, the study also recommends future research to address issues that are not covered in this research.

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Chapter 1: Introduction

This chapter introduces the research project "The Suitability of Double-layer Space Structures for Super-tall Buildings". It begins with the background that motivated the author to undertake the project, and describes the rationale of the research. This leads on to the research question, which is the starting point of the research. The structure of the dissertation is briefly explained to show how the research has been conducted. The research significance is then presented, and finally the definitions of terms used in this research are briefly explained.

1.1. Background

Double-layer space structures, defined by Stevens (1975) as two parallel layers connected by diagonal members working together as a structure, have never been used as the structures of super-tall buildings. Double-layer space structures have many advantages as long-span structural systems and have been widely applied as horizontal structures. However, they appear to have a potential for high-rise applications. This is based on the rationale that several beneficial characteristics of double-layer space structures could address the main issues in tall building designs as explained in the following section.

Tall Buildings

Tall buildings have increased in number and height in many countries around the world. Population growth drives urban development not only horizontally but also vertically. As a city develops, high-rise buildings are built in larger numbers, bigger, and taller.

Engineers who design taller buildings normally face two major issues: how to achieve structural rigidity and systems integration. These issues are explained as follows:

- Structural systems of tall buildings must be designed to be very rigid to resist lateral loads that are more critical than gravity loads (Taranath, 1988). To make buildings more rigid, structural designers have developed various structural systems and materials. The designers mainly increase the volume and strength capacity of vertical structural elements such as columns, shear walls, and possibly diagonal braces. However, increasing the volume of structural members can lead to another issue that is described below.

- Systems integration, where building systems share space and function, is required in tall buildings (Ali & Armstrong, 2006). This is because tall buildings can be very inefficient in terms of the space required for the building systems (Aminmansour & Moon, 2010; Elnimeiri & Gupta, 2008). For example, structural elements consume considerable volume and space in a building in order to provide structural rigidity. The space needed for mechanical and electrical components also increases in proportion to the space needed for the building's occupants. For instance, as more people inhabit a building, it needs more elevators. Services components, such as transformers, water pumps, and boilers, also require strategic areas in the building, while pipes, wires, and ducts need access to every room. Structural and services systems require a lot of space for their components. These large components not only reduce usable floor area, but can also disturb architectural aspects of the building including the façade, interior space, and building form.

Generally, tall buildings require a rigid structural system that is also able to integrate with other building systems by sharing space and function. This will be discussed further in Chapter 2.

Double-layer Space Structures

The basic idea of space structures comes from the concept of a triangle, the most rigid geometric structure (Ambrose, 1994). The triangle concept has been developed into trusses as two-dimensional structures, and space structures as three-dimensional structures as shown in Figure 1.1. According to Stevens (1975), space structures are categorised into single- and double-layer grids. The three-dimensional action of single layer space grids relies on their curved geometries, while the dual layers of space structures connected by diagonal members also work in a three-dimensional action. In practice, space structures are mostly used horizontally to resist vertical loads. These structures are efficient for very long spans because they are relatively rigid and light-weight.

Besides these structural advantages, double-layer space structures also have benefits in terms of systems integration. The space between the two structural layers can be used for the distribution of building services components like pipes and ducts. Figure 1.2 (a) shows an example of systems integration using a double-layer space structure in the B+B Italia Office Building by Piano Rogers (Wilkinson, 1996). In addition, the regular pattern of these structures can be potentially exposed as part of a building's aesthetic as shown in Figure 1.2 (b). These examples show how double-layer space structures have the potential to share space and function with other building systems. The concept of double-layer space structures, their current application and their advantages for systems integration is discussed further in Chapter 2.

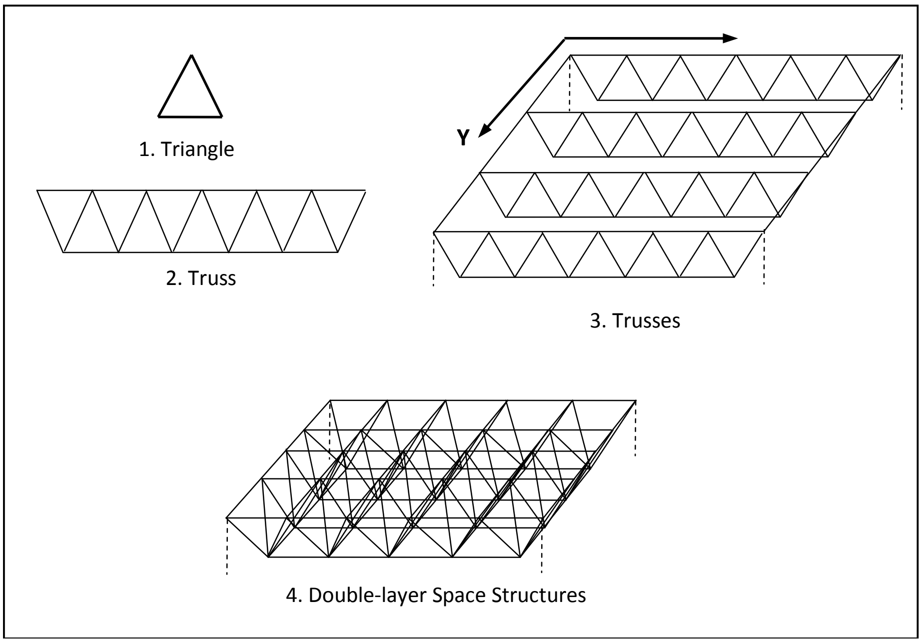


Figure 1.1 The development of space structures from a triangle

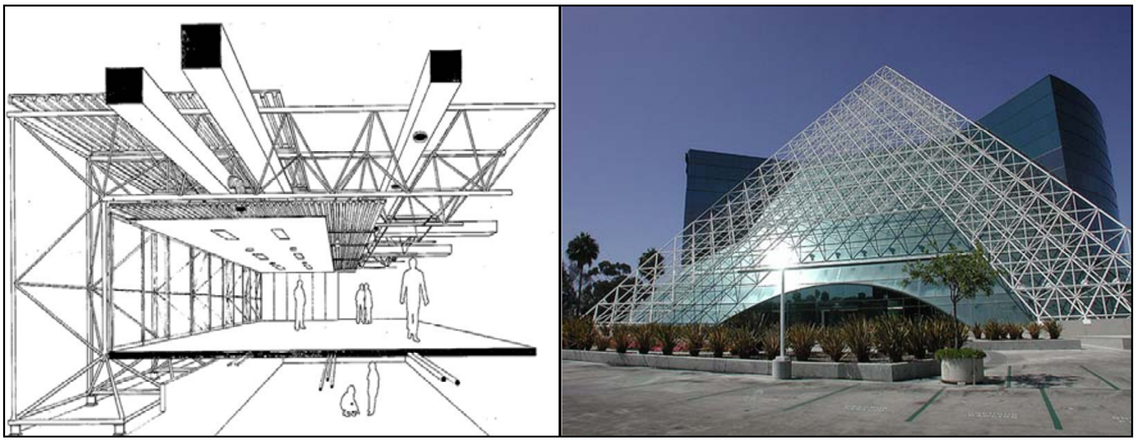


Figure 1.2 (a) Double-layer space structure shares space with ducts and pipes (Wilkinson, 1996, p. 59); (b) Double-layer space structure contributes to the building form ("Delta Structures," 2010)

In this study, the advantages of double-layer space structures in providing structural rigidity and systems integration are investigated for a high-rise application. The rationale behind this application is explained in the following section.

1.2. Rationale

This section discusses the rationale for the potential of double-layer space structures to meet the challenges of tall building designs.

Structural Point of View

As mentioned previously, this study analyses double-layer space structures as vertical structures to resist horizontal and vertical loads by locating the structure around the building perimeter. Figure 1.3 shows a section of a tall building using a vertical double-layer space structure. From a structural point of view, positioning a double-layer space structure at the building perimeter maximises its capacity to resist lateral loads that are more dominant in taller buildings. This argument is supported by Ali and Moon (2007) who classify tall structural systems into interior and exterior structures. The classification suggests that buildings can be built taller using exterior structures, where the majority of structural members are located at the building perimeter.

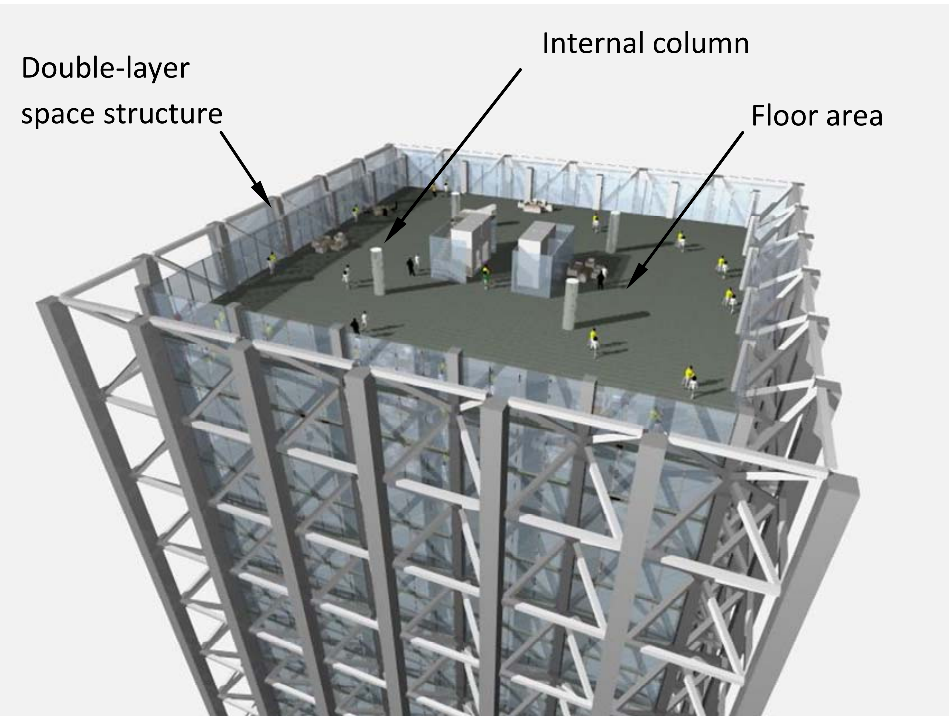


Figure 1.3 A double-layer space structure as a vertical structure of tall buildings

Systems Integration Point of View

As explained previously, double-layer space structures have the potential to integrate with other building systems by sharing space and function. In this research, part of the space between the external and internal layers is used for services components like elevators, stairs, vertical pipes, and ducts as shown in Figure 1.4. The structure, also on the building perimeter, is also expressed and integrated with the building façade.

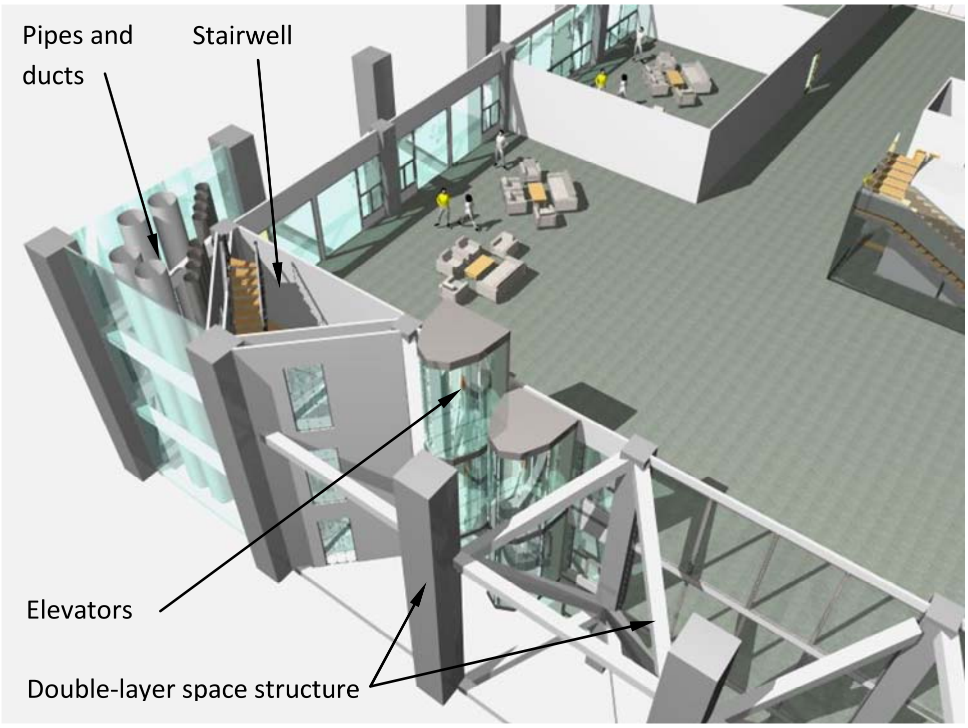


Figure 1.4 Elevators, stairs, pipes and ducts are located in the space between the external and internal layers of the vertical space structure

Since double-layer space structures have not yet been applied as the structural systems of multi-storey buildings, this application raises questions about their structural efficiency when compared to other current tall structures. It also raises questions as to what degree systems integration can be applied; the impact of these structures on architectural aspects; and the construction feasibility in relation to fire safety and energy efficiency. These issues are briefly explained in the following section.

1.3. Research Question and Scope

The purpose of this research is to evaluate the extent to which double-layer space structures might be suitable for super-tall buildings. Hence, the primary research question is:

"Are double-layer space structures suitable for super-tall buildings?"

This primary research question is sub-divided as follows:

1. Structural system:
   - What are the structural features of a double-layer space structure as a vertical structure?
   - How efficient are these structures as compared to other current structural systems?
2. Services systems:
   - To what extent can services systems integrate with double-layer space structures?
   - To what degree can these structures integrate with fire safety and egress systems?
   - How stable are these structures during fire and in the event of localised failure?
   - To what degree is this structural system compatible with energy efficient design concepts to be found in the current literature?
   - What are the advantages and disadvantages of this integration?
3. Architectural aspects:
   - What strategies can be used to integrate the structure with architectural components including façades, entrances, interior spaces, and building geometry?
   - What are the advantages and disadvantages of this type of and degree of integration?
4. Construction:
   - What construction methods, including primarily structural members' profiles and connections, erection methodologies, and construction equipment are suitable for this application?
   - What are the impacts of vertical double-layer space structures on construction costs?

The scope of this research:

- This study has two perspectives, structural system and building systems integration, with the reason outlined in Chapter 2. The research covers aspects of structural system, structural-services integration including the aspects of fire safety and energy efficiency, structural-architectural integration, and construction.

- A double-layer space structure is applied vertically at the building perimeter as the main structural system of super-tall buildings. The structural material for the double-layer space structure is steel with the reason outlined in Section 7.1.
- Super-tall buildings, defined as buildings over 300 meters / 984 feet high (CTBUH, 2011d), are modelled as 100-storey, 400 metres high, rectangular buildings in this research. These models represent super-tall buildings in a range of 75 to 125 storeys or 300 to 500 metres high as explained further in Section 3.2.

1.4. Structure of the Dissertation

The dissertation is structured in eight chapters as follows:

1. Chapter 1: Introduction

   This chapter introduces this research project "The Suitability of Double-layer Space Structures for Super-tall Buildings" by presenting the background, rationale, research question, structure of the dissertation, its significance, key terms and their definitions.

2. Chapter 2: Literature Review

   The literature about tall and super-tall buildings, structural systems of tall buildings, systems integration, and double-layer space structures is reviewed. The aim is to capture all relevant knowledge in order to reveal knowledge gaps that this research responds to.

3. Chapter 3: Research Methodology

   This chapter explains the research methodology consisting of quantitative and qualitative approaches. The quantitative aspect of the study uses the computer software, ETABS (*ETABS version 9*, 2005), to design and analyse these structures using case studies. The qualitative approach involves reviewing existing technologies in tall buildings and investigating their possible applications in a multi-storey double-layer space structure using various computer models as case studies. The case studies in both quantitative and qualitative approaches are designed to represent current super-tall buildings; therefore the results from this study would be applicable for general super-tall buildings within the scope of this study.

4. Chapter 4: Structural Design Analysis

   100-storey double-layer space structures are modelled, designed, analysed, and then compared with other structural systems of buildings with the same geometry. The analysis covers the force distribution in the structure, lateral deflections, and structural weight. This chapter also discusses the structural sensitivity and the thermal expansion when the structure is exposed.

5. Chapter 5: Building Services

   Services systems including heating, ventilating and air conditioning (HVAC), elevators, and stairs are designed for the 100-storey double-layer space structure building. The design focuses on optimising the space between the two layers of the structure for the services components. Fire safety including egress and structural protection of a double-layer space structure building and the structure's stability during fire and in the event of localised failure is investigated as well. As a part of services aspect, approaches to energy efficiency including applications of sun shading devices, double-skin façade, wind turbines and Photovoltaics are also discussed. The advantages and disadvantages of this structural-services integration are finally discussed.

6. Chapter 6: Architectural Integration

   This chapter explores various possibilities for structural-architectural integration. The study covers building façades, entrances, lobbies, interior space, open views, and building geometries.

7. Chapter 7: Construction

   The constructability of a double-layer space structure as a multi-storey structural system is investigated by considering various possible structural profiles and connections, erection methodologies and construction equipment. The investigation also covers the installation of services components and building façades to the structure. Factors that potentially affect construction costs are also discussed.

8. Chapter 8: Discussion, Conclusions and Recommendations

   This final chapter summarises the discussion from Chapter 4 to 7 in order to answer the research sub-questions. Based on this discussion, the conclusion addresses the main research question. Research limitations that lead to recommendations for further research are also raised.

1.5. Research Significance

The research contributes to understanding the limits of existing structural technology in super-tall buildings. It offers a new structural option for the design of relatively efficient super-tall buildings from the perspective of structure and systems integration.

The results of this research are relevant to the development of super-tall buildings for many large cities in the world, such as New York, Chicago, London, Dubai, Hong Kong, Tokyo, Shanghai, Seoul, Singapore, and others. Efficient structural designs of super-tall buildings are needed in many large cities in the world.

This research is also of value to structural designers, architects and building consultants, who are involved in the design of tall and super-tall buildings. It gives a wider perspective regarding integrated tall building design.

1.6. Definition of Terms

This section presents definitions of key terms used in this study for the purpose of clarity and consistency.

Super-tall buildings:

Buildings over 300 metres / 984 feet in height (CTBUH, 2011d).

Space structures:

“load-bearing structures applied in architecture that really make use of [their] three-dimensional action as a structure” (Eekhout, 1989, p. 10).

Double-layer space structures:

Space structures that have two parallel layers connected by diagonal members working together as a structure (Stevens, 1975).

Building systems integration:

There is no specific definition of integration in the building domain (Rush, 1986). Systems integration is classified by Bachman (2003, p. 4) into: physical integration (systems share space), visual integration (systems share image), and performance integration (systems share functions).

These key term definitions are explained further in the following chapter.

Chapter 2: Literature Review

This chapter reviews literature on super-tall buildings, structural systems of tall buildings, building systems integration, and double-layer space structures. The aims are to identify any knowledge gaps in relevant areas and justify this research. The discussion begins with a general review on the development of tall and super-tall buildings. It shows how structural technologies and systems integration are two important factors in super-tall building design. It continues with a discussion on how structural systems of tall buildings have developed, and the concept of building systems integration, including its applications. Double-layer space structures including the concept, their development and characteristics are then discussed. Finally, the findings of this chapter are summarised.

2.1. Super-tall Buildings

This section discusses tall and super-tall buildings including their definitions, history, and future, as well as important factors in their design. Definitions of a tall building from various perspectives are discussed to justify the terms "tall buildings" and "super-tall buildings" in this research. The history of tall buildings shows a number of reasons for people building higher and how this might influence the future of tall buildings. It also briefly discusses structural systems and building systems integration as two important factors in super-tall building design.

2.1.1. Definition of Tall and Super-tall Buildings

Before starting the discussion about tall and super-tall buildings, terminologies have to be defined and justified clearly for the purpose of this research. The important factor in defining a tall building is the definition of building tallness. Tallness of a building is relative and until recently there have been many different perceptions and opinions about what constitute tall buildings.

A tall building has been defined in many ways. Taranath (1988), for example, describes a tall building not in terms of its height or number of floors, but more on its appearance compared to neighbouring buildings. From a historic point of view, the modern skyscraper, which is another term used for tall buildings, is defined as a building of great height constructed with a steel skeleton and provided with high-speed electric elevators (Mujica, 1977). From the structural point of view, one definition of a tall building is: “A building whose height creates different conditions in the design, construction, and use than those that exist in common buildings of a certain region and period” (Kowalczyk, Sinn, Kilmister, & CTBUH, 1995). Most definitions do not specify a particular height or number of floors.

The Council of Tall Buildings and Urban Habitat (CTBUH) offers the definition of a tall building from a more specific view point. The CTBUH, founded in 1969 and based in Chicago, is “an international not-for-profit organization supported by architecture, engineering, planning, development, and construction professionals, that has a mission to disseminate multi-disciplinary information on tall buildings and sustainable urban environments, to maximize the international interaction of professionals involved in creating the built environment, and to make the latest knowledge available to professionals in a useful form” (CTBUH, 2011c). It suggests that a tall building should follow one or more of the following criteria: height relative to the area/city in which the building exists, proportion of height to width to give the appearance of a tall building, and requires high-rise technologies like elevators and structural wind bracing. The Council also considers that a ‘tall building’ is a building of 14 or more storeys (or over 50 metres / 165 feet in height). It defines a ‘super-tall building’ as a building over 300 metres / 984 feet high (CTBUH, 2011d).

The scope of this research includes only super-tall buildings, as mentioned in Section 1.3 and explained in Section 3.2. The reason for covering only super-tall buildings is due to their current and future rapid development. CTBUH (2011b) records that 49 super-tall buildings had been completed at the beginning of 2011 and nearly 100 super-tall buildings are under construction (CTBUH, 2011a). This research is conducted to accommodate the need for super-tall buildings now and in the future. The development of tall and super-tall buildings is discussed in the following section.

2.1.2. History of Tall and Super-tall Buildings

The brief history below gives an overview of how people have built tall buildings in the world. The history of tall buildings begins from the ancient era of the Tower of Babel and the pyramids of Egypt. Since then people have built bigger and taller buildings with limited knowledge and technology (Taranath, 1988). The development of building technologies at the end of the nineteenth century, such as the application of cast-iron frames and electric passenger elevators, enabled people to build higher (Mujica, 1977). Since then, taller buildings have been built in larger numbers.

A number of reasons have motivated people to develop the tall buildings. Taranath (1988) believes that pride, ego, and competition have been the inner motivations for people building high since the ancient era. For example, people had a dream to reach the sky by building the Babel Tower several thousands of years ago. Another factor, however, that naturally conditions people to build taller is city growth (Schueller, 1977). In many countries of the world, cities develop horizontally and vertically. Tall buildings are an alternative to develop cities with high land prices. A large number of tall buildings have been built in Chicago and New York as a solution for the need for office buildings (Lepik, 2004). This condition has also occurred in other large cities in the world.

Tall buildings, however, rely on building technologies, especially elevator and structural systems. For example, Mujica (1977) explains that as passenger elevators were developed as vertical transportation, buildings were built twice as high. The availability of electricity enabled high-speed electric elevators, which made taller buildings possible. In terms of structures, cast-iron replaced the masonry load-bearing wall system as a structural material for tall buildings in the nineteenth century. Cast-iron is lighter and more adaptable to be integrated with elevators than masonry (Taranath, 1988). In later years, cast-iron as a structural material was replaced by steel, high-strength reinforced concrete and composite materials of steel and reinforced concrete. In terms of structural systems, conventional rigid frame systems have been replaced by more sophisticated structural systems, such as shear walls, outriggers, and tube systems, for taller buildings.

Generally, as buildings are designed taller, building technologies develop, following building needs.

Figure 2.1 shows the development of the world's tallest buildings from 1885 until 2008.

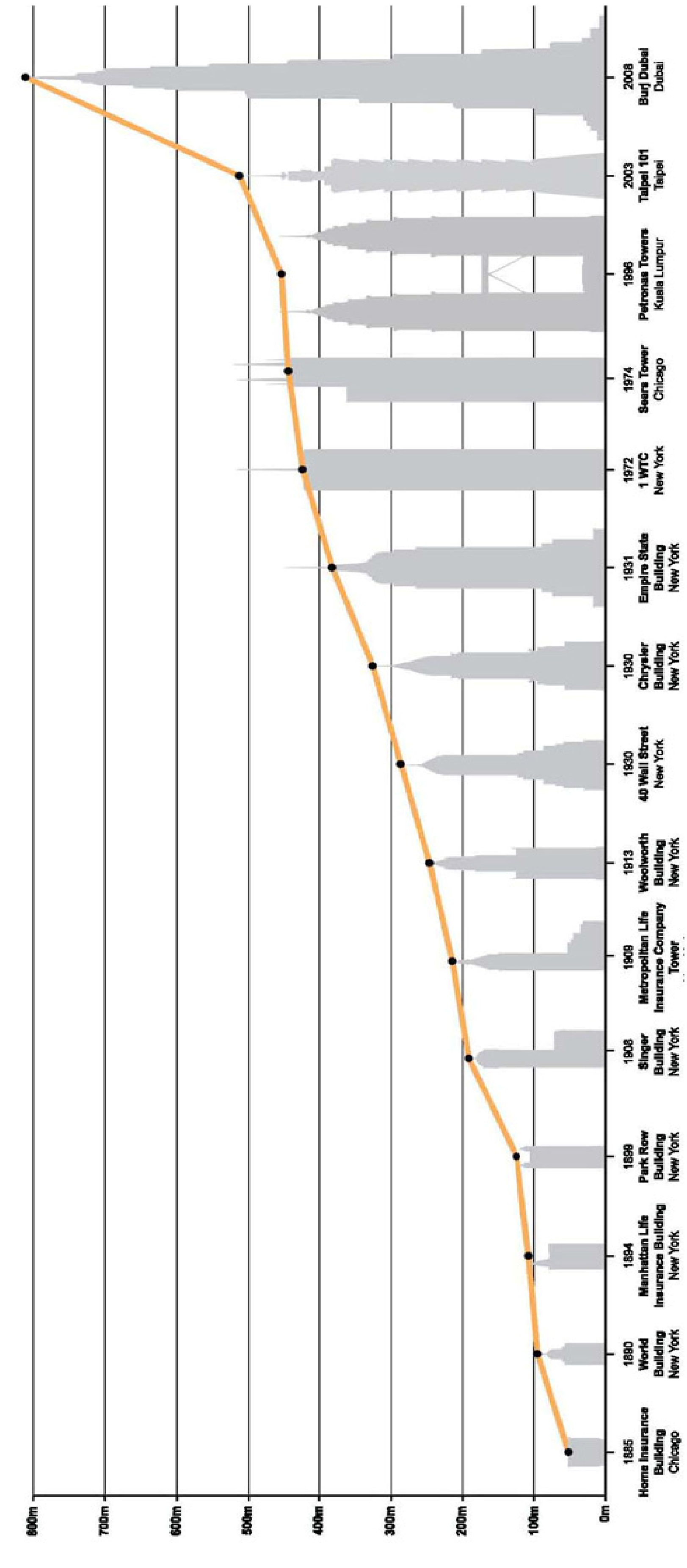


Figure 2.1 Diagram of the history of the world's tallest buildings (CTBUH, 2008, p. 40)

2.1.3. The Future of Super-tall Buildings

The future of tall buildings follows a trend towards vertical cities. This is illustrated by currently constructed buildings and proposals for future tall buildings.

Mixed-use buildings are the type of tall buildings being constructed currently and proposed for the near future. They are designed to accommodate various needs in a city. CTBUH (CTBUH, 2011a) records that a large number of super-tall buildings under construction will combine office, residential, hotel, and retail functions. A mixed-use super-tall building is representative of a simple vertical city.

Vertical cities are proposed as an alternative to cope with problems of highly populated cities. For example, Swenson (1971) proposed 150-storey super-frame towers to change the urban landscape of Chicago city to accommodate existing office needs and city expansion. In 1989 Norman Foster designed the Millennium Tower to be built in Tokyo, Japan. The concept of the building is a vertical city that has 170 storeys, 840 metres high, and can house 60,000 people. This tower concept is proposed as a future city that is sustainable and efficient (Howeler, 2003). Another project that was proposed to accommodate some of the high population of Tokyo is DIB-200 by Kobori, Ban, Kubota, and Yamada (1992). The physical form of the 200-storey building consists of twelve units of 50 metres diameter and 50-storey cylindrical high-rise building units where each unit is connected vertically and horizontally at sky lobbies. There are many other vertical city projects that are proposed such as the Bionic Tower by Javier Pioz, Maria Rosa Cervera and Eloy Celaya that was designed to accommodate 100,000 people (Pioz & Cervera, 2008), the Shimizu Mega City Pyramid proposed over Tokyo Bay in Japan to house 750,000 people ("Shimizu Mega-City Pyramid," 2009) and the X-Seed 4000 proposed by Taisei Construction Corporation that is 4000 metres high and accommodates 1 million people (Davis, 2007). These projects consist of huge scale structures and can accommodate large numbers of people. They were designed to function as cities of the future, but they have not yet been executed. The realisation of these super-tall building projects requires sophisticated technologies.

2.1.4. Discussion

The previous sections have discussed the development of tall and super-tall buildings in the past, current period, and in the future. As mentioned above, the development of tall and super-tall buildings relies on technology. Several vertical city projects, which were proposed as future super-tall buildings, have not been realised because they require more sophisticated and advanced technologies than are currently available, especially the structural and elevator systems.

Technologies of building structures have developed in terms of structural materials and structural systems. The aim is to provide efficient structures to transfer building loads to the ground. Khan (1970) notices that the structural design of tall buildings is dominated by lateral loads. Tall structures must be designed to be very strong and rigid to resist them. Structural materials have developed from cast-iron to reinforced concrete and steel in order to increase the available strength. Structural systems have also developed from conventional rigid frame systems to more rigid structural systems such as shear walls, outriggers, and tube systems. The development of technologies in tall building structures is discussed in the following section.

Elevator systems also have developed specifically to fulfil the needs of vertical transportation of super-tall buildings. The current elevator systems in super-tall buildings are zoned, double-decker elevators, and sky-lobby systems (Fortune, 1997). These systems are normally combined to achieve an efficient vertical transportation system to provide the best service for the building users.

Structural and elevator systems are two very important factors in super-tall buildings. As buildings rise higher, structural components are larger and elevators require a larger proportion of floor area. Structural designers mainly increase the volume of structural components to make the structure more rigid. Large columns and braces can be seen in current super-tall buildings. For example, the composite columns in Jin Mao tower, Shanghai, vary from 1.5m x 4.8m on the ground level to 0.9m x 3.3m at level 87 (Korsita, Sarkisian, & Abdelrazaq, 1996). In Taipei 101, the concrete-filled-steel-tube columns have the maximum size of 2.4m x 3.0m (Shieh, Chang, & Jong, 2003). Elevators also occupy a large floor area in super-tall buildings. This is because the space needed for elevators increases in proportion of the number of the occupants. In addition, services components, such as HVAC ducts, water pipes, electrical components, and stairs, also consume large floor areas in super-tall buildings. As a result, usable floor areas are minimised especially at the lower floors. Figure 2.2 shows the large services areas at the ground floors of some existing super-tall buildings. These conditions require strategies to optimise usable floor area by minimising or integrating services and structural components; this is part of the Research Method that analyses structural-services integration as explained in Section 3.4.

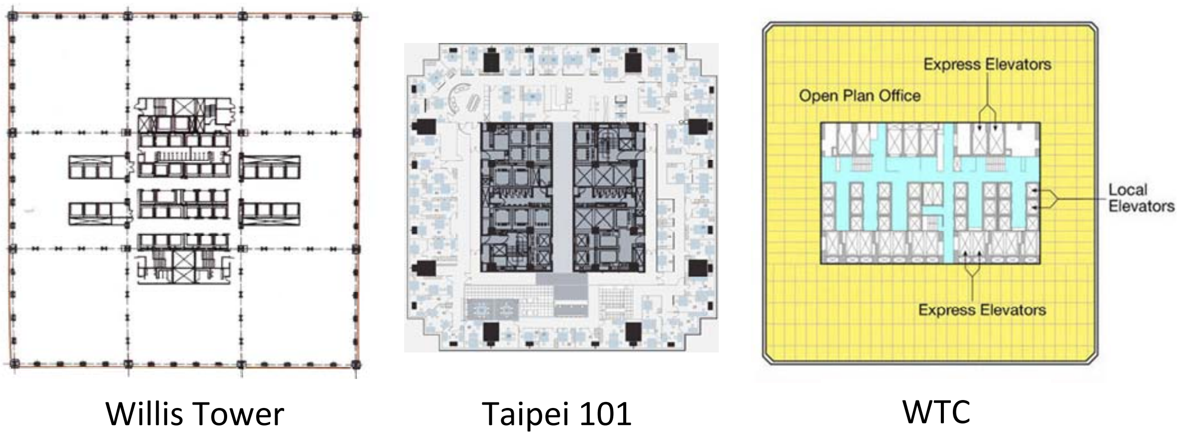


Figure 2.2 Floor plans of Willis tower, Chicago (Binder & CTBUH, 2006, p. 32); Taipei 101 ("Taipei 101," 2011); and the World Trade Center, New York (Source: Wikimedia.org)

As mentioned above, building systems should be integrated to optimise usable floor area. Systems integration is where building systems share space and function (Bachman, 2003). The aim of system integration is to meet the demands for high efficiency and maximize rentable areas (Schuler, 2003). When building systems share space and function, the space required for building components is less; as a result, a larger space for building occupants can be provided. In this research, systems integration is used as one of the parameters for the application of double-layer space structures in super-tall buildings, as explained Chapter 3. The concept of systems integration and its applications are discussed further in Section 2.3.

2.2. Structural Systems of Tall Buildings

This section discusses general concepts of structural systems for tall buildings. It also shows how various structural systems have developed and impacted upon other building systems.

2.2.1. General Concepts of Tall Building Structures

Building structures carry different types of loads, classified into vertical and horizontal loads. Vertical loads are commonly known as gravity loads and horizontal loads are normally known as lateral loads. Taranath (1988) explains that lateral loads impact tall buildings much more than gravity loads and their effect increases hugely as a building rises higher. This can be seen in Figure 2.3, where structural weight per unit floor area for lateral bracing designed to resist lateral loads rapidly increases when the number of floor increases. As a result, total structural volumes also increase with the number of floors. The structural system of a tall building can be assumed as a vertical beam cantilevering from the earth (Taranath, 1998). Lateral forces such as wind and earthquake tend to push it over, producing shear and moment in the building. The design concept of tall structures is that they must resist the combined forces of primarily, horizontal loads, and secondly, vertical loads. As buildings rise higher, structural rigidity becomes the most dominant factor. Structural systems of tall buildings have developed from conventional rigid frames to other systems that are more rigid and efficient.

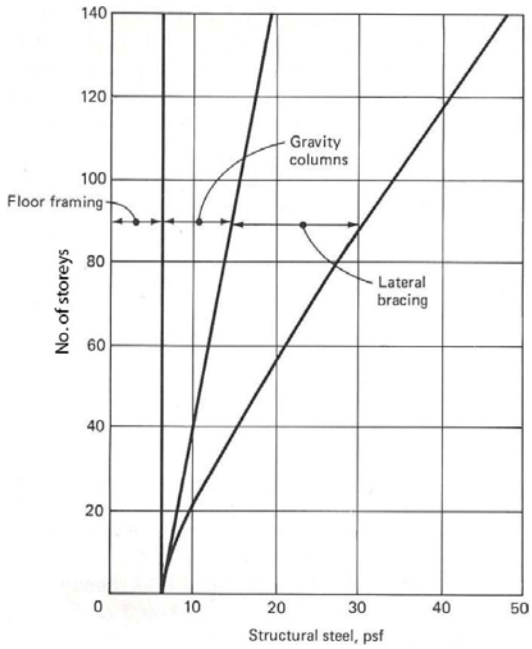


Figure 2.3 A relationship between structural weight per unit floor area and number of storeys (Taranath, 1988, p. 12)

2.2.2. Structural Systems of Recent Tall Buildings

Technologies in tall building structures have developed in terms of their structural materials, construction methodology, and structural systems.

Structural materials of tall buildings are now stronger, lighter, more easily constructed, and relatively cheaper. For example, the masonry load-bearing wall system was replaced by cast-iron and then later replaced by stronger materials like steel, reinforced concrete, and composite materials of steel and reinforced concrete.

Construction methodologies of tall buildings aim for cheaper, faster, and higher quality construction (Lin, 2001). Many new techniques and equipment for building construction, such as precast and prefabricated structures, self-climbing formwork, the use of tower cranes, concrete pumps, and other methodologies, have been developed to achieve this aim.

Current structural systems of super-tall buildings have also developed from two-dimensional to three-dimensional structures to efficiently resist lateral loads. Fazlur Khan argued that a structure can be designed to be more efficient as a three-dimensional unit (Ali, 2001). He classified tall structures into a range of structural systems, such as rigid frame, shear wall, belt truss, and various tubular systems, with different structural materials (Ali, Armstrong, & CTBUH, 1995; Schueller, 1990). Rigid frames, which are normally analysed as two-dimensional structures, are not efficient for taller buildings. Tubular systems, like framed-tube, tube-in-tube, bundled-tube, and braced-tube, are an example of three-dimensional structures that have been used in several super-tall buildings, such as World Trade Center, New York, and the John Hancock Center and Willis Tower, both in Chicago.

Structural systems of tall building structures were classified by Gunel and Ilgin (2006) based on their resistance to lateral loads. The systems are illustrated in Figure 2.4 and briefly explained as follows:

- Rigid frames

  These systems rely on rigid beam-to-column connections. Their stiffness is proportional to the beam and the column dimensions and the spacing between columns. They are suitable for up to 30 storeys.
- Braced frames or shear-walled frames

  Bracing or shear wall systems combine with rigid frame systems. They can be seen in the 77-storey Chrysler Building, New York.
- Outriggers

  These comprise a central core with horizontal outrigger trusses or girders connecting the core to the external columns. In most cases the external columns are interconnected by an exterior belt girder like in the 42-storey First Wisconsin Center, Milwaukee.

- Framed-tubes

  Closely-spaced outer columns are interconnected by deep beams, so that the whole building acts as a giant vertical tube cantilever resisting lateral loads. These systems were used in 110-storey World Trade Center, New York.

- Braced-tubes

  The concept is to increase the building rigidity by adding bracing to tube systems like in the John Hancock Center, Chicago.

- Bundled-tubes

  Several framed-tubes are combined and bundled to make them work together. Bundled-tube systems are suited to buildings that are both high and wide as in the 108-storey Willis Tower, Chicago.

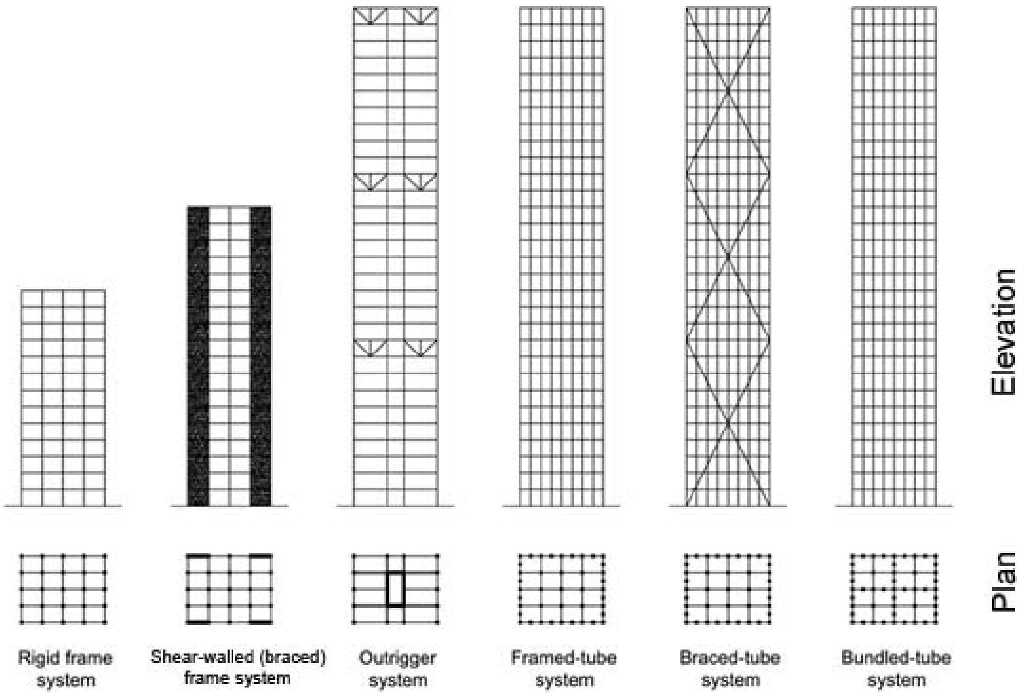


Figure 2.4 Structural systems of tall buildings

Since the late 20th century, a relatively new structural system, known as diagrid, has been applied in several tall buildings. This structural system comprises diagonal components at the building perimeter, and perimeter columns are eliminated (Moon, Connor, & Fernandez, 2007). Diagrid structures are not only efficient in resisting lateral loads, but also can achieve an aesthetically pleasing structural expression (Moon, 2009). The pattern of diagrid structural members are explicitly expressed and integrated in building forms of Swiss Re, London, built in 2004, and Hearst Tower, New York, completed in 2006, as shown in Figure 2.5.

Figure 2.5 (a) Hearst Tower, New York (Source: Wikimedia.org); (b) Swiss Re Building, London (Source: Wikimedia.org)

Recently, diagrid structures have been used by optimising their structural and architectural advantages, especially for buildings with complex geometries. For example, a diagrid structure is applied in a leaning tower, Capital Gate, Abu Dhabi, shown in Figure 2.6. The diagonal members of this structural system work effectively to resist dead loads caused by the leaning geometry. They are also aesthetically expressed and visually integrated with the building façade.

Figure 2.6 Capital Gate, Abu Dhabi (Source: Wikimedia.org)

Integration of structural action and architectural aesthetic has been a demand in recent tall building designs (Moon, Connor, & Fernandez, 2007). For example, during the design process of the John Hancock Center, Kahn (1983), the structural designer, finally convinced the architectural design team to integrate the structural diagonal bracing with the architectural expression of the building.

Ali and Moon (2007) classified the structural systems of tall buildings into interior structures and exterior structures, based on the position of the majority of the lateral load resisting structural members in the building. Interior structures consist of rigid frames, braced hinged frames, shear wall frames, and outrigger structures. Exterior structures include tubular systems, diagrid structures, space truss structures, super frames, and exo-skeletons. This classification shows that exterior structures can be more effective in taller buildings than interior structures. They considers not only the structural characteristics, but also advantages and disadvantages affecting other factors such as fire safety, construction, interior planning, view obstructions, and architectural building façade and geometry.

2.2.3. Discussion

Structural systems have developed to fulfil the demand for taller buildings. Two-dimensional structures have been replaced by more sophisticated three-dimensional structures to optimise structural effectiveness for super-tall buildings. Structural systems of modern super-tall buildings are expected not only to be optimised structurally, but also integrate with other building systems, such as services, building façade, and the interior.

The development of structural systems of super-tall buildings indicates two main challenges in the design process, structural efficiency and systems integration. These two points are used as parameters in this research, explained in Chapter 3, in order to investigate if double-layer space structures can be successfully applied in super-tall buildings. The concept of building systems integration and its application is discussed in the following section.

2.3. Building Systems Integration

This section discusses building systems integration and why it is important in the design of super-tall buildings. The discussion covers integration concepts and their classification as well as how to measure systems integration. The purpose is to review the literature on systems integration and to establish the criteria by which systems integration might be incorporated into the Research Method described in Chapter 3.

The Research Method incorporates some of the significant systems integration factors in this section related to systems integration of double-layer space structures within super-tall buildings. However, external factors like interaction with the city, urban setting, and civic infrastructure are excluded.

2.3.1. The Importance of Building Systems Integration

Systems integration is particularly important for super-tall buildings given the demand for high efficiency and the need to maximize rentable areas (Schuler, 2003). As discussed previously, tall buildings commonly require large components like beams, columns, ducts, and shafts for services. As a result, these elements consume much space. Building systems integration aims to optimize the rentable areas by minimizing the area consumed by such elements.

Building systems integration requires that systems work together (Bachman, 2003). This is important to minimise several issues that normally occur in tall buildings. For example, in their classification of structural systems for tall buildings, Ali and Moon (2007) note that several types of exterior structures, where the majority of lateral structural components are at the building perimeter, cause view obstructions. Shear wall frames that effectively resist lateral loads pose interior planning limitations. Diagrid structures that are efficient in resisting lateral loads have complicated joints and slow construction rates. These examples show that structural efficiency does not always lead to building systems effectiveness. Building systems integration aims to optimise the co-ordination of all building systems

2.3.2. Concept of Building Systems Integration

Some authors describe the concept of building systems integration by explaining its definition, objectives, and goals. However, according to Rush (1986) there is no specific definition of integration in the building domain. Integration comprises three distinct objectives: components need to share space, the arrangement should work aesthetically, and suitable building systems have to work together (Bachman, 2003). The main goal of integration is to reduce the amount of construction time, materials used and space occupied, and to produce a balance of all three aspects (Rush & Stubbs, 1986).

Bachman (2003) classifies building systems integration into three categories: physical, visual, and performance integration.

Physical Integration

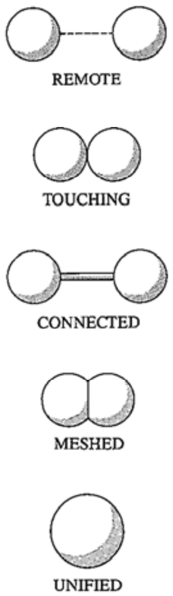
Physical integration is the condition where building systems share space by occupying the same volume (Bachman, 2003). An example can be seen in Te Papa, New Zealand's national museum. In this building, HVAC ducts are placed within three-dimensional trusses. Figure 2.7 shows how services and structural systems occupy the same space.

Figure 2.7 Physical integration of HVAC ducts and trusses in Te Papa, New Zealand's national museum (Photo by: Hendry Y Sutjiadi)

Rush and Stubbs (1986) classify five levels of the physical integration, from the lowest to the highest levels: remote, touching, connected, meshed, and unified, as shown in Figure 2.8 (a). In the remote level, two systems are physically separate from each other, while in the unified level, they are physically one form. Higher integration levels optimise the space used by the systems, and are expected to maximise usable floor area.

However, the levels listed above may not be accurate indicators of the best solution. For example, tubular columns can also be used for services ducts, but they might have a problem with maintenance. In the matrix shown in Figure 2.8 (b), Rush and Stubbs (1986) describe the most probable integration of Structure (S), Interior (I), Envelope (E), and Mechanical (M) in typical buildings. The matrix illustrates that not all building systems are integrated at the highest level. Designers need to consider the advantages and disadvantages of systems integration in all aspects, such as maintenance, construction, fire safety and sustainability.

The design associated with this research tries to provide as highly integrated design alternatives as possible by integrating double-layer space structures with other building systems. All aspects, which can be advantages and disadvantages, of these design alternatives are analysed in order to identify the best solution. This research also discusses less beneficial impacts and how to minimise them.



	remote	touching	connected	meshed	unified
S+E		●	●		●
S+M			●	●	
S+I		●	●		●
E+M			●	●	
E+I	●		●		●
M+I		●	●	●	●

S: Structure

I: Interior

E: Envelope

M: Mechanical

Figure 2.8 (a) Five levels of physical integration (Rush & Stubbs, 1986, p. 320); (b) The most probable systems integration in typical buildings (Rush & Stubbs, 1986, p. 322)

Visual Integration

Visual integration is the expression of building systems as a visual design element (Bachman, 2003). Rush and Stubbs (1986) classify visual integration in five levels. The first level of integration is the condition where a building system is hidden to building users, so modification of its surface, shape or location for any aesthetic reason is unnecessary. For example, HVAC equipment in a plant room does not need colour or position changes for aesthetic reasons. In the second level, different systems are visible but no modification is needed. This level of integration can be seen in buildings with exposed structures, such as Hearst Tower, New York, and Swiss Re Building, London, shown in Figure 2.5. The structural pattern of these buildings is expressed and visually integrated with the building façade. From levels three to five, different systems are clearly visible and need some modifications for aesthetic reasons. These modifications include surface changes in level three, shape changes in level four, and location or orientation changes in level five.

This research seeks to integrate double-layer space structures with other building systems without, or as little as possible, changing members' surfaces, shapes or positions to provide an aesthetically acceptable building. The structural form and pattern of double-layer space structures are designed to visually integrate with façades, entrances, and interiors.

Performance Integration

Performance integration is the condition where building systems share functions (Bachman, 2003). Performance integration is shown in O-14, Dubai. The structure comprises a folded exo-skeleton, where the primary lateral structural components are outside the building (Reiser & Umemoto, 2007). The structure also works as the building façade as shown in Figure 2.9.

Figure 2.9 Performance integration between the structure and façade of O-14 building, Dubai (Source: Flickr.com)

According to Hartkopf, Loftness, and Mill (1986) there are six performance states of integration: spatial performance, thermal performance, indoor air quality, acoustic performance, visual performance, and building integrity. This research tries to incorporate these performance states in the design alternatives of double-layer space structures. For example, these structures can be integrated to form a double-skin façade to enhance indoor air quality, thermal, and acoustic performance, as explained further in Chapter 5.

2.3.3. Systems Integration in Tall Buildings

Systems integration is common in the designs of existing tall buildings. This is because of the need for space efficiency and the optimisation of usable floor areas.

Several approaches have been applied to tall buildings to integrate building systems. For example, CTBUH suggests that a strategic location for the core is in the centre a building (Codella, Henn, & Moser, 1981). The core accommodates mechanical components including elevators, stairs, ducts, and pipes. The cores are normally surrounded and sub-divided by structural walls. This concept has been used in many tall and super-tall buildings because it optimises mechanical and structural capacity. This is an example of performance integration. Physical integration is also achieved because mechanical and structural components share space.

An example of visual integration has been briefly discussed in Section 2.2.2. Figure 2.5 shows how the structures of Hearst Tower and Swiss Re are expressed and visually integrated with building façade. Several examples of visual integration, which commonly include structural components and building façade, are discussed further in Chapter 6.

Systems integration in tall buildings is not limited to the three categories (physical, visual, and performance integration) discussed in Section 2.3.2. Ali and Armstrong (2006) note that tall buildings should interact with the city. The process of integration requires a multi-disciplinary approach covering architectural and structural systems, vertical transportation, fire safety, energy conservation, and communication systems, and consider environmental effects, constructability, urban setting, and civic infrastructure (Ali & Armstrong, 2006). In addition, the efficiency of building maintenance should be considered as a part of the systems integration during the design process (Aminmansour & Moon, 2010).

2.3.4. Discussion

The discussion above has shown the importance of systems integration to enhance building efficiency that is highly necessary in super-tall buildings. In this research, double-layer space structures as a structural system of super-tall buildings are analysed for their potential for systems integration. The classification of building systems integration explained in Section 2.3.2 can be used to analyse and describe the types of integration. This research attempts to achieve high level integration by focusing on the three integration objectives: sharing space, aesthetic, and working together (Bachman, 2003). It also uses a multidisciplinary approach that includes structural, architectural, services, maintenance, fire safety, constructability, construction costs, and sustainability. The following section reviews literature on double-layer space structures and their potential for systems integration.

2.4. Double-layer Space Structures

This section discusses space structures including their definition, basic concepts, and classification. It specifically discusses double-layer space structures, their development and structural characteristics, and how they are applied in this research.

2.4.1. General Concept of Space Structures

Space structures are defined as three-dimensional structures.

> "Space structures are load-bearing structures applied in architecture that really make use of their three-dimensional action as a structure"
>
> (Eekhout, 1989, p. 10)

Space structures are based on the concept of a triangle as a rigid structure. A number of triangles then can form a truss. Ambrose (1994) explains that the initial concept of the truss is to triangulate a framework to make it stable and rigid as shown in Figure 2.10. The triangle then becomes the basic unit of planar trusses. The truss concept is then applied to a three-dimensional truss system: space structures. Wilkinson (1996) explains that planar trusses as two-dimensional structures work and can only resist loads one way, but space structures work as three-dimensional structures in which loads are distributed in each member to the foundations. Figure 2.11 illustrates the deflections of a planar truss and a space structure caused by concentrated loads in the structure. The deflections of the structures indicate how the loads are distributed.

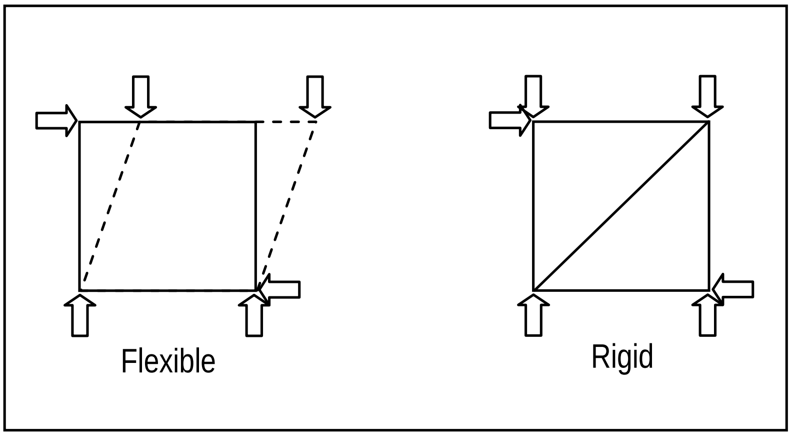


Figure 2.10 Triangular action makes a frame more rigid (Engel, 1997, p. 139)

As three-dimensional structures, space structures have various geometrical forms. According to Stevens (1975) space structures are categorized into:

- Single-layer curved grids, where load capacity is developed by membrane action.
- Double-layer planar or curved grids, in which flexural and shear resistance is developed by the parallel chords and the diagonal members of the systems.

The following section discusses the development of space structures and double-layer space structures.

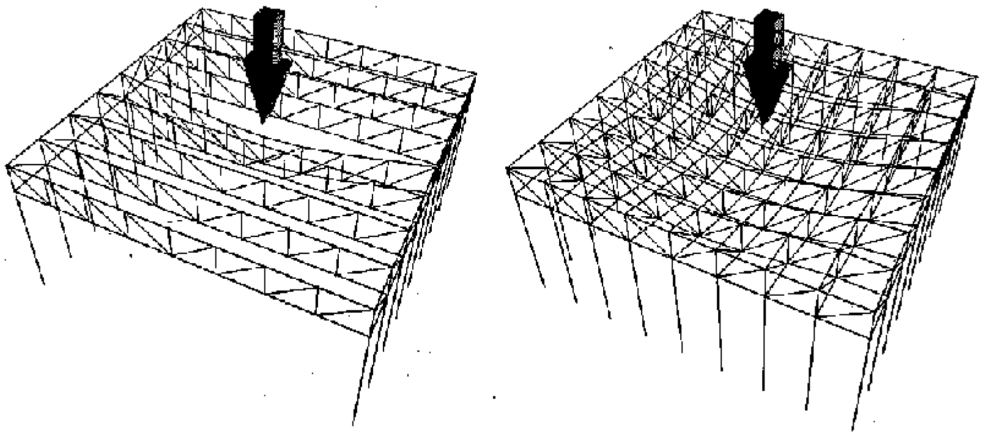


Figure 2.11 Deflection of planar trusses and a space structure under concentrated loads (Chilton, 2000, p. 13)

2.4.2. Development of Double-layer Space Structures and their Applications

A brief history of space structures and double-layer space structures is described below to give an overview of their development. Eekhout (1989) explains that space structures have been known and applied in buildings for about 200 years, when the first iron skeleton dome was built in Paris in 1806 by Belanger and Brunet. These structures were then further developed and applied in several buildings such as the Eiffel Tower in Paris by using space truss elements. In 1907 Alexander Graham Bell made the first real attempt to design and realise space frames into an aeroplane. Space structures became popular in 1950s and have been accepted by architects especially for long-span buildings.

Double-layer space structures are mainly applied in long-span buildings such as sports halls, airport hangars, churches, and exhibition centres. The structures are mostly used as the roof structure but some buildings such as Biosphere 2 in Arizona (Poynter, 2006), and the Crystal

Cathedral (Bachman, 2003) use double-layer space structures to support the building envelopes; roofs and external walls.

Double-layer space structures are not only for large-span buildings. The Instant Glass House in Amsterdam is an example of a space frame in a residential building. This house is composed of two rectangular plane trusses and the structure sits on space frames that transfer loads into the foundations (Bachman, 2003). Another space frame application, the project of N55 Space Frame, was designed by Remmer as a lightweight construction that was easily moveable. Each unit can contain 3-4 people or more by changing its size and configuration. The building systems are totally integrated with each other using space frames as the structure of roofs, ceilings, walls, and floors (Hunting, 2003). El-Sheikh (1996) suggests using composite structures of steel space frames and top concrete slabs as floor structures. These examples of the development of double-layer space structures show that they have potential to be applied as various elements of buildings, like floors, ceilings, building envelopes, and roofs.

In this research, double-layer space structures are investigated for their potential as primary vertical structural systems of super-tall buildings.

2.4.3. Characteristics of Double-layer Space Structures

Double-layer space structures have two parallel layers of chord members with diagonal web members (Stevens, 1975). Double-layer space structures can be classified into planar and curved grids. Planar double-layer space structures are commonly known as space frames.

Space frames are the most common type of space structures, mainly because they are more adaptable and more easily constructed than spatial curved structures (Eekhout, 1989). According to Ambrose (1994) the term “space frames” is misused, but has been commonly used to describe a three-dimensional truss. Space frames are described as flat structures constructed from two layers of members that are interconnected by numbers of diagonal members (Kneen, 1975).

This research investigates double-layer space structures because of possible advantages in structural efficiency and the potential for systems integration. Several benefits of double layer space structures for long-spans are as follows (Chilton, 2000; Makowski, 1981):

1. Structural efficiency.
   - Loads are distributed in three dimensions through all structural members.
   - High rigidity.
   - Works as a diaphragm under lateral loads.
   - Structural redundancy which means that failure of limited number of elements does not necessarily lead to overall collapse of the structure.
   - Less material and light-weight structures.
   - Freedom of choice of support locations.
   - Economical in cost for long-span structures and buildings that have few supports.
2. Systems integration.
   - Useful space between the top and bottom layers for mechanical and electrical components.
   - Architectural expression of the regular pattern of structural members.

This study investigates double-layer space structures as a structural system for high-rise buildings because of their potential to fulfil challenges in super-tall building designs, and these are summarised in Table 2.1.

Table 2.1 Challenges in super-tall building designs are fulfilled by the advantages of double-layer space structures

Challenges in Super-tall Building Designs	Advantages of Double-layer Space Structures
- Structures should be designed as a three-dimensional unit.	- They work in a three-dimensional action (loads are distributed in all members).
- High rigidity is required to minimise the impact of wind load.	- High rigidity is caused by a triangular action.
- Structural efficiency is achieved when less material are used.	- Less material is needed.
- Structural and services components, which take a great proportion in a tall building, should be physically integrated to optimise usable floor area.	- Space between the top and bottom layers can be used for services components.
- Visual integration of structural and architectural components is desired.	- The module of the structures can be expressed architecturally. Visual integration of structural and architectural components is possible

2.4.4. Applications of Double-layer Space Structures in Super-tall Buildings

Double-layer space structures have never been applied to tall and super-tall buildings. However, some designers have considered their potential for high-rise structural systems.

In 1956 Kahn and Tyng proposed a project for a 184.8 metre high building using space structures (Ayad, 1997). The tower, named the City Tower, is a triangulated precast and pre-stressed concrete frame, as shown in Figure 2.12 (a). The structural system consists of nine levels of space frames at 19.8 metre intervals. However, this project was not executed for structural and economic reasons (Komendant, 1975).

In 1971, Swenson proposed a 150-storey building using a large-scale super-frame or double layer space structure as the structural system, shown in Figure 2.12 (b). It consists of two elements. The first element is a vertical double-layer space structure of large steel tubes that vary from 2.1 metres in diameter at the bottom to 1.2 metres at the top. The second element is a series of eight two-storey deep trussed floors that are connected to the vertical elements. The floor trusses also function as mechanical equipment areas. Each truss supports 10 floors above, and 10 floors below are hung from it (Swenson, 1971). Unfortunately, this project also has yet to be realised.

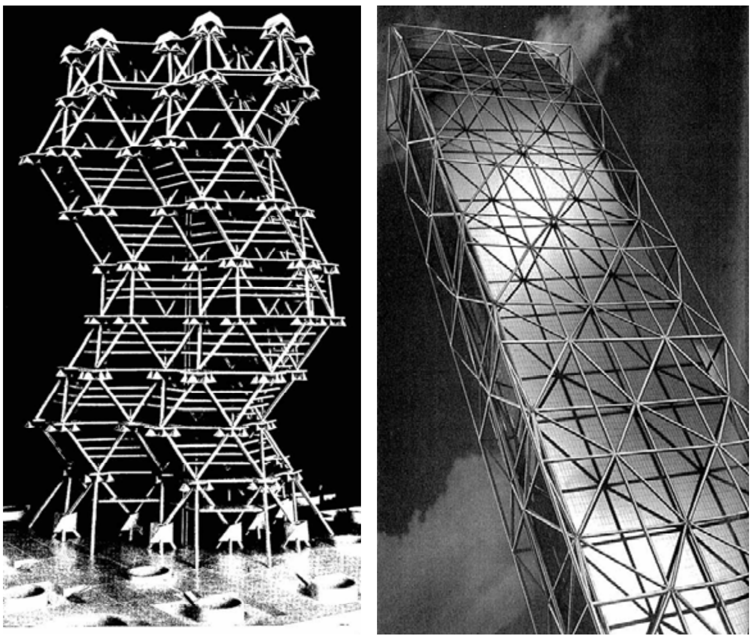


Figure 2.12 (a) The City Tower, project by Kahn and Tyng (Ayad, 1997, p. 139);
(b) Super-frame tower proposed by Swenson (1971, p. 58)

Both projects mentioned above have adopted double-layer space structures. This shows that architects and structural designers have considered the potential of double-layer space structures for high-rise applications. Unfortunately, no literature has discussed or explained the details of these applications and their impacts on other factors, like architectural and services systems, fire safety, construction, costs, and sustainability.

The following section discusses the need for investigating the potential of double-layer space structures in super-tall buildings.

2.5. Knowledge Gap and Research Justification

This section summarises literature on tall and super-tall buildings including structural systems and systems integration as important factors in the design of super-tall buildings, as well as the potential of double-layer space structures to fulfil the design requirements of super-tall buildings. This summary identifies a knowledge gap and becomes the starting point of, and justification for, this research.

The literature discussed above has shown how taller buildings require more advanced technologies, especially within structural systems and elevators. Structural systems have developed from two-dimensional structures like rigid frames to three-dimensional structures like tubular systems, in order to provide more efficient and rigid structures. Advanced elevator systems have also been applied in super-tall buildings, such as zoned elevator systems, double-decker elevators, and sky-lobby systems.

As buildings rise higher, more space is required for structural and services components including ducts, stairs, and elevators. As a result, usable floor areas in super-tall buildings need to be optimised. In addition, large structural components can ruin the façade aesthetic and obstruct views. This condition leads to the requirement for building systems integration that covers physical, visual, and performance integration, and uses a multi-disciplinary approach during the design process.

The potential of double-layer space structures as a structural system of super-tall buildings is based on two factors, structural efficiency and systems integration. As explained previously, double-layer space structures are of a relatively rigid form that operates in a three-dimensional action. This condition may fulfil the required criteria for efficient structural systems in super-tall buildings. Double-layer space structure can also be integrated with services systems by providing space between the top and bottom layers for mechanical and electrical components. In addition, visual integration can be achieved by the architectural expression of the regular pattern of double-layer space structure members.

Double-layer space structures have been proposed for two tall and super-tall building projects. This indicates that architects and structural designer have considered the potential of double-layer space structures for tall buildings. However, these two projects have not been realised and double-layer space structures have not yet been built as vertical structures. No literature has discussed this type of application, including its advantages and disadvantages. Here, the literature review leads to a knowledge gap, which raises several questions:

- What are the characteristics of a double-layer space structure as a vertical structure?
- How structurally efficient are these structures compared to other structural systems?
- To what extent can these structures integrate with services and architectural systems?
- What are the impacts of this integration?
- How safe are these structures during fire?
- Are these structures constructible?
- What structural profiles and connections are suitable?

These questions are summarised in the main research question:

“Are double-layer space structures suitable for super-tall buildings?”

This research intends to discover new knowledge about the application of double-layer space structures as a structural system of super-tall buildings.

Chapter 3: Research Methodology

This chapter describes the methodology used in this research in order to answer the research question. It covers the research framework, justification of the research methodology and the explanation of the quantitative and qualitative approaches using case studies.

3.1. Research Framework

The research framework is shown in Figure 3.1 and explained as follows:

- The research begins with a literature review that shows how double-layer space structures have the potential to fulfil the challenges posed by super-tall building design. This review is the **background** of this research.
- The **rationale** for the potential of double-layer space structures as a structural system of super-tall buildings is then considered.
- As double-layer space structures have not yet been applied in super-tall buildings, and no literature has been found providing detailed information about this application, this condition is identified as a **knowledge gap**. This gap is then expressed as a **research question**: "Are double-layer space structures suitable for super-tall buildings considering structural efficiency, building services and architectural integration, and construction?"
- To answer the research question, quantitative and qualitative approaches are used as **the research methodology**. The quantitative approach involves structural design and analysis using ETABS to investigate structural efficiency. The qualitative approach is necessary to investigate aspects of services and architectural integration, and construction. The overall methodology covers the following steps: reviewing relevant literature, proposing models or strategies, analysis of advantages and disadvantages, and discussion. These quantitative and qualitative approaches are discussed further in the following section.
- **Results** of this research are summarised and conclusions drawn, research limitations revealed, and aspects requiring further development are discussed.

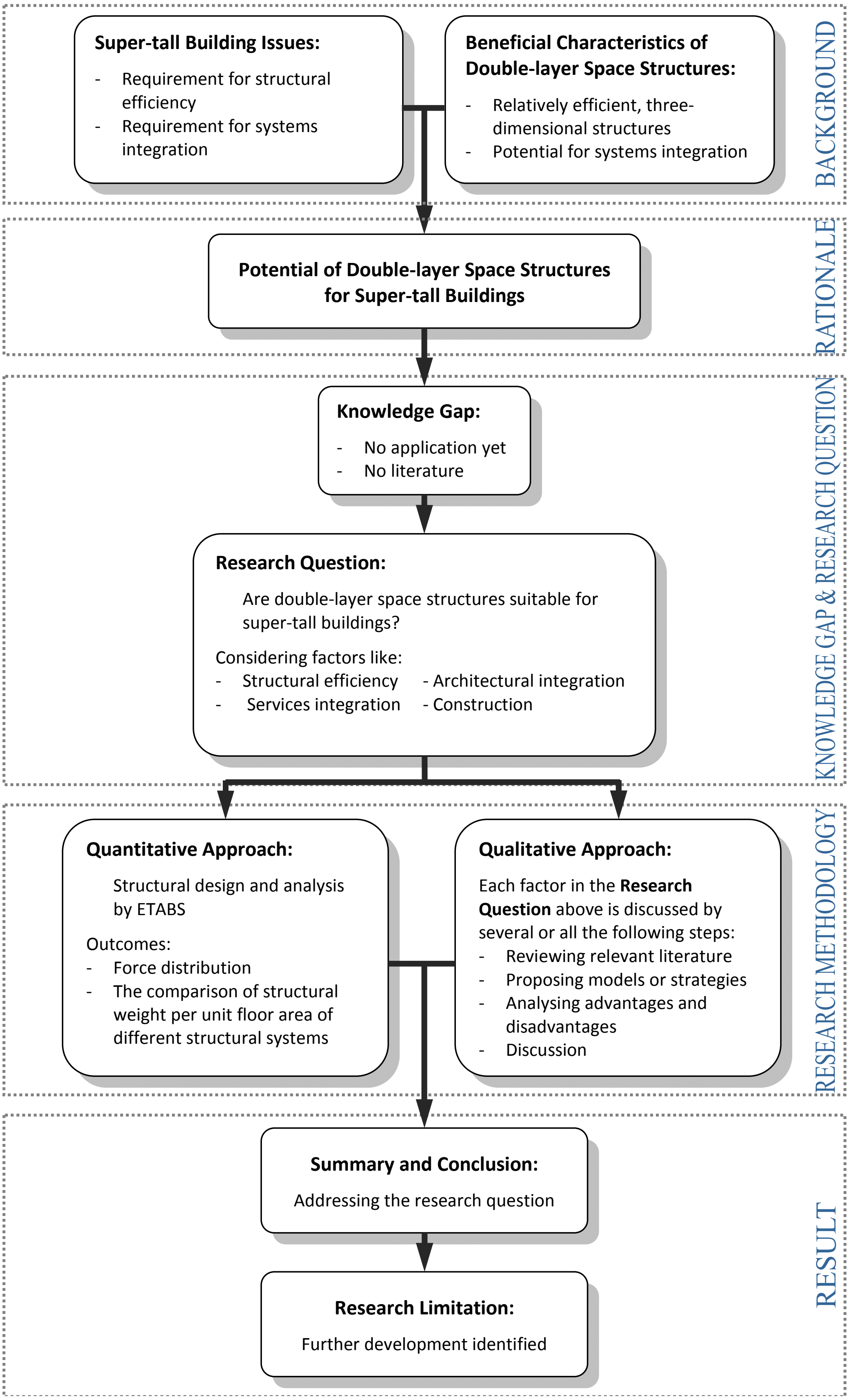


Figure 3.1 Research framework

3.2. Justification of the Research Methodology

The research methodology is intended to answer the primary research question about the suitability of double-layer space structures for super-tall buildings, in terms of structural efficiency and systems integration. The methodology requires two different approaches, quantitative and qualitative. Both use various case studies that are designed to represent existing super-tall buildings and apply current high-rise technologies. The purpose is that the findings of this study are not only applicable for the case-studied buildings, but also for super-tall buildings in general.

Quantitative Approach

In order to test the capability of double-layer space structures in high-rise applications, an analysis using numerical data by a quantitative approach is used in this research. In this case study, structural efficiency is the parameter of the quantitative approach.

Structural efficiency is commonly presented in structural weight per unit floor area (Taranath, 1988). Structural systems of tall buildings are commonly designed to fulfil two criteria: strength and deflection limits. The results from structural design and analysis provide information about structural member sizes that are adequate to fulfil the design criteria, and then the total structural weights can be calculated. Lighter structure indicates more efficient structures. Structural weight per unit floor area is used as a parameter for the comparison of structural efficiency of different structural systems.

A quantitative approach by case study is used in this research to investigate structural efficiency. This methodology is chosen because one of its characteristics focuses on the real-life context (Goat, 2001). The efficiency of multi-storey steel double-layer space structures are compared with the efficiency of other structural systems.

In order to represent current super-tall buildings, case studies using computer models of 100-storey, 400 metres high, rectangular buildings are designed and analysed. With that particular height, the findings of these case studies are relevant for buildings in the approximate range of 75 to 125 storeys or 300 to 500 metres high. Since the main purpose of the quantitative approach in this research is to obtain a clue about structural member sizes, the findings of this case study will not be significantly different for other buildings with heights within the range.

The case studies are designed to represent current super-tall buildings, which have been commonly designed and built in that range of heights. A data base composed in September 2011 shows that 96% super-tall buildings have been built between 300 and 500 metres high (CTBUH, 2011b), and from 68 super-tall buildings under construction 60 buildings will be in those heights when completed (CTBUH, 2011a).

In this case study, rectangular shapes are preferred in order to simplify the calculation and comparison with different structural systems. The analysis of super-tall buildings with different shapes will not significantly have different findings of structural member sizes. This is because building heights have more impact on structural design than building shapes (Taranath, 1988). The details of this quantitative approach are discussed in Section 3.3.

Qualitative Approach

A qualitative approach is used in this research in order to investigate if double-layer space structures can integrate with other building systems in high-rise applications. The three categories of systems integration, suggested by Bachman (2003) as discussed in Section 2.3.2, have grades and a sub-category; physical and visual integration has five grades, while performance integration is sub-divided in six performance states. This study assess the systems integration and focuses on realising as possible the three integration objectives: sharing space, aesthetics, and working together (Bachman, 2003). It also uses a multidisciplinary approach including services, architectural systems, and construction in its scope.

A qualitative approach using various case studies is used in this research to explore strategies for systems integration and investigate the advantages and disadvantages of the integrated approaches. The exploration of systems integration has three main steps:

- **Interpretive-historical research** (Wang, 2001a) through observation and evaluation of existing buildings, relevant literature, and codes as precedents.

- **Simulation and modelling** using various computer models based on the observation and evaluation of results from the first step. According to Wang (2001b, p. 280), *"computer images must be considered simulation"* because they can provide measurable information close to the real conditions. Strategies to integrate double-layer space structure with services and architectural systems are explored and illustrated using computer models.
- **Analysis** of advantages and disadvantages of the results from the second step.

The findings of these case studies are not limited to any specific condition, but can be applied to general situations. This is because the simulation and modelling are based on observation of existing tall and super-tall buildings from the first step. This means that this simulation can also be applied for the case studies modelled using ETABS in the quantitative approach. The details of this qualitative research will be discussed in Section 3.4.

3.3. Quantitative Approach

This section describes the steps of the research using a quantitative approach by case study designs, analyses and comparisons in order to answer the research sub-questions about the Structural and Services Systems, as mentioned in Section 1.3.

Structural System

Research sub-questions:

- What are the structural features of a double-layer space structure as a vertical structure?
- How efficient are these structures as compared to other current structural systems?

The case study is conducted using the following steps:

1. A computer model of a 100-storey 48m x 48m building using double-layer space structures as lateral structural systems is designed and analysed using the computer software, ETABS.

   The results of the design and analysis provide information about:

   - Force distribution
   - Lateral deflection profiles
   - Structural member sizes

2. Another computer model of a 100-storey 60m x 60m building using the same structural system is designed and analysed. The aim is to compare the structural weight per unit area of double-layer space structure buildings using different slenderness. The results from each building are compared to those of other structural systems of super-tall buildings (a bundled-tube, a braced-tube, and a diagrid) that are designed using the same approach and assumptions.
3. Double-layer space structures are also analysed to resist wind and seismic loads using hand calculation and the computer software, ETABS. The base shears from these two different types of lateral loads are compared.
4. The structural sensitivity to wind load is analysed by changing several member sizes. Their additional structural weight and lateral deflections are compared. The aim is to investigate structural modifications that significantly impact on structural deflection and weight.
5. Thermal expansion of exposed double-layer space structures is analysed.
6. The results from the design and analysis answer the two research sub-questions as follows:
   - Structural characteristics of multi-storey double-layer space structures are revealed by their force distribution, lateral deflection pattern, base shears from wind and seismic loads, structural sensitivity to wind load, and thermal expansion.
   - The efficiency of these structures is shown by the comparison of their structural weight with those of other structural systems.

This case study is discussed further in Chapter 4.

Services Systems: Fire Safety

As part of the services aspects, a research sub-question about fire safety is:

- How stable are double-layer space structures during fire and in the event of localised failure?

To answer this question, the research is approached as follows:

1. A computer simulation of a 100-storey double-layer space structure, designed in Chapter 4, is re-analysed when selected structural components of several floors have collapsed.

2. The computed demand/capacity ratios of the structural members indicate whether the structure remains stable. The structure is stable when these ratios are less than one.

This analysis and its finding are explained further in Section 5.4.5.

These case studies investigating structural performance of double-layer space structures require the following resources:

- Computer software, ETABS (*ETABS version 9*, 2005). ETABS is particularly suitable for tall structures that have identical floor plans. ETABS has been used for the design and analysis of existing super-tall buildings like Taipei 101 (Poon, Shieh, Joseph, & Chang, 2002) and Burj Khalifa, Dubai (Baker, Korista, & Novak, 2007).
- Building codes from the United States (US), where tall building design has developed. For more than 100 years, the world's tallest buildings have been in the US, as shown in Figure 2.1. Technologies for tall buildings, building codes, and standards have been developed in the US; many countries have developed their own standards based on the US standards. Therefore, the case study in this research is relevant to general building designs that apply building codes from other countries than the US. The building codes used in this research are explained in Chapter 4.

3.4. Qualitative Approach

This section explains the steps of the qualitative approach using case studies in order to answer the research sub-questions covering the aspects of services, architecture, and construction as discussed in Section 1.3.

Services Systems

Research sub-questions:

- To what extent can services systems integrate with double-layer space structures?
- To what degree can these structures integrate with fire safety and egress systems?
- To what degree is this structural system compatible with energy efficient design concept to be found in the current literature?
- What are the advantages and disadvantages of this integration?

A case study is conducted using the following steps:

1. The design of the services systems including HVAC, stairs, and elevators for the 100-storey building is conducted. The design is conditioned to represent current services systems that have been commonly used in tall and super-tall buildings.
2. The design is then analysed to consider to what extent the structure could accommodate the services components. Graphical modelling illustrates the integration of structural and services components. The categories and levels of integration explained in Section 3.2 are used to assess the models.
3. As a part of services systems, fire safety aspect is also analysed. The analysis begins with observing fire safety and egress systems in existing tall and super-tall buildings including the destroyed New York World Trade Center and recommendation from FEMA (2002) and NIST (2005). Based on this observation, fire safety and egress systems are designed for double-layer space structure buildings. This topic is discussed further in Section 5.4
4. As a part of services integration, approaches to energy efficiency are also discussed. The study analyses the inherent capability of double-layer space structures to accommodate other building components in order to approach energy efficiency. These approaches are described further in Section 5.5.
5. To answer the second sub-question, the advantages and disadvantages of the proposed structural-services integration are analysed and discussed. The analysis also covers how to provide a larger usable floor area than in typical high-rise buildings.

Architectural Aspects

Research sub-questions:

- What strategies can be used to integrate the structure with architectural aspects, such as façades, entrances, interior space, and building geometry?
- What are the advantages and disadvantages of this integration?

To answer these sub-questions, the research undertakes:

1. Observation and evaluation of existing buildings focusing on the integration of structures with building façades, entrances, interior, and building forms including some with complex geometry.

2. Computer modelling illustrates various possible integrated structural and architectural component designs.
3. Design options are analysed, considering their advantages and disadvantages, and summarised to provide a number of strategies for structural-architectural integration that future designs of double-layer space structures can select from.

The study about architectural integration of double-layer space structures is discussed further in Chapter 6.

Construction

The research sub-questions are:

- What construction methods, including primarily structural members' profiles and connections, erection methodologies, and construction equipment are suitable for this application?
- What are the impacts of vertical double-layer space structures on construction costs?

The research is conducted as follows:

1. An evaluation of construction methods in existing tall buildings is conducted, especially those that are relevant to the construction of multi-storey double-layer space structures.
2. Based on this evaluation, various construction aspects, including structural members' profiles and connections, erection methodologies, and construction equipment, are proposed using computer models to answer the first research sub-question.

To answer the second research sub-question:

1. Observation and evaluation of the factors that affect construction costs of tall buildings including construction costs are obtained from several existing projects from the literature.
2. The advantages and disadvantages of using double-layer space structures from the perspective of construction costs are analysed. This analysis includes structural materials, structural members and connections, and installation of building façades.

The details of this study are explained in Chapter 7.

Chapter 4: Structural Design and Analysis

This chapter discusses vertical double-layer space structures from a structural point of view. The study applies the steps mentioned in Chapter 3 covering structural design and analysis, comparisons of structures with different slenderness and with other structural systems, lateral load analysis, structural sensitivity analysis, and thermal expansion analysis. Each of these analyses is explained in each of the following sub-chapters. The aim is to answer the research sub-questions outlined in Section 3.3 by investigating the structural characteristics and applicability of double-layer space structures in super-tall buildings, and analysing their structural efficiency by comparing them with current efficient tall structural systems.

4.1. Structural Design and Analysis of the Case Study Buildings

This section explains the case study using structural design and analysis. A 100-storey 400 metre-high double-layer space structure was designed to resist gravity and lateral loads. The aim was to investigate the force distribution in the structure and determine structural member sizes. As mentioned previously in Section 3.2, this building model with that particular height was designed to represent current super-tall buildings. The findings of this analysis are therefore applicable for super-tall buildings within the range of 300 to 500 metres high, which is most current super-tall buildings.

In this case study, a double-layer space structure is positioned at the building perimeter in order to maximise its capacity to resist lateral loads that are more dominant in taller buildings. In their classification, Ali and Moon (2007) show that buildings can be built taller if the majority of structural members are located at the building perimeter. The literature study in Section 2.2.2 has discussed that recent super-tall structural systems, like various tubular systems, have the majority of structural members at the building perimeter in order to maximise their capacity to resist lateral loads. By maximising the capacity of double-layer space structures to resist lateral loads, this case study has optimised their structural efficiency; this is the optimum arrangement of double-layer space structures in general high-rise applications.

4.1.1. Design Information

This section explains the design information of the case study. Some information, like floor-to-floor height and slab material, is adopted from those normally used in high-rise buildings designs, so the results of this study can be applied generally. The design case of double-layer space structures in super-tall buildings is characterised by:

1. Building properties:
    a. Number of storeys: 100; building height: 400 metres.
    b. The plan geometry is square.
    c. Floor-to-floor height: 4 meters.
    d. Building plan dimensions: 48m x 48m.
    The building is relatively slender, with a height/width ratio of 8.33, as compared to the World Trade Center with a ratio of 6.5. The building has twelve bays of four metres each.
    e. The building location is assumed to be in Los Angeles, California.
    The reason for choosing this location is because it is a seismic area in the US, the country where the building code applies as mentioned in Chapter 3, that has relatively high wind load. Therefore, the findings from wind and seismic analyses, discussed in Section 4.3, of the case study are more critical than those in areas that have less seismic intensity and lower wind load.

2. Structural system:
    a. The structural model is shown in Figure 4.1.
    b. The lateral load resisting system comprises a double-layer space structure located at the building perimeter.
    c. The gravity load resisting system consists of the perimeter vertical double-layer space structure and two-storey deep horizontal double-layer space structures located at four different levels: level-23, level-48, level-73, and level-98. Gravity columns are suspended from the horizontal double-layer space structures. The horizontal double-layer space structures transfer gravity loads from the concrete slabs, steel beams, and gravity columns to the perimeter vertical double-layer space structure. This is beneficial to reduce the internal gravity column sizes, in

order to get larger floor areas, and counter the tension forces in the perimeter structure.

d. The double-layer space structures, gravity columns and beams are steel ASTM A500, Grade C, fy= 50 ksi or 345 MPa (AISC, 2005).

e. The slabs are concrete fc'= 27.5 MPa.

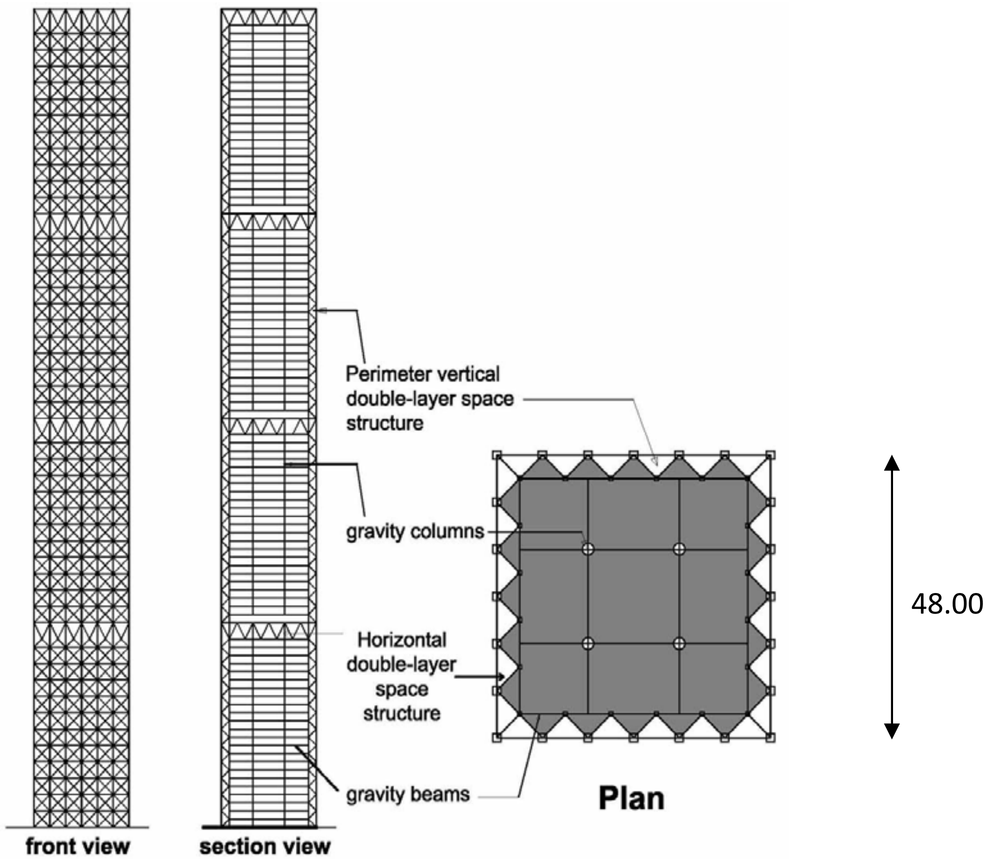


Figure 4.1 The building model

3. Building codes:

   Building codes and standards are adopted from the United States (US) for the reason outlined in Chapter 3:

   a. "Minimum Design Loads for Buildings/ASCE 7-05" (ASCE, 2005) for building loads combined with "International Building Code" (IBC, 2006).

   b. "Specification for Structural Steel Buildings and Other Structures/AISC 360-05" (AISC, 2005) for steel structural design and analysis.

ASCE 7-05 was used as the design calculations were conducted in 2009. Further studies should use ASCE 7-10 (ASCE, 2010) or the latest subsequent version of the standard.

4. Building loads:

According to “Minimum Design Loads for Buildings/ASCE 7-05” (ASCE, 2005), the building loads consist of:

a. Dead loads:

- The self-weight of the steel structure that has density of 78.3 kN/m^3 (AISC, 2005; *ETABS version 9*, 2005).
- The concrete slabs with a density of 24 kN/m^3 are 3”+2.5” thick for typical office floors and 3”+3” thick for the roof, assumed for roof garden and assembly purposes and referred from Table 4-1 in ASCE (2005), using gage 16 corrugated metal sheets, which are 0.16 kN/m^2 (Cordeck, 2009) The technical data is shown in Appendix A. The concrete slabs on the plant room are 200 mm thick without corrugated metal sheets. The maximum factored live loads are 1.6 x (office + partition loads) = 1.6 x (2.4 + 0.718) = 4.99 kN/m^2 for typical office floors and 1.6 x (roof load) = 1.6 x 4.79 = 7.66 kN/m^2. A table provided by Cordeck (2009) shows live load capacities 9.24 kN/m^2 for 3”+2.5” thick slabs and 10.05 kN/m^2 for 3”+3” thick slabs, which are sufficient to carry the loads. Live loads information is provided later.
- Cladding consists of double-glazing with a total thickness of 16 mm, 6 mm for internal glass and 10 mm for external glass. The glass density is 25.1 kN/m^3 (ASCE, 2005). The cladding weight is 16 mm x 25.1 kN/m^3 x 4 meters high for one floor, and an assumed additional 50 % of the total weight for the glazing frame. The weight of one floor of cladding becomes 2.41 kN/m.
- Ceilings, mechanical, and lighting armatures are assumed to be 0.50 kN/m^2 (White & Salmon, 1987)
- Floor finish load is 0.46 kN/m^2 (ASCE, 2005).
- The load on the mechanical equipment rooms is 10 kN/m^2 (White & Salmon, 1987).

b. Live loads:

- Office load is 2.4 kN/m^2 (ASCE, 2005).
- Partition load is 0.718 kN/m^2 (ASCE, 2005).
- Roof live load is 4.79 kN/m^2 (ASCE, 2005).

c. Wind load:

Lateral loads that normally limit the height of a building are wind and seismic loads (Khan, 1972). However, as buildings become taller and more slender, wind load effects are more significant than seismic load effects (Willford, Whittaker, & Klemencic, 2008). Many existing super-tall buildings have been designed under wind load to fulfil two requirements, strength and serviceability (Miyamoto & Gilani, 2007). Khan (1969) argues that the lateral drift is a dominant factor in the design of buildings beyond 10 storeys.

The wind load was calculated according to the procedure in "Minimum Design Loads for Buildings" (ASCE, 2005) based on the following information:

- Wind speed in California is 85 miles per hour (ASCE, 2005, p. 32).
- Exposure type is B, with the assumption for urban areas.
- Importance factor, I=1.15, is based on the assumption for occupancy category III.
- Topographical factor, K_{zt}=1, is based on the assumption that the building is on flat land.
- The structure is assumed as flexible structures, which their fundamental natural frequency is less than 1 Hz (ASCE, 2005, p. 21).
- Gust factor, G_f=1.607, which is explained further in Section 4.3.1.
- Directionality factor, K_d= 0.85, is based on assumption for main wind force resisting system.
- Pressure coefficients are C_p= 0.8 for windward and C_p= (-0.5) for leeward.

The building loads are summarised in Table 4.1.

Table 4.1 The building loads

DEAD LOADS				**WIND LOADS**		
1	Structural self-weight			- Wind speed	85	
	- steel	7.83	kN/m^3	- Exposure	B	mph
	- concrete	2.4	kN/m^3	- Importance factor (I)	1.15	
2	Cladding	2.41	kN/m'	- Topographical factor (K_{zt})	1	
3	Ceiling, mechanical & lighting	0.50	kN/m^2	- Gust factor (G_f)	1.607	
4	Floor finishes	0.46	kN/m^2	- Directionality factor (K_d)	0.85	
5	Mechanical Equipment Room	10.00	kN/m^2			
				- C_p, windward	0.8	
LIVE LOADS				- C_p, leeward	0.5	
1	Office	2.40	kN/m^2			
2	Partition	0.718	kN/m^2			
3	Roof	4.79	kN/m^2			

This information was input to the computer program, which program then generates the wind load on the structure. As a double-check, a manual calculation was performed based on the calculation procedure from the standard. These two different calculation methods produced the same results.

5. Load combinations:

Two types of load combinations according to “Minimum Design Loads for Buildings/ASCE 7-05” (ASCE, 2005) are used; the first combination is for strength limit design, and the second combination is for deflection limit design. These load combinations are used to anticipate all possibilities of different conditions that might happen to the building.

a. For the strength limit state, the load combinations are:
   - 1.4 D
   - 1.2 D + 1.6 L + 0.5 L_r
   - 1.2 D + 1.6 L_r + L or 0.8 W
   - 1.2 D + 1.6 W + L + 0.5 L_r
   - 0.9 D + 1.6 W

   Where:

   D: dead load

   E: earthquake load

   L: live load

   L_r: roof live load

   W: wind load

b. For the deflection limit state, the load combinations is determined as follows:
   - 1.0 D
   - 1.0 D + 1.0 L + 1.0 L_r
   - 1.0 D + 1.0 W
   - 1.0 D + 1.0 L + 1.0 L_r + 1.0 W

The first and the second combinations are relevant for the design of secondary beams and the main structure. The other combinations are for the design of the main structure only.

6. Structural analysis computer program:

   The structural design and analysis is conducted using ETABS (*ETABS version 9*, 2005).

7. Design limitations

   The limitations of the structural design are:

   a. Strength limit: load and resistance factor design with yield stress of 50 ksi or 345 MPa (AISC, 2005), which is commonly used in steel construction.

   b. Lateral deflection limit of H/500 (where H is the building height). Although lateral deflection limits of tall buildings vary between H/200 and H/800 (Khan, 1970), the limit H/400 to H/500 is generally sufficient to minimize damage to cladding and non-structural internal walls in tall buildings (Taranath, 2005).

4.1.2. Design Procedure

This section explains the design procedure of the case study. The design and analysis of the structure was conducted by ETABS and the procedure is shown in Figure 4.2.

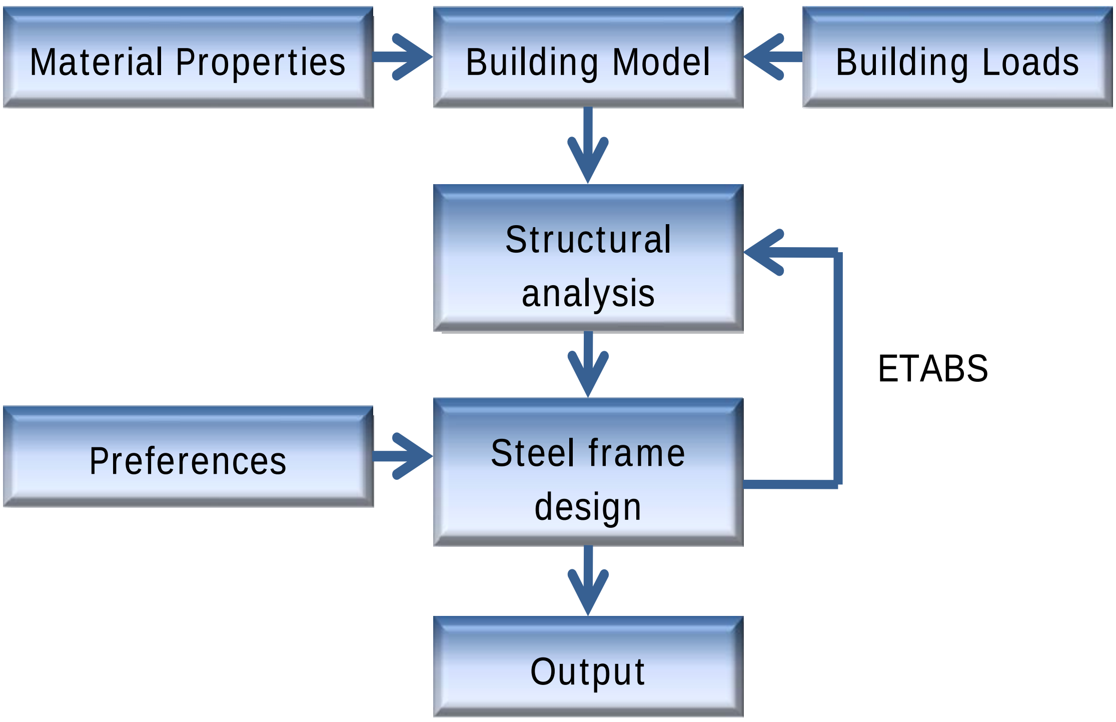


Figure 4.2 Flow chart of the structural design and analysis using ETABS

The steps of the structural design and analysis are as follows (*ETABS version 9*, 2005):

1. Creating the building model including defining material properties and building loads.

   Material properties, including structural materials and profiles, can be either input by users or selected from the list provided by ETABS. For determining structural member sizes, a range of structural profiles are selected and input by users and ETABS then initially selects the profiles, which are the middle sizes from the range, for the structural analysis process.

   Building loads and the load combinations are input by user. The mass of the structural materials are automatically included in the building loads by ETABS.
2. Running the building analysis. ETABS provides internal structural forces including moment, shear, axial, and torsion.
3. Selecting frame materials and preferences.

   Users select the frame materials, such as steel, concrete or composite frame designs. Then, various versions of relevant building standard are selected.
4. Designating a lateral displacement target as the design limit.
5. Starting the frame design and checking process.
6. ETABS shows demand/capacity ratios from the analysis process and may recommend other profiles, which can be stronger or more efficient. This process can only be done when a range of profiles have been selected at the first step above. ETABS also shows how many members have different profiles between the analysis and design process.
7. Iteration of the analysis and design process continues until the different profiles between analysis and design process are almost zero. In this research, this difference is limited to less than 1% of structural members to avoid unending process.

4.1.3. Structural Model

This section explains the model used in the case study. The input data, such as structural member profiles and idealization, adopt values normally used in multi-storey steel structures and horizontal double-layer space structures as discussed in Section 7.1, so the results can be applied in general. The structural model of this case study is designed using structural members and idealizations as follows:

1. The vertical perimeter double-layer space structure consists of internal and external vertical members, horizontal members, and diagonal members. The structural profiles,

which are input to the computer program, comprise various rectangular hollow sections from Box 200.200.20 (breadth, width, thickness in mm) to Box 1250.1250.125.

2. The horizontal double-layer space structures consist of top and bottom chords, and diagonal chords. The structural profiles comprise various rectangular hollow sections from Box 200.200.20 to Box 600.600.60.
3. The gravity columns comprise various dimensions of circular hollow tube sections from Pipe 200.20 (diameter and thickness in mm) to Pipe 1600.160.
4. The gravity beams consist of various dimensions of I-beams provided by ETABS and have a composite action with the concrete slabs.
5. The area of the concrete slab with a corrugated deck is shown in Figure 4.3.
6. The structure has pinned joints except the connection between two gravity beams shown in Figure 4.3.

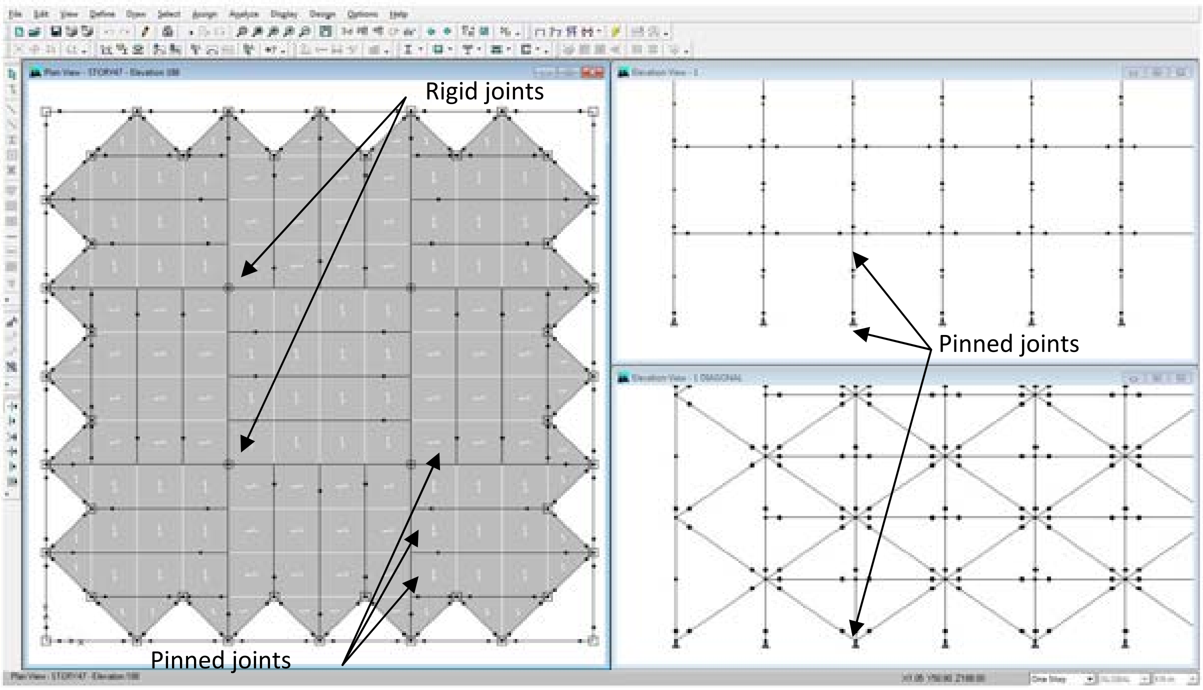


Figure 4.3 Idealization of the structural connections

4.1.4. Results

This section discusses the results that show wind and gravity forces distribution, structural member sizes and stress demand/capacity (D/C) ratio. The results of the design and analysis in this case study can be applied in general high-rise applications within the scope of this study because the input data is based on those normally used in high-rise buildings. For example, wind and gravity force distribution is always the same for vertical double-layer space structures positioned at the building perimeter. Various structural member sizes can be used as long as they have the same profile areas and moment of inertia with the results in this case study. The stress demand/capacity (D/C) ratios are applied to the buildings with similar slenderness. The following section discusses other case studies with different slenderness and different structural systems.

The results show the structural behaviour as explained below:

1. Wind forces distribution.
    a. Wind load is transferred as compression and tension mainly through the vertical and diagonal members of the double-layer space structure to the foundation.
    b. The wind load acting on the structure causes an overturning moment, which is resisted by the vertical members in compression and tension. The external vertical members make a large contribution to resisting the wind load.
    c. The structure acts as two different systems, a vertical cantilevered beam and a moment resisting frame as shown in Figure 4.4 (a). As a cantilevered beam, the moment is distributed as compression and tension to the two sides of the vertical structure that is perpendicular to the wind load. Frame action is caused by the horizontal double-layer space structure. The frame resists wind load in local bending, which causes compression and tension at the external and internal vertical layers. The accumulation of compression at the external vertical layer on the lee ward side causes larger compression on the bottom floors. On the other hand, compression at the internal vertical layer on the lee ward side is reduced by tension from the local moment. As a result, the external vertical members have larger axial forces on the lower floors, but the axial forces in the internal vertical members decrease on the lower floors as shown in Figure 4.4 (b).

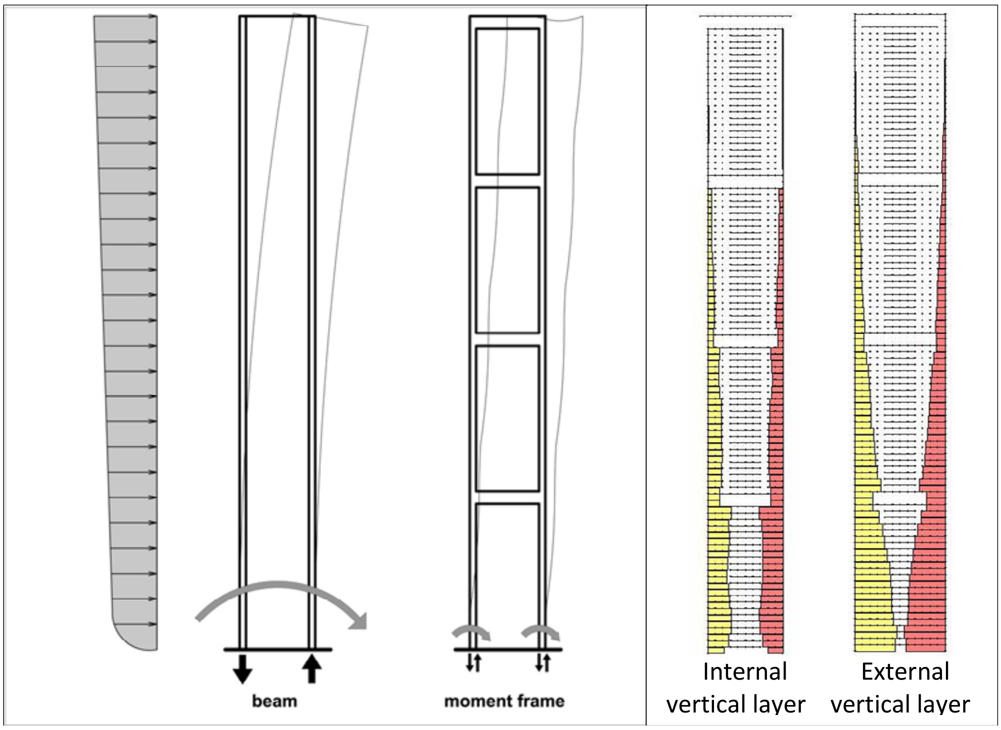


Figure 4.4 (a) Beam and frame actions; (b) Axial force distribution in the vertical members under wind load

d. Figure 4.5 shows axial forces in the column at ground floor. They are distributed uniformly at the external columns that are perpendicular to the wind direction. The internal columns take a small proportion of the axial forces. Axial loads at the outer internal columns are larger than those at the middle internal columns because of shear lag effect. Figure 4.5 (a) shows the axial forces in the columns of the external and internal layers. Figure 4.5 (b) shows the proportion of the axial forces working in the columns of the internal layer only.

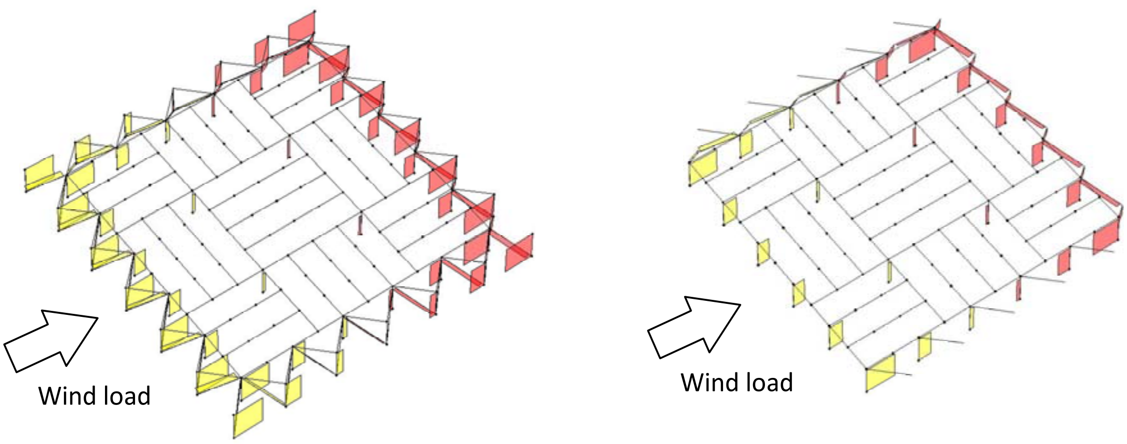


Figure 4.5 (a) Axial forces in the columns on the ground floor under wind load; (b) Axial forces in the internal columns on the ground floor under wind load

e. Figure 4.6 (a) shows how wind load are resisted mainly by two sides of the structure parallel to the wind direction. Section A-A of Figure 4.6 (b) shows the axial forces in the diagonal members of the sides parallel to the wind direction. Compression and tension increase from the top to the bottom members. Section B-B shows the difference between shear distributions in the diagonal members in the side perpendicular to the wind direction (left side of the structure) and parallel to the wind direction (right side of the structure).

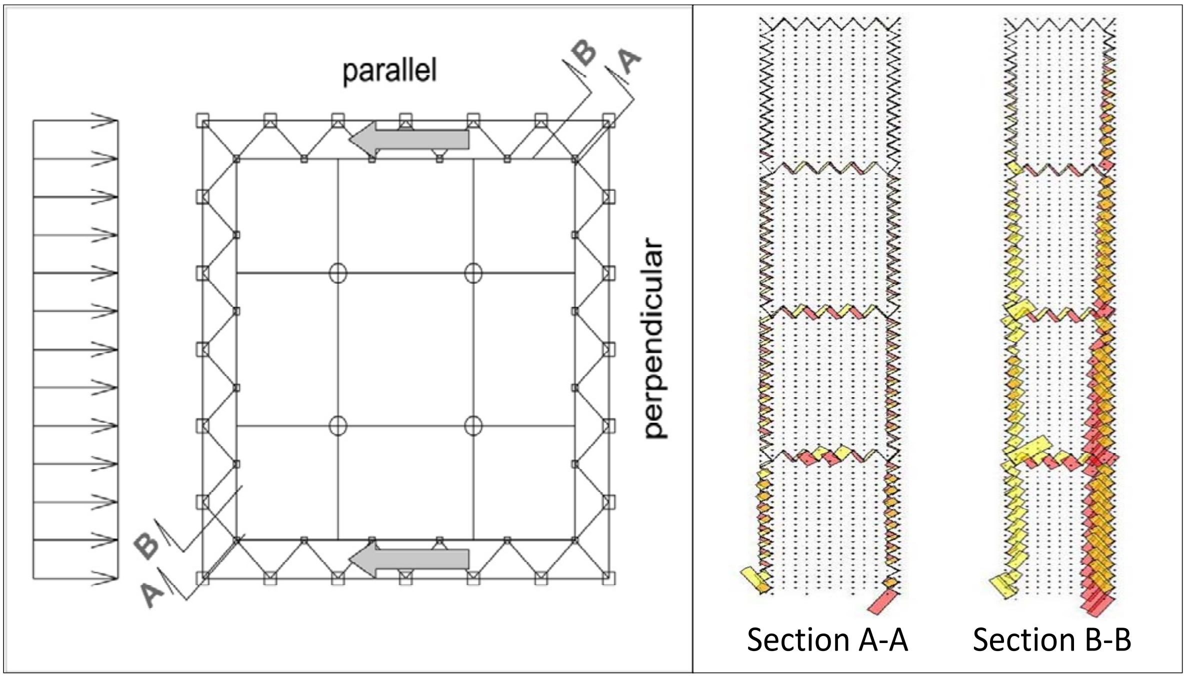


Figure 4.6. (a) Two sides of the perimeter structure parallel to the wind load resist the shear caused by the wind load; (b) Axial forces under wind load in the diagonal members

2. Gravity force distribution
   a. Figure 4.7 (a) shows gravity loads travelling from the steel beams through the suspended gravity columns to the horizontal double-layer space structures, and then down through the perimeter structure to the foundation. Figure 4.7 (b) shows the axial forces in the suspended columns and vertical members of the perimeter structure.
   b. The horizontal double-layer space structure acts as a deep beam/slab. Figure 4.7 (c) shows large axial loads in the diagonal members resisting shear force.

3. Structural member sizes

   The structural members have various dimensions from the bottom to the top floor. Table 4.2 shows alternative structural profiles as designed by ETABS. These profiles are sized for lateral stiffness, fulfilling lateral deflection criteria rather than the strength limit.

4. Stress demand/capacity (D/C) ratio

   In many structural members, the strength demands are much less than the strength capacities. The average D/C ratio of all structural members is 0.52. This occurs because the lateral displacement target H/500 is more critical than the strength limit.

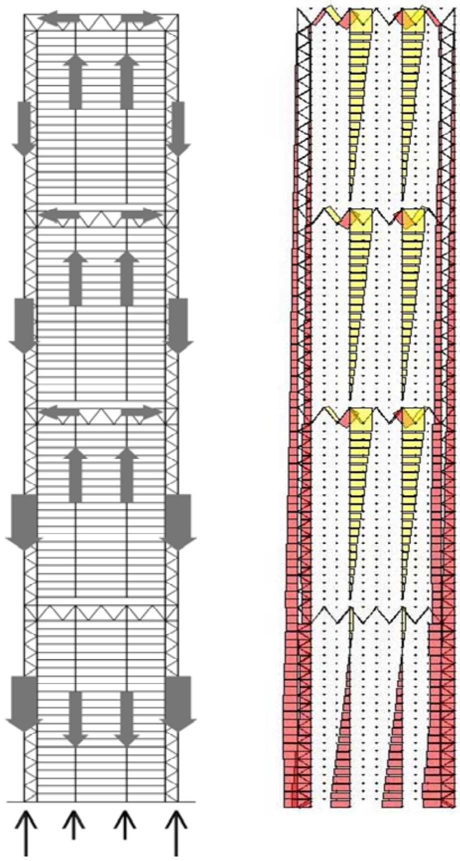


Figure 4.7 (a) Gravity loads travel to the foundation; (b) Axial gravity forces in the double-layer space structure

Table 4.2 Structural profiles (in millimetres)

Vertical double-layer space structure		
1	External vertical members:	
	on the top floor	Box 300x300x30
	on the bottom floor	Box 950x950x95
2	Internal vertical members:	
	on the top floor	Box 350x350x35
	on the bottom floor	Box 900x900x90
3	Diagonal members:	
	on the top floor	Box 450x450x45
	on the bottom floor	Box 750x750x75
4	Horizontal members:	
	on the top floor	Box 250x250x25
	on the bottom floor	Box 300x300x30
Horizontal double-layer space structures		
	Top layers	Box 300x300x30
	Bottom layers	Box 400x400x40
	Diagonal members	Box 500x500x50
Suspended columns		
	on the top floor	Tube 800x80
	on the bottom floor	Tube 200x20

4.2. Structural Comparisons

This section discusses two comparisons; the first is the comparison of two vertical double-layer space structures with different slenderness, and the second is the comparison of the vertical double-layer space structures with other structural systems of high-rise buildings. The aim is to analyse the efficiency of vertical double-layer space structures in super-tall buildings by looking at the effects of different slenderness and comparing them with different lateral resisting systems. This is explained further in the two sections below.

4.2.1. Comparison of Buildings with Different Slenderness

Another structural model using 60m x 60m floor plan was designed to investigate the structural behaviour of a less slender structure than the previous model. Compared to the first model, this model will have the same force distribution, but different structural member profiles that indicate structural weight per unit area, as well as demand/capacity (D/C) ratios. The main purpose of this comparison is to obtain a clue about the structural member sizes of buildings with different slenderness in order to develop strategies for services and architectural integration discussed in Chapter 5 and 6, and analyse construction aspects discussed in Chapter 7.

The reason for analysing buildings with 48m x 48m and 60m x 60m buildings is to simplify the calculation for the comparison of buildings with different slenderness. Each building has six modules; the 48m x 48m building is made by 8-metre modules, while the 60m x 60m building has 10-metre modules. The 60m x 60m building has a 6.67 height/width ratio; it is similar to those of the World Trade Center (WTC), New York, which had a ratio of 6.5. The WTC New York also had similar heights and number of storeys, and the same shape with the models. Other super-tall buildings, such as Willis Tower, John Hancock Center, Jin Mao Tower, Petronas Towers and Taipei 101, have similar heights and slenderness, but different shapes. The comparison of double-layer space structures with different slenderness is applicable for current super-tall buildings that commonly have similar slenderness to the second model, and also for more slender buildings as in the first model.

In this comparison, the loads, load combinations, structural dimensions, and idealizations of the first model were also used in the second model. The structural design and analysis were conducted using ETABS with exactly the same procedure as the previous model. The design information of the second model, compared to the previous structure, is shown in Table 4.3.

Table 4.3 Design data for the two models of double-layer space structures

Item	Model-1	Model-2
Floor plan	48m x 48m	60m x 60m
Height	400 m	400 m
Height/width ratio	8.33	6.67
Number of bays	6	6
Bay length	8 m	10 m
Distance between the 2 layers	4 m	5 m

Results from the design and analysis of the second model shows the same force distributions as those in the previous model. The structural member sizes of the 60m x 60m double-layer space structure designed by ETABS are compared to those of the 48m x 48m building and shown in Table 4.4.

Compared to 48m x 48m building, the structural profiles in 60m x 60m building have similar size proportion but the majority are slightly larger. This is because the models have the same structural composition, but different loading areas. The average D/C ratio 0.58 is slightly higher than the previous model's ratio, which is 0.52. The profiles of both models are sized to fulfil lateral deflection criteria rather than strength limit.

Table 4.4. Member sizes comparison of the 60m x 60m and 48m x 48m buildings (in millimetres)

Vertical double-layer space structure	60m x 60m building	48m x 48m building
1 External vertical members:		
on the top floor	Box 350x350x35	Box 300x300x30
on the bottom floor	Box 1100x1100x110	Box 950x950x95
2 Internal vertical members:		
on the top floor	Box 400x400x40	Box 350x350x35
on the bottom floor	Box 900x900x90	Box 900x900x90
3 Diagonal members:		
on the top floor	Box 450x450x45	Box 450x450x45
on the bottom floor	Box 550x550x55	Box 750x750x75
4 Horizontal members:		
Minimum	Box 250x250x25	Box 250x250x25
Maximum	Box 300x300x30	Box 300x300x30
Horizontal double-layer space structures		
Top layers	Box 500x500x50	Box 300x300x30
Bottom layers	Box 550x550x55	Box 400x400x40
Diagonal members	Box 700x700x70	Box 500x500x50
Suspended columns		
on the top floor	Tube 1100x110	Tube 800x80
on the bottom floor	Tube 200x20	Tube 200x20

4.2.2. Comparison with other Structural Systems

This section compares the vertical double-layer space structures with three other current efficient structural systems, a bundled-tube, a braced tube, and a diagrid. The comparison includes lateral deflection profiles, steel weight per unit area, and structural member sizes. General applications of these comparisons are explained as follows:

- The comparison of lateral deflection profiles indicates the structural characteristic, which can be in bending, shear or their combination, of these four systems in resisting lateral loads. These deflection profiles can be applied to general high-rises using these four structural systems.
- Steel weights per unit areas cannot be applied generally to other tall building designs because different design information will produce different structural weight. However, the comparison of different structural systems using consistent design information will indicate to what extent the efficiency of each structural system in this comparison; this will apply generally.
- As explained in Section 4.1, various structural member sizes can be used as long as they have the same profile areas and moment of inertia with the results in this case study. Since the design information in this case study adopt those normally applied in existing super-tall buildings, therefore the results will not be significantly different to other high-rise designs using different input data. As mentioned in the previous section, information about structural member sizes is important because they have a significant impact on developing strategies for services and architectural integration.

Generally, this case study is not to provide design results that are ready to use for all other super-tall buildings, but to compare the four different structural systems using parameters explained above; this comparison can be applied generally to all super-tall buildings. The main purpose of this comparison is to analyse to what extent the efficiency of double-layer space structures in super-tall applications when compared to current efficient structural systems of super-tall buildings.

As mentioned above, three current efficient structural systems, a bundled-tube, a braced-tube and a diagrid, are compared with double-layer space structures. The literature study especially in Section 2.2 has discussed the development of structural systems in tall and super-tall buildings from two dimensional structures to more efficient three-dimensional structural systems like various tubular systems and diagrid structures. Bundled-tube and braced tube have been used as structural systems of existing super-tall buildings and they have been categorised as current efficient structural systems (Ali & Moon, 2007; Gunel & Ilgin, 2006). Diagrid is a relatively new structural system for tall buildings, but has been applied in several new tall buildings and proposed for several new projects of super-tall buildings (Ali & Moon, 2007).

The three structural systems have a similarity with double-layer space structures; the majority of their structural components are located at the building perimeter. However, they also have different and unique characteristics in resisting lateral loads:

1. Bundled-tube: the structural rigidity is achieved by the deep beams and columns acting as perforated tube (Iyengar, 1972).
2. Braced-tube: the rigidity is enhanced by the corner columns and perimeter diagonal braces forming a vertical truss action (Khan, 2004).
3. Diagrid: this structural system does not have columns. The triangulated pattern formed by the horizontal and diagonal members carries both gravity and lateral loads (Moon, Connor, & Fernandez, 2007).

In this case study, each structure was designed using two floor areas, 48m x 48m and 60m x 60m. The loads, load combinations, structural dimensions, and idealizations used in the double-layer space structure models were also used in these three models. The structural designs and analyses were conducted using ETABS with the same procedures as in the previous designs. The concrete slabs with the same properties and dimensions as those in the first model were applied to this model because the slab capacities are still larger than the live loads. The reason for this similarity in the design information is for the consistency in this comparison, so the results can be applied generally.

Chapter 2 has discussed the applications of bundled-tubes, braced-tubes and diagrid structures in existing buildings, such as Willis Tower, John Hancock Center, Hearst Tower and Capital Gate. The idealization and design information of these structural systems shown in Figure 4.8 adopts those applied in these buildings. The purpose is that the designed case study can also be applied for real life. The structural idealization and design information are discussed as follows:

1. The bundled-tube consists of nine small tubes. The voids for services in the floor plan area are as large as those in the floor of the double-layer space structure. The aim is to provide the same value of gravity loads for the three structural systems. The beam-column joints of the lateral structure are fully rigid to provide a tube performance. The beams span four metres between column centre lines. Since the bundled-tube mainly works in bending and shear, the lateral beams and columns comprise various sizes of wide flange sections from WF 500.250.25.50 (depth, breadth, and web and flange thicknesses in mm) to WF 1100.550.55.110 to optimise the members. Gravity columns are not used because the gravity beams span between the columns. This structural arrangement and member sizes are similar to those applied in Willis Tower, the tallest steel bundled-tube building (Iyengar, 1972).
2. The braced-tube consists of five vertical bracing modules, where each module is 20 storeys high. The braces are rigidly connected to the perimeter columns. The lateral beams span eight metres between column centre lines. The lateral braces, columns, and beams comprise various rectangular hollow profiles from Box 400.200.40 to Box 2000.1000.200 (breadth, width, and thickness in mm). This structural arrangement and member sizes follow those in John Hancock Center in Chicago, a steel braced-tube building that has 100-storeys (Khan, 1983; Khan, 2004).
3. The diagrid structure consists of diagonal and horizontal members only, forming triangulated patterns on the entire building façade. The diagonal and horizontal members are rigidly interconnected for practical reasons. One diagonal member spans the height of two floors and a triangulated module has the same length as the double-layer space structure modules. Various rectangular hollow profiles from Box 200.100.20 to Box 1400.700.140 (breadth, width, and thickness in mm) are used for the diagonal and horizontal members. The structural arrangement and member profiles in this model are adopted from several high-rise diagrid structures, such as Capital Gate in Abu Dhabi, Hearst Tower in New York, Swiss Re Building in London, and other diagrid projects (Ali & Moon, 2007; "Capital Gate," 2010; Moon, Connor, & Fernandez, 2007).

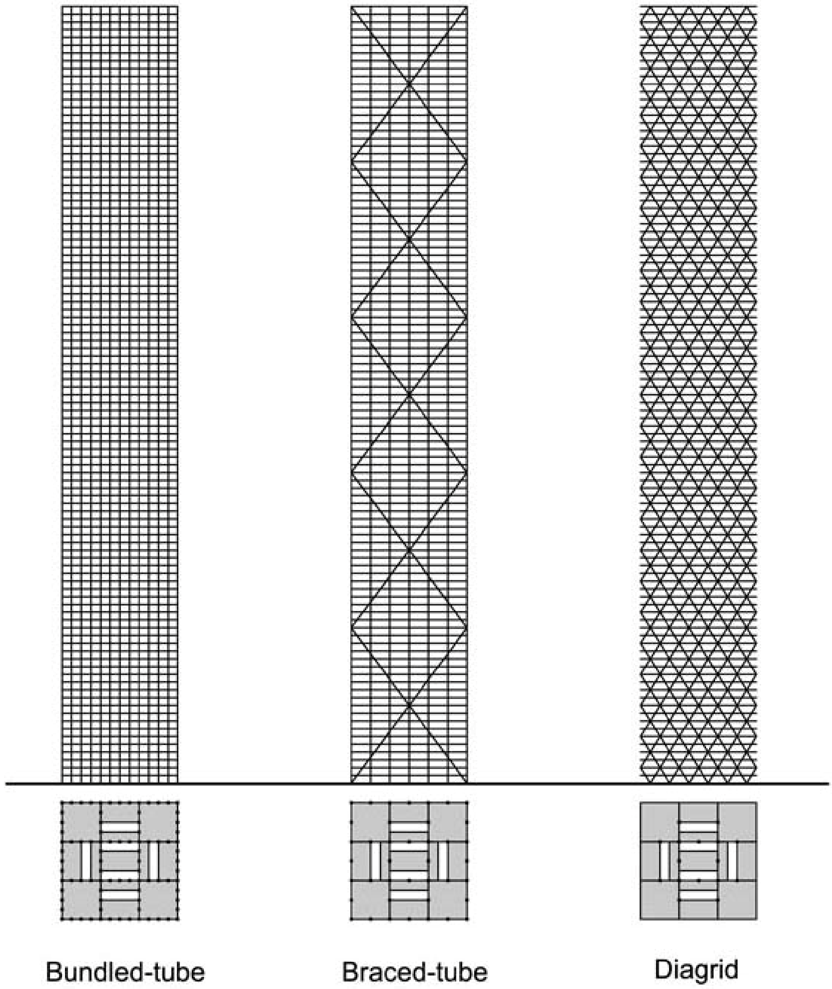


Figure 4.8 Structural idealization of the bundled-tube, braced-tube and diagrid structure

4.2.3. Results

The comparison of the vertical double-layer space structures using two different floor areas, 48m x 48m and 60m x 60m, shows that both designed models are driven by the lateral limit criteria. However, the less slender building, 60m x 60m, is more efficient because it has lower D/C ratio. This analysis shows that the building slenderness has a significant impact on the structural efficiency.

The comparison of the four different structures, double-layer space structure, bundled-tube, braced-tube, and diagrid structures, using two different floor areas are discussed as follows.

Lateral Deflection

The lateral deflections of the four different structures satisfy the same deflection limit of 800 mm. All four designed structural systems are driven by lateral deflection criteria. The average D/C ratios are as follows:

1. Double-layer space structures: 0.52 for the 48m x 48m building, and 0.58 for the 60m x 60m building.
2. Bundled-tubes: 0.22 for the 48m x 48m building, and 0.31 for the 60m x 60m building.
3. Braced-tubes: 0.56 for the 48m x 48m building, and 0.61 for the 60m x 60m building.
4. Diagrids: 0.29 for the 48m x 48m building, and 0.43 for the 60m x 60m building.

This information shows that the braced-tubes are the most efficient structural system in achieving the lateral deflection limit because they have the highest D/C ratios. The bundled-tube is the least efficient structural system. The D/C ratios of the 60m x 60m buildings are larger than those of the 48m x 48m buildings for all structural systems. It means that the less slender buildings are more efficient in optimising the structural strength.

Figure 4.9 shows the lateral deflections of the four structural systems, discussed as follows:

1. The deflected shape of the double-layer space structure forms a curve, showing that this structure responds more in bending than in shear.
2. In the bundled-tube, the lateral deflection pattern is linear. This structure deforms predominantly in shear.
3. The lateral deflection of the braced-tube is curved, but not smooth because of the bracing modules effect.
4. In the diagrid structure, the deflected shape is totally curved.

This comparison shows that linear deflected shape only occurs in structures that do not have diagonal components like bundled-tube. Each component mainly resists lateral loads by bending and shear. This makes lateral displacement relatively high. Structural systems with diagonal components have more curved deflection. The lateral displacement is relatively low because lateral forces are transferred through the diagonal members to the foundation. The structural system without columns has the most curved deflection. These mean that the combination of vertical and diagonal components, as applied in braced-tubes and double-layer space structures, has a large contribution in resisting lateral loads. This is the most desirable condition of tall structural systems.

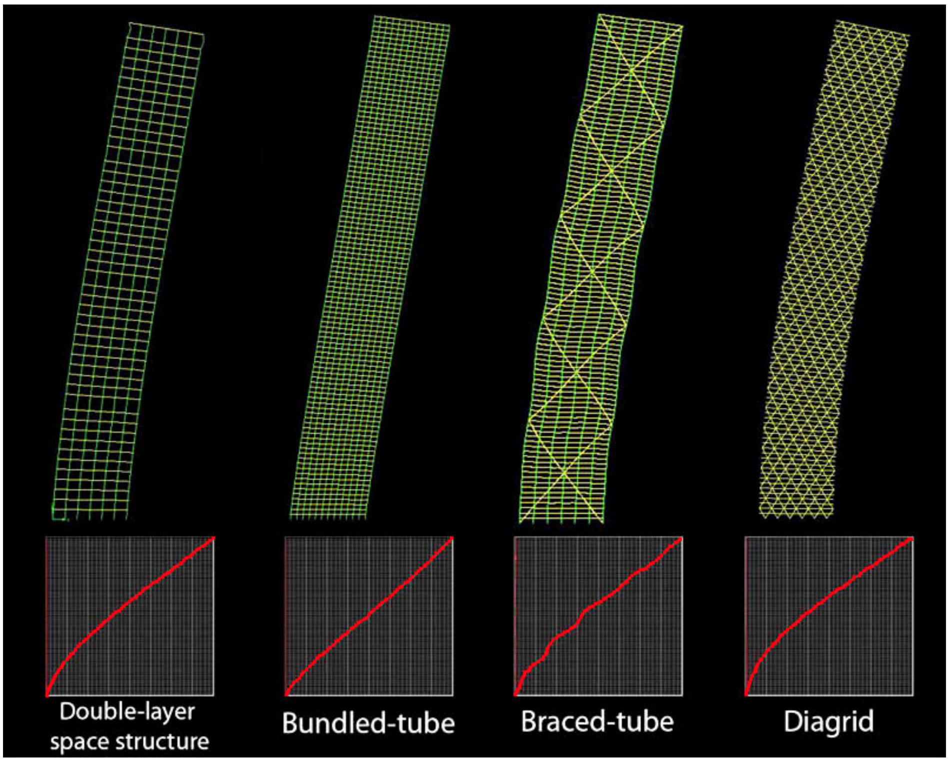


Figure 4.9 Lateral deflection patterns of the double-layer space structure, bundled-tube, braced-tube and diagrid

Steel Weight per Unit Area

Steel weight per area is the total steel weight divided by the total gross floor area of the building, including voids for services. The steel weight per area of the double-layer space structure 48m x 48m is calculated as follow:

- Total gross areas of 100 storeys = (48 x 48) x 100 = 230,400 m^2.
- Total steel weight from ETABS = 743,416 kN.
- Steel weight per area = 743,416 kN / 230,400 m^2 = 3.23 kN/m^2 or 65 psf.

The comparison of the steel weights per area is shown in Figure 4.9. The braced-tube is the lightest structure and double-layer space structure is the second lightest structure. The bundled-tube and diagrid, which are the heaviest, have similar steel weights per unit floor areas. The four structural systems have the same composition of structural weight per area for both, 48m x 48m and 60m x 60m buildings. The more slender buildings, 48m x 48m, have higher steel weight per area. It shows the significant negative impact of building slenderness on structural efficiency.

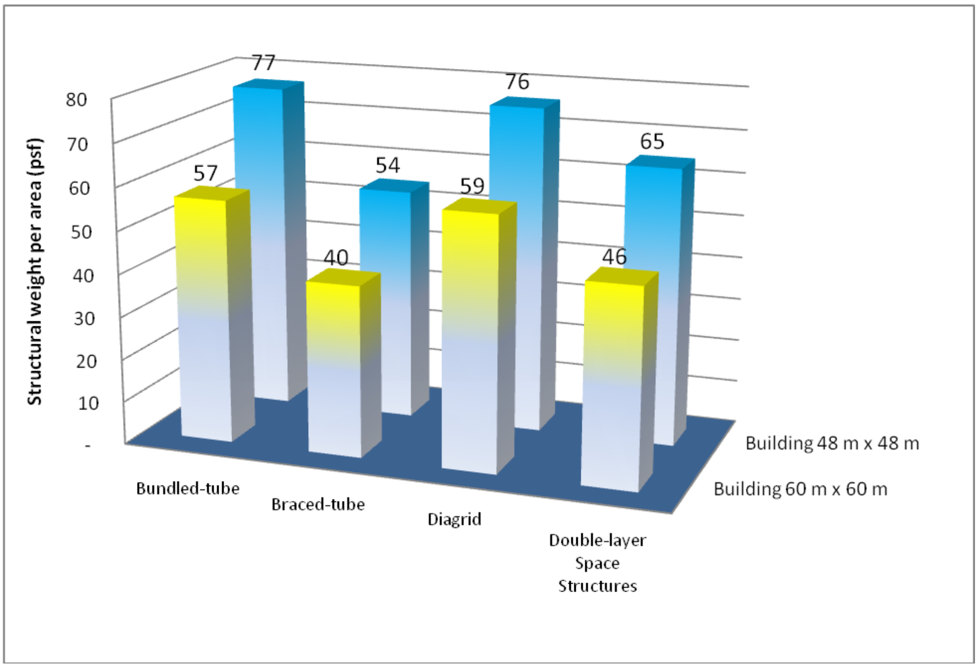


Figure 4.9 Structural weight per area

These comparisons show that vertical double-layer space structures are not the most efficient structural system. However, they can be categorised as reasonably efficient structural systems when compared with current efficient tall structural systems.

As mentioned in the early part of this section, steel weights per unit areas cannot be applied generally to other tall building designs because different design information will produce different structural weights. This is shown when the building models are compared to other buildings that have similar conditions, such as single steel structural system, similar heights and slenderness; the structural weights per unit floor areas are as follows:

- Empire State Building = 42.2 psf
- John Hancock Center = 29.7 psf
- World Trade Center = 37.0 psf
- Sears Tower = 33.0 psf

The comparison shows that the eight models are very heavy when compared to several existing steel super-tall buildings. Several reasons for these differences are:

1. The geometries of the eight model buildings are very slender. The structural design and analysis is more driven by lateral deflection limit rather than strength limit. Large volumes of the structural members are required to provide deflection control.

2. Super-tall buildings, like Empire State Building, John Hancock Center and Sears Tower have tapered forms, which are relatively efficient for resisting lateral loads and minimising lateral deflections.
3. Different gravity systems and concrete slabs are used in the constructed buildings. For example, the World Trade Center used light-weight concrete and trusses for its gravity system, and 10 different steel grades from 36 ksi to 100 ksi (NIST, 2005).
4. Design information, such as the wind load, steel grades, and other design requirements are unknown.

The results from the building models are definitely heavier because the case study has been designed with extreme conditions, such as relatively high wind speed, high slenderness, rectangular shapes, and using common steel grade; while the other buildings were designed using several approaches, such as tapered building forms, low slenderness, and various steel grades, in order to decrease structural weight per area. Therefore the results should have wide application beyond the specific situation studied.

Structural Member Sizes

The structural member sizes and the span between structural members are discussed and compared below. Since the four structures can all be categorised as perimeter structures, they have the potential to affect other aspects of the buildings' designs, such as structural-façade integration, open views between their structural members, areas for natural light and to provide entrances. Sizes, numbers and composition of structural members also have an impact on the construction.

Table 4.5 shows the structural member sizes of the four different structural systems from the design and analysis using ETABS. The comparison of the profile sizes is discussed below:

1. In the double-layer space structures, the distance between two perimeter columns are about 8 to 10 metres, which are common for steel structures. These structures have the smallest structural member sizes compared to the other structures. However, they consist of a large number of structural members. This potentially causes a structural-façade integration issue. The external layer components can obstruct open views from

the façade. Structural-architectural integration, especially with aspect to the building façade, is discussed in Chapter 6.

2. The bundled-tubes have a very short distance between two columns and the largest number of structural components. The beams and columns are relatively large and the different sizes between those at the lower floors and upper floors are not significant. This means that a large area of the building façade is potentially blocked by the structural components, and only small open view areas can be provided. The advantage of this structural system is that no diagonal members are used. This benefits the construction because structural connections are geometrically less complex.

Table 4.5 Member sizes of the four structural systems (in millimetres)

	Double-layer space structure	**Bundled-tube**	**Braced-tube**	**Diagrid**
Building 48 m x 48 m				
Beam span	8 m	4 m	8 m	4 m & 8 m
Structural components	19,456	20,992	12,589	12,892
Top floors				
Horizontal members	Box 250.250.25	WF 500.250.25.50	Box 400.200.40	Box 500.250.50
Vertical members	Box 300.300.30	WF 500.250.25.50	Box 800.400.80	N/A
Diagonal members	Box 450.450.45	N/A	Box 800.400.80	Box 300.150.30
Bottom floors				
Horizontal members	Box 300.300.30	WF 900.450.45.90	Box 400.200.40	Box 900.450.90
Vertical members	Box 950.950.95	WF 1100.550.55.110	Box 1700.850.170	N/A
Diagonal members	Box 750.750.75	N/A	Box 1800.900.180	Box 1300.650.130
Building 60 m x 60 m				
Beam span	10 m	5 m	10 m	5 m & 10 m
Structural components	19,456	20,992	12,430	12,892
Top floors				
Horizontal members	Box 250.250.25	WF 500.250.25.50	Box 400.200.40	Box 500.250.50
Vertical members	Box 350.350.35	WF 500.250.25.50	Box 800.400.80	N/A
Diagonal members	Box 450.450.45	N/A	Box 500.250.50	Box 400.200.40
Bottom floors				
Horizontal members	Box 300.300.30	WF 900.450.45.90	Box 400.200.40	Box 900.450.90
Vertical members	Box 1100.1100.110	WF 1100.550.55.110	Box 2000.1000.200	N/A
Diagonal members	Box 550.550.55	N/A	Box 1600.800.160	Box 1400.700.140

3. In the braced-tubes, the span between two columns can be lengthened and more open views through their structural members can be provided. However, several areas of the building façade are blocked by the large braces. The columns and braces of this structural system are relatively large, especially at the lower floors. An integrated

structural-architectural design is necessary. This structural system also has significant issues in construction. This requires special structural connections of the large columns and diagonal components, and special erection techniques and construction equipment for the erection of the large structural components.

4. The triangulated modules of the diagrid structures provide the potential for structural-façade integration. The diagonal components are relatively large especially at the lower floors. The disadvantage of these structures is that special structural joints, which connect at least six components at one node, are required. This causes an additional expense.

The vertical double-layer space structures have several advantages such as having relatively small components and column-to-column spans that enable reasonable views and natural light for the occupants. This issue will be discussed further in Chapter 6. The number, sizes and composition of the structural components of double-layer space structures have an impact to the construction, and this is discussed in Chapter 7.

4.3. Lateral Loads

Since lateral loads dominate the structural design of super-tall buildings, this section elaborates on how the vertical double-layer space structure is designed for and acts under wind and seismic loads. This study compares the base shear of the designed models from wind and seismic loads, in order to analyse which load that is more dominant. The base shears in this case study cannot be generally applied to other tall buildings because different design information, such as structural weights and building locations, will produce different results. However, since this case study is designed for high-seismic intensity and relatively high wind load, the results will be more extreme than those in areas that have less seismic intensity and lower wind load, and thus should have wide application beyond the specific situation studied.

4.3.1. Wind Load

This section discusses wind load analysis of the case study. Wind load on the 48m x 48m double-layer space structure building has been analysed using two types of calculations, a manual hand calculation and by the computer program, ETABS.

References and Design Information

ASCE 7-05 (ASCE, 2005, pp. 21-30) provides three methods to calculate the wind load:

- Method-1: Simplified procedure, for a simple diaphragm and low-rise building, but not a flexible building.
- Method-2: Analytical procedure, for a regular-shape building.
- Method-3: Wind tunnel procedure, for buildings that do not meet the requirements of Methods-1 and 2.

The building models in this research are designed using Method-2 due to the following reasons:

- The buildings have a regular shape.
- The purpose of the design is only for comparison of the three different structural systems with the same height. Method-3 that requires wind tunnel testing needs a more specific study of wind engineering, which is outside the scope of this research. However, the Method-3 would be more suitable for real super-tall projects.

The design information is as follows:

- The buildings are assumed in Los Angeles city, California.
- The basic wind speed is 85 miles per hour (ASCE, 2005, p. 32).
- Occupancy Category III is for a structure where more than 300 people congregate in one area (ASCE, 2005, p. 3).
- Exposure type is B, with the assumption for urban areas.

The Design

The design procedure follows the steps in section 6.5.3 ASCE (2005, p. 25) as follows:

1. Basic wind speed

   The basic wind speed, **V= 85 mph**, is based on the building location in Los Angeles City as shown in Figure 4.10. Wind directionality factor, **K_d= 0.85**, is used for designing the main wind force resisting system (Table 4.6).

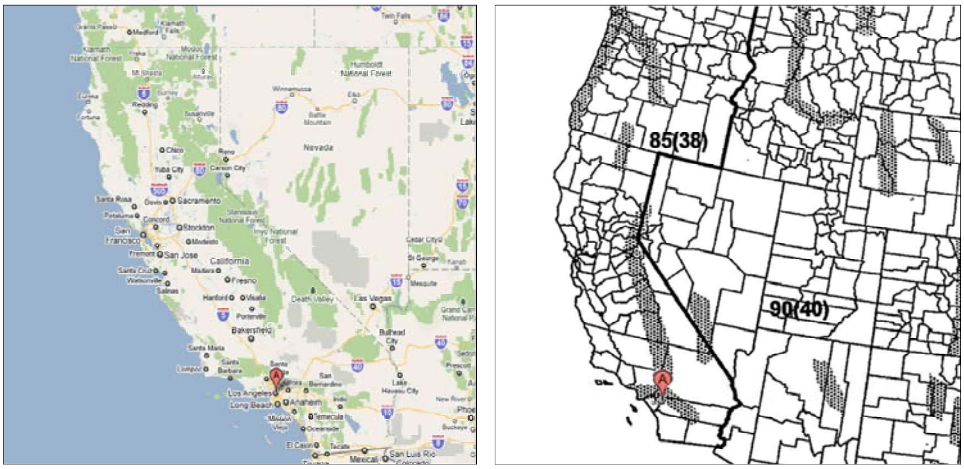


Figure 4.10 (a) California map (Source: Google maps); (b) Basic wind speed (ASCE, 2005)

Table 4.6 Wind directionally factor, Kd (ASCE, 2005, p. 80)

Structure Type	Directionality Factor K_d*
Buildings	
Main Wind Force Resisting System	0.85
Components and Cladding	0.85
Arched Roofs	0.85
Chimneys, Tanks, and Similar Structures	
Square	0.90
Hexagonal	0.95
Round	0.95
Solid Signs	0.85
Open Signs and Lattice Framework	0.85
Trussed Towers	
Triangular, square, rectangular	0.85
All other cross sections	0.95

2. Importance factor

The importance factor, **I= 1.15**, is based on Table 4.7 assuming Occupancy Category III (ASCE, 2005, p. 3).

Table 4.7 Importance factor, I (ASCE, 2005, p. 77)

Category	Non-Hurricane Prone Regions and Hurricane Prone Regions with V = 85-100 mph and Alaska	Hurricane Prone Regions with V > 100 mph
I	0.87	0.77
II	1.00	1.00
III	1.15	1.15
IV	1.15	1.15

3. Exposure category

$K_z = 2.01 (z/z_g)^{2/\alpha}$ for 15 ft. $\leq z \leq z_g$

$K_z = 2.01 (15/z_g)^{2/\alpha}$ for $z < 15$ ft.

Where: Exoposure B, assuming urban and suburban areas (ASCE, 2005, p. 25)

z_g = 365.76 m or 1,200 feet (Table 4.8)

z= variable in height (m)

α= 7.0 (Table 4.8)

Table 4.8 Terrain exposure (ASCE, 2005, p. 78)

Exposure	α	z_g (m)	$\hat{a}$	$\hat{b}$	$\bar{\alpha}$	$\bar{b}$	c	ℓ (m)	$\bar{\epsilon}$	z_{min} (m)*
B	7.0	365.76	1/7	0.84	1/4.0	0.45	0.30	97.54	1/3.0	9.14
C	9.5	274.32	1/9.5	1.00	1/6.5	0.65	0.20	152.4	1/5.0	4.57
D	11.5	213.36	1/11.5	1.07	1/9.0	0.80	0.15	198.12	1/8.0	2.13

4. Topographic factor

The building was assumed to be located on a flat area, according to section 6.5.7.2 ASCE (2005, p. 26) **K_{zt} = 1**.

5. Gust effect factor

Gust factor was determined by the equation from section 6.5.8.2 in ASCE (ASCE, 2005, p. 26) based on assumption of flexible structures as follows:

$$G_f = 0.925\left(\frac{1 + 1.7I_{\bar{z}}\sqrt{g_Q^2 Q^2 + g_R^2 R^2}}{1 + 1.7g_v I_{\bar{z}}}\right)$$

Where:

a. Value of g_Q and g_v

g_Q is a peak factor for background response and g_v is a peak factor for wind response. The value of **g_Q** and **g_v** shall be taken as **3.4**, as required by the code.

b. Value of g_R

g_R is a peak factor for resonant response using the following equation:

$$g_R = \sqrt{2\ln(3{,}600 n_1)} + \frac{0.577}{\sqrt{2\ln(3{,}600 n_1)}}$$

where: n_1 = building natural frequency, based on equation C6-19 in ASCE (2005, p. 294)

= 150 / H (ft) for H > 400 ft

= 150 / 1333

n_1 = 0.1125 Hz

Then,

$$g_R = \sqrt{2\ln(3{,}600 \times 0.1125)} + \frac{0.577}{\sqrt{2\ln(3{,}600 \times 0.1125)}}$$

g_R = 3.63

c. *Value of Q*

Q is a background response factor, which is

$$Q = \sqrt{\frac{1}{1 + 0.63\left(\frac{B + h}{L_{\bar{z}}}\right)^{0.63}}}$$

where: B = 48 m (building width to wind direction)

h = 400 m (mean roof height of the building)

$L_{\bar{z}} = \ell\left(\frac{\bar{z}}{10}\right)^{\bar{\epsilon}}$ is the integral length scale of turbulence at the equivalent height, and these following values are taken from Table 4.8:

l = 97.54

€ = 1/3

ź = 400 m (equivalent height of the structure)

$= 97.54\,(400/10)^{1/3}$

= 333.58 m

Then: $Q = \frac{1}{\sqrt{1 + 0.63\,((48+400)/333.58)^{0.63}}} = 0.88$

d. *Value of R*

R is a resonant response factor, which is $R = \sqrt{\frac{1}{\beta} R_n R_h R_B (0.53 + 0.47 R_L)}$

where:

- β = 1% for steel structure (ASCE, 2005, p. 294; Irvine, 2004; Tamura, 2010)
- $R_n = \frac{7.47 N_1}{(1 + 10.3 N_1)^{5/3}}$

  where: $N_1 = \frac{n_1 . L_z}{V_z}$ where: $n_1 = 0.1125$ Hz

  $L_z = 333.58$ m

  V_z = mean hourly wind speed at height ź

  = b (ź/10)^{ά}V, where b and ά is from Table 3 and V is the basic wind speed (mph)

  $= 0.45 (400/10)^{0.25} 85$

  = 96.19 mph

  $N_1 = \frac{0.1125 \times 333.58}{96.19} = 0.39$

  then,

  $R_n = \frac{7.47 \times 0.39}{(1 + (10.3 \times 0.39))^{5/3}} = 0.20$

- $R_h = \frac{1}{\eta} - \frac{1}{2\eta^2}(1 - e^{-2\eta})$ where $\eta = 4.6\, n_1 h / V_Z$ and h = 400 m (building height)

  $= 4.6 \times 0.1125 \times 400 / 96.19$

  $= 2.15$

  $= \frac{1}{2.15} - \frac{1}{2 \times 2.15^2}(1 - 2.72^{-(2 \times 2.15)})$

  $= 0.36$

- $R_B = \frac{1}{\eta} - \frac{1}{2\eta^2}(1 - e^{-2\eta})$ where $\eta = 4.6\, n_1 B / V_Z$ and B = 48 m (building width)

  $= 4.6 \times 0.1125 \times 48 / 96.19$

  $= 0.26$

  $= \frac{1}{0.26} - \frac{1}{2 \times 0.26^2}(1 - 2.72^{-(2 \times 0.26)}) = 0.85$

- $R_L = \frac{1}{\eta} - \frac{1}{2\eta^2}(1 - e^{-2\eta})$ where $\eta = 15.4\, n_1 L / V_Z$ and L = 48 m (building length)

  $= 15.4 \times 0.1125 \times 48 / 96.19$

  $= 0.86$

  $= \frac{1}{0.86} - \frac{1}{2 \times 0.86^2}(1 - 2.72^{-(2 \times 0.86)}) = 0.61$

Then, $R = \sqrt{\frac{1}{0.01} \times 0.20 \times 0.36 \times 0.85 \times (0.53 + (0.47 \times 0.61))}$

$= 2.21$

e. Value of I_z

$I_z = c\,(ź/10)^{€}$

where these following values are taken from Table 4.8:

c = 0.30

€ = 1/3

ź = 400 m (equivalent height of the structure)

then,

$I_z = 0.30\,(400/10)^{1/3}$

$= 0.162$

Gust factor is $G_f = 0.925\left(\frac{1 + 1.7 I_{\bar{z}} \sqrt{g_Q^2 Q^2 + g_R^2 R^2}}{1 + 1.7 g_v I_{\bar{z}}}\right)$

$= 0.925\left(\frac{1 + 1.7 \times 0.162 \times \sqrt{3.4^2 \times 0.88^2 + 3.63^2 \times 2.21^2}}{1 + 1.7 \times 3.4 \times 0.162}\right)$

G_f = 1.61

6. Enclosure classification

   Enclosure classification was not applied in these building models.

7. Internal pressure coefficient

   Internal pressure coefficient was not applied in these building models.

8. External pressure coefficient

   External pressure coefficient was determined as follows (ASCE, 2005, p. 49):

   C_p = 0.8 windward wall

   C_p = -0.5 leeward wall

9. Velocity pressure

   Velocity pressure is variable values in N/m^2 based on

   $q_z = 0.613 K_z K_{zt} K_d V^2 I$

Where K_z = exposure category explained above

K_{zt} = 1, topographic factor explained above

K_d = 0.85, wind directionally factor explained above

V = 85 mph or 38 m/s, basic wind speed explained above

I = 1.15, importance factor explained above

10. Design wind load

The wind load was determined based on assumption of flexible buildings as follows:

$P = qG_fC_p – q_i(GC_{pi})$

since $q_i(GC_{pi})$ for internal pressure is not applicable, then

$\mathbf{P = qG_fC_p}$

where: $q = q_z$ for windward walls

$q = q_h$ for leeward walls, evaluated at height h= 400 m.

G_f = 1.61, gust factor explained above

C_p = external pressure coefficient explained above

The Results

The wind load distributions are vertically curved on the windward side and linear on the leeward side. The average wind pressure on the windward side is 1,787 N/m^2 with the maximum pressure 2,293 N/m^2 at the top floor. The wind pressure on the leeward side is 1,433 N/m^2.

The total wind loads are V= 61,831 kN consisting of 34,314 kN for windward and 27,517 for leeward. Using the same steps above, the total wind load on the 60m x 60m building is V= 77,289 kN. These results are similar to those from by ETABS, which are V= 61,850 kN for 48m x 48m building and V= 77,313 kN for the 60m x 60m building.

In conclusion, errors in determining the wind loads on the building models have been minimised because the results from both calculation methods rendered similar values.

4.3.2. Seismic Load

This section discusses static and dynamic seismic analyses of the vertical double-layer space structure for two 100-storey buildings. The Static Analysis is conducted by hand calculation and also run by ETABS while the Dynamic Analysis is run by ETABS only. The calculation of the 48m x 48m building is presented as an example.

References and Design Information

The seismic analysis of the vertical double-layer space structure is based on:

- *Minimum Design Loads for Buildings/ASCE 7-05* (ASCE, 2005) combined with *International Building Code* (IBC, 2006).
- *The Seismic Design Handbook* (Naeim, 2001).
- Structural Analysis software using ETABS (*ETABS version 9*, 2005).

The seismic design information is as follows:

- The building was assumed to be located in Los Angeles city, California as shown in Figure 4.11 (a).
- Site spectral accelerations were taken from the National Seismic Hazard Maps (USGS, 2008), which are:
    - o S_S = 1.20g, is the 0.2-second horizontal acceleration with 10% probability of occurring in 50 years as shown in Figure 4.11(b).
    - o S_1 = 0.40g, is the 1-second horizontal acceleration with 10% probability of occurring in 50 years as shown in Figure 4.11(c).
- The soil properties were unknown, and then Site Class D was used based on section 11.4.2 in ASCE (2005, p. 115).
- Occupancy Category III was for a structure where more than 300 people congregate (ASCE, 2005, p. 3).

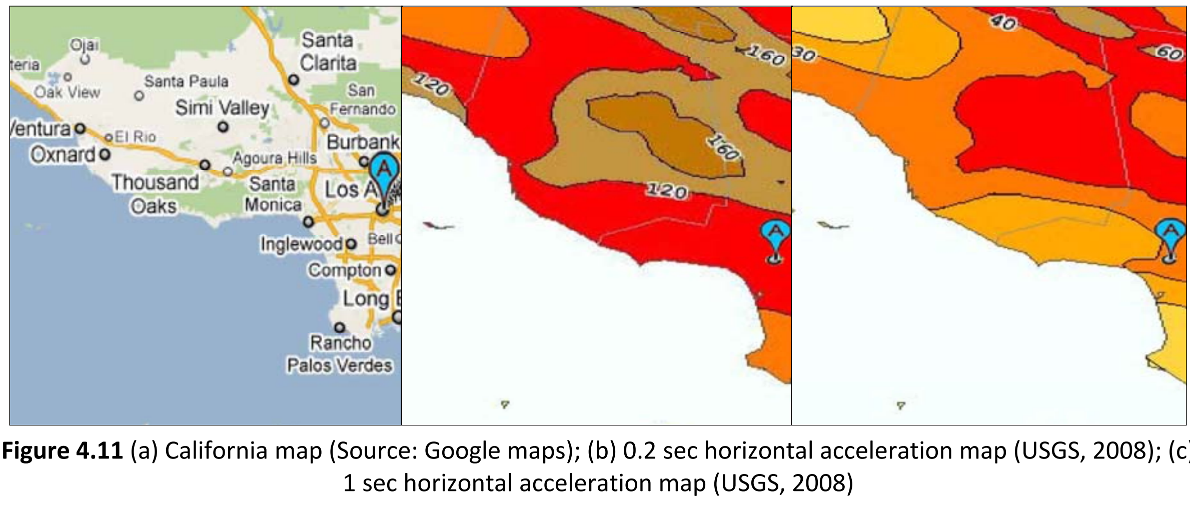


Figure 4.11 (a) California map (Source: Google maps); (b) 0.2 sec horizontal acceleration map (USGS, 2008); (c) 1 sec horizontal acceleration map (USGS, 2008)

Static Analysis using Hand Calculation

Static analysis, which covers calculations of spectral acceleration, fundamental building period, and seismic base shears, was calculated by hand as a check on the ETABS analysis. The static analysis has several limitations including:

- Structural damping is not included in the calculation.
- The analysis only covers the first mode of vibration

Spectral Acceleration (ASCE, 2005, pp. 108 - 117; IBC, 2006, pp. 303-307)

A calculation to obtain the response spectrum of Los Angeles City uses the steps as follows:

1. Site Coefficients

   $S_{MS} = F_a \cdot S_s$ and $S_{M1} = F_v \cdot S_1$

   The value F_a was taken by interpolation from Table 4.9, and the value F_v was taken from Table 4.10 from ASCE (2005, p. 115), based on Site Class D and the values of S_S and S_1.

Table 4.9 Site Coefficient, Fa (ASCE, 2005, p. 115)

Site Class	Mapped Maximum Considered Earthquake Spectral Response Acceleration Parameter at Short Period				
	$S_S \leq 0.25$	$S_S = 0.5$	$S_S = 0.75$	$S_S = 1.0$	$S_S \geq 1.25$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0	1.0
D	1.6	1.4	1.2	1.1	1.0
E	2.5	1.7	1.2	0.9	0.9
F	See Section 11.4.7				

NOTE: Use straight-line interpolation for intermediate values of S_S.

Table 4.10 Site Coefficient, Fv (ASCE, 2005, p. 115)

Site Class	Mapped Maximum Considered Earthquake Spectral Response Acceleration Parameter at 1-s Period				
	$S_1 \leq 0.1$	$S_1 = 0.2$	$S_1 = 0.3$	$S_1 = 0.4$	$S_1 \geq 0.5$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.7	1.6	1.5	1.4	1.3
D	2.4	2.0	1.8	1.6	1.5
E	3.5	3.2	2.8	2.4	2.4
F	See Section 11.4.7				

NOTE: Use straight-line interpolation for intermediate values of S_1.

Figure 4.12 Long-term transition period, T_L
(ASCE, 2005, p. 228)

Then, $S_{MS} = F_a . S_s = 1.02 \times 1.2 = 1.224$

$S_{M1} = F_v . S_1 = 1.6 \times 0.4 = 0.64$

2. Spectral Acceleration Parameters

   $S_{DS} = 2/3 . S_{MS} = 2/3 \times 1.32 = 0.82g$

   $S_{D1} = 2/3 . S_{M1} = 2/3 \times 0.64 = 0.43g$

3. Response Spectrum

   The Response Spectrum has been plotted as follows:

   - *Periods, T in seconds (x-axis):*

     $T_0 = 0.2 . S_{D1} / S_{DS} = 0.2 \times 0.43 / 0.88 = 0.097$ secs

     $T_S = S_{D1} / S_{DS} = 0.43 / 0.88 = 0.485$ secs

     $T_L = 8$, from Figure 4.12.

   - *Accelerations, S_a in g (y-axis):*

     $S_a = S_{DS} (0.4 + 0.6 T/T_0) = 0.88 \times (0.4 + 0.6 T / 0.097)$

     for periods (T) less than T_0.

     $S_a = S_{DS} = 0.88$

     for periods (T) greater than or equal to T_0 and less than or equal to T_s.

     $S_a = S_{D1} / T = 0.43 / T$

     for periods (T) greater than T_S and less than or equal to T_L.

     $S_a = (S_{D1} . T_L) / T^2 = (0.43 \times 8) / T^2$

     for periods (T) greater than T_L.

   The Response Spectrum is shown in Figure 4.13.

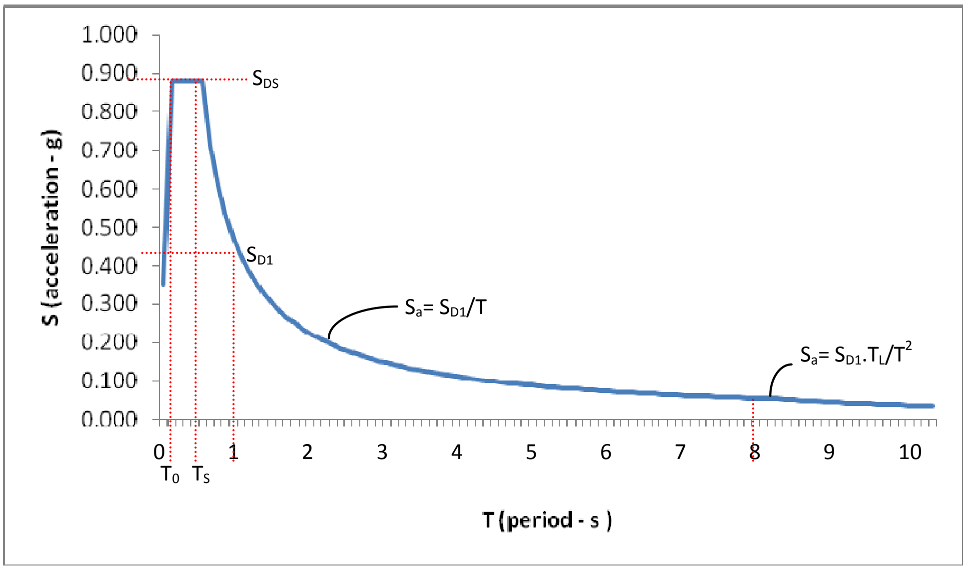


Figure 4.13 The Response Spectrum

Building Period

The fundamental building period was determined based the equations from ASCE 07-05.

Building Period based on ASCE (2005, p. 129).

The fundamental period can be determined as:

$T_a = C_t . h_n^x$

Using Table 4.11, the structure type is "all other structural systems".

C_t = 0.0488

h_n = 400 m (the highest level of the structure)

x = 0.75

$T_a = C_t . h_n^x = 0.0488 \times 400^{0.75} =$ **4.36 secs**

The fundamental period of the structure shall not exceed:

$T = C_U . T_a$ where: $C_U = 1.4$ for $S_{D1} \geq 0.4$ (Table 4.12).

= 1.4 x 4.36 = 6.11 secs

Table 4.11 Parameter C_t and x (ASCE, 2005, p. 129)

Structure Type	C_t	x
Moment-resisting frame systems in which the frames resist 100% of the required seismic force and are not enclosed or adjoined by components that are more rigid and will prevent the frames from deflecting where subjected to seismic forces:		
Steel moment-resisting frames	0.028 (0.0724)[a]	0.8
Concrete moment-resisting frames	0.016 (0.0466)[a]	0.9
Eccentrically braced steel frames	0.03 (0.0731)[a]	0.75
All other structural systems	0.02 (0.0488)[a]	0.75

[a]Metric equivalents are shown in parentheses.

Table 4.12 Parameter C_U (ASCE, 2005, p. 129)

Design Spectral Response Acceleration Parameter at 1 s, S_{D1}	Coefficient C_U
≥ 0.4	1.4
0.3	1.4
0.2	1.5
0.15	1.6
≤ 0.1	1.7

<u>Seismic Base Shear</u> (ASCE, 2005, p. 129)

The seismic base shear based on the fundamental period T= 4.36 secs was determined by:

$V = C_s.W$

The value of C_s

C_s was determined as follows:

$C_s = S_{DS} / (R/I)$

$= 0.82 / (3.25/1.25) = 0.31$

C_s needs not exceed the following:

$C_s = S_{D1} / (T (R/I))$

$= 0.43 / (4.36 \times (3.25/1.25))$

$= 0.0376$

where: $S_{DS} = 0.82g$

$S_{D1} = 0.43g$

T = 4.36 secs

R = 3.25 for ordinary steel concentrically braced frames (ASCE, 2005, p. 120)

I = 1.25 for occupancy category III (ASCE, 2005, p. 116)

In conclusion, $\mathbf{C_s = 0.0376}$.

The Response Modification Coefficient, R= 3.25 is based on the assumption of ordinary steel concentrically braced frames (ASCE, 2005, p. 120). However, this value does not represent the real ductility of vertical double-layer space structures because the structural system does not meet the criteria shown in Table 12.2-1 (ASCE, 2005, pp. 120-122). This is issue will be discussed further in Section 4.3.3.

The value of W

W is effective seismic weight including:

- Total dead load:
- Total weight of partitions
- Total weight of permanent equipment like that in plant rooms.

W has been determined from the building reactions from ETABS:

W = 1,747,408 kN

Then,

$V = C_s.W = 0.0376 \times 1{,}747{,}408$

V = 65,697 kN

Static Analysis by ETABS

The seismic design information for the Static Analysis run by ETABS and the results are shown in Table 4.13. Information in the table is the case EQX which is seismic load in the X-direction. The case EQY, which is seismic load in Y-direction, has the same design information and results as those in the case EQX shown in Table 4.13.

Table 4.13 Seismic design information and result by ETABS

Case	EQX	SiteClass	D
Dir	X	Ss	1.20
EccRatio	-	S1	0.40
EccOverrides	No	TL	8.00
PeriodCalc	Prog Calc	Fa	1.02
Ct	0.02	Fv	1.60
x	0.75	Sds	0.82
UserT	-	Sd1	0.43
TopStorey	STOREY100	**TUsed**	**6.11**
BotStorey	BASE	**CoeffUsed**	**0.045**
R	3.25	**WeightUsed**	**1,736,202.93**
I	1.25	**BaseShear**	**77,920.79**

The Shear force diagram from the Static Analysis by ETABS is shown in Figure 4.14.

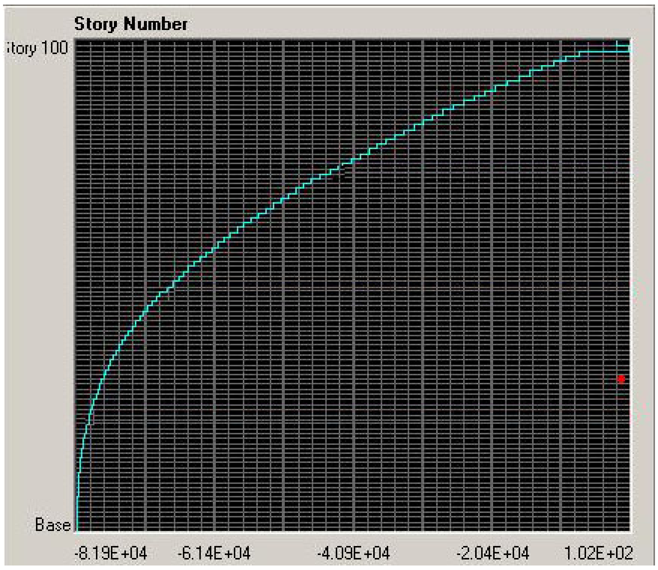


Figure 4.14 Seismic shear force diagram from the Static Analysis by ETABS

Dynamic Analysis by ETABS

The dynamic analysis has been conducted based on:

- Complete Quadratic Combination (CQC) method as the modal combination method (ASCE, 2005, p. 132).
- Square Root of the Sum of the Squares (SRSS) as the directional combination (ASCE, 2005, p. 132).
- Damping ratio is assumed as 0.01 for steel buildings (Irvine, 2004; Tamura, 2010).

Seismic Design Information

The information for the Dynamic Analysis run by ETABS is as follows:

a. Response Spectrum Case Function

Ss	S1	TL	Site Class	Fa	Fv	SDS	SD1
1.2	0.4	8	D	1.02	1.6	0.816	0.4267

b. Response Spectrum Case Data

Case	Damping	Modal Combo	GMCf1	GMCf2	Dir Combo	ABSSF
SPEC1	0.01	CQC			SRSS	

U1Func	U1SF	U2Func	U2SF	UZFunc	UZSF	Angle	Eccen	Overrides
FUNC1	9.8	FUNC1	9.8			0	0	No

The Results

The results of the Dynamic Analysis run by ETABS consist of storey shears, modal participating mass ratios, building period, and response spectrum base reactions.

a. Storey shears

The shear forces at the ground floor, V_X = 173,026 kN and V_Y = 186,081 kN (Figure 4.15).

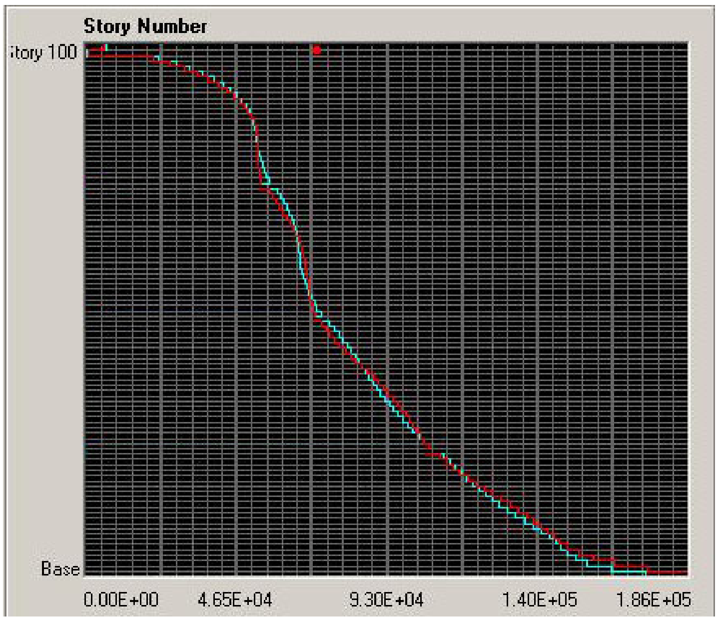


Figure 4.15 Shear forces from the Dynamic Analysis in X and Y directions

b. Modal participating mass ratios

Modal participating mass ratios conducted by ETABS are shown in Table 4.14.

Table 4.14 Modal participating mass ratios from ETABS

Mode	Period	UX	UY	UZ	SumUX	SumUY	SumUZ
1	6.370419	58.1393	0.0627	0	58.1393	0.0627	0
2	6.332746	0.0626	58.1075	0	58.2019	58.1702	0
3	1.903971	0	0.0006	0	58.2019	58.1708	0
4	1.762244	22.5087	0.076	0	80.7106	58.2468	0
5	1.755747	0.0735	22.4386	0	80.7841	80.6854	0
6	0.912006	1.4948	6.2431	0	82.2789	86.9285	0
7	0.910859	6.1478	1.5119	0	88.4267	88.4405	0
8	0.600429	2.9867	0.7303	0	91.4134	89.1708	0
9	0.592003	0.7173	3.6799	0	92.1307	92.8507	0
10	0.401034	2.543	0.1838	0	94.6737	93.0346	0
11	0.305662	0.3352	4.5202	0	95.0089	97.5548	0
12	0.220223	3.3906	0.2142	0	**98.3995**	**97.769**	0

Table 4.14 shows that the building period of the first mode is 6.37 seconds with 58.14% of the building mass participating in X direction. The first mode building period alone cannot represent the actual building period because less than 90% of the actual mass participates. Twelve modes cover 98.4% of the building mass, which is more than the required 90% (ASCE, 2005, p. 132).

c. Response spectrum base shears

With respect to Table 4.15:

- F1 are the base shears in the X-direction and F2 in the Y-direction.
- The response spectrum base shears were determined for each mode as:

$$V = W \,.\, U_X .\, S$$

Where:

W = building weight, which is 1,736,202.93 (shown in Table 4.13).

U_X = modal participating mass ratio (Table 4.14).

S = acceleration from the Response Spectrum Graphic in Figure 4.13.

For example: mode 1

U_X = 58.14% (Table 4.14)

S = 0.067 (Figure 4.14)

V = W . U_X. S = 1,736,202.93 x 58.14% x 0.067 = 67,631 kN

This value is very close to F1 = 67,928 kN (Mode 1 Table 4.15)

Table 4.15 Response spectrum base shears

Spec	Mode	Dir	F1	F2
SPEC1	1	U1	67,928	2,231
SPEC1	2	U1	74	- 2,241
SPEC1	3	U1	0	1
SPEC1	4	U1	95,152	- 5,528
SPEC1	5	U1	312	5,451
SPEC1	6	U1	12,334	- 25,207
SPEC1	7	U1	50,794	25,189
SPEC1	8	U1	38,346	- 18,962
SPEC1	9	U1	9,316	21,102
SPEC1	10	U1	36,154	- 9,721
SPEC1	11	U1	4,766	17,501
SPEC1	12	U1	48,205	- 12,117
SPEC1	1	U2	2,231	73
SPEC1	2	U2	- 2,241	68,308
SPEC1	3	U2	1	3
SPEC1	4	U2	- 5,528	321
SPEC1	5	U2	5,451	95,232
SPEC1	6	U2	- 25,207	51,515
SPEC1	7	U2	25,189	12,492
SPEC1	8	U2	- 18,962	9,377
SPEC1	9	U2	21,102	47,797
SPEC1	10	U2	- 9,721	2,614
SPEC1	11	U2	17,501	64,265
SPEC1	12	U2	- 12,117	3,046
SPEC1	**All**	**All**	**155,809**	**160,874**

- Square Root of the Sum of the Squares (SRSS) method has been used to determine the directional combination base shear using formula:

  $V1 = \sqrt{\Sigma (F1^2)}$ and $V2 = \sqrt{\Sigma (F2^2)}$

- The response spectrum base shears are:

  V1 = 155,809 kN

  V2 = 160,874 kN

These results assume that the building acts in an elastic condition. The building occupancy category (I factor) and the response modification coefficient (R factor) have not been considered.

- The I and R factors are included as follows: V = V1 / (R/I)

$$\mathbf{V_X} = 155{,}809 / (3.25/1.25) = \mathbf{59{,}926\ kN}$$

$$\mathbf{V_Y} = 160{,}874 / (3.25/1.25) = \mathbf{61{,}875\ kN}$$

Summary and Conclusion

The results from the Static Analysis hand calculation and ETABS calculation, and the Dynamic Analysis by ETABS are summarised in Table 4.16.

Table 4.16 Comparison of the three different seismic analysis calculations (X-direction)

No.	Item	Period secs	C	Base Shear kN	Notes
1	**Static Analysis by hand calculation**				
	T is based on ASCE	4.36	0.038	65,697	
2	**Static Analysis by ETABS**				
	T is based on ASCE	6.11	0.045	77,920	
3	**Dynamic Analysis by ETABS**				
	CQC modal comb + SRSS directional comb	6.37		59,926	I and R factors is included
	The first mode: 58% mass				in the base shear

Static Analyses by hand calculation and by ETABS use the same calculation procedure, which is based on the building code. Their different results come from the determination of the building periods that affect the base shears. In the building code, the building period is determined empirically by the building height and the structural type. The building slenderness does not affect the building period. However in ETABS, the building periods are generated by analysing all aspects of the building geometries. As a result, buildings that have the same height but different structural composition and slenderness have different building periods.

The C values of the structure are about 4%. In California, the base shear of a 60-storey steel moment frame building is about 4% of the building mass according to Taranath (2005). The first mode building periods from ETABS are about 6 seconds, which are similar to the 5.7

seconds period of the 421-metre Jin Mao building, Shanghai (Taranath, 2005) and 6.21 seconds period of the Taipei 101, 508 metres high (Fan, Li, Tuan, & Xu, 2009).

The base shears from the Static Analysis are greater than those from the Dynamic Analysis. In this research, the Dynamic Analysis is preferred because it provides more accurate results by including various modal and directional combinations, which represent the dynamic behaviour more closely.

4.3.3. Comparison and Discussion

This section discusses the comparison of wind load and seismic load in the vertical double-layer space structures of the 48m x 48m and the 60m x 60m buildings. Table 4.17 shows the base shears from the wind and seismic dynamic analysis as explained previously.

Table 4.17 Base shears from the wind and seismic dynamic analyses

No.	Item	Period	Base Shear
		secs	kN
	Building 48 m x 48 m		
1.	Seismic load	6.37	59,926
2.	Wind load		61,831
	Building 60 m x 60 m		
1.	Seismic load	7.05	54,781
2.	Wind load		77,289

In the 60m x 60m building, the base shear is lower than that of the 48m x 48m building because the building period is longer. The comparison also shows that the wind base shear is slightly greater than the seismic base shear. In this case study, the buildings are assumed to be located in Los Angeles city, which is an area with high intensity of earthquakes. Generally, the wind load is more significant than the seismic load in structural designs of tall buildings (Willford, Whittaker, & Klemencic, 2008).

As mentioned previously in Section 4.3.2, the R value or the ductility of vertical double-layer space structures, is not covered by the building code (ASCE, 2005). The seismic base shears shown in Table 4.16 are based on the assumption of a structural ductility, R=3.25. Further research has to be conducted to determine if this ductility is appropriate for vertical double-layer space structures.

Vertical double-layer space structures have several similar characteristics to braced-tubes. Both these structural systems have diagonal structural members that transfer the building shear, high levels of rigidity, and the same lateral deflection patterns showing a cantilever action. According to Fazlur Khan, a braced-tube is a rigid system and insufficiently ductile in high-seismic zones (Khan, 2004). Based on this argument and the limitation of this study, vertical double-layer space structures should not be used for super-tall buildings in high-seismic areas before further research on their structural ductility is conducted.

4.4. Sensitivity Analyses

The previous section has discussed the significant impact of the wind load on the design of vertical double-layer space structures. This section analyses the structural sensitivity to wind load by changing several member sizes, and then their additional structural weight and lateral deflections are compared. The aim is to investigate the types of structural modifications that significantly impact on structural deflection and weight, in order to provide an optimum design. In this case study, the changes are very limited, but they can represent overall possible modifications because the changes cover three primary elements of vertical double-layer space structures: vertical members, diagonal members, and the slope of diagonal members.

4.4.1. Structural Design using Various Configurations

Another 100-storey double-layer space structure was designed as a bench mark. The design followed the same procedure as discussed previously. The geometry of the structure shown in Figure 4.16 is slightly different to the previous model:

- The floor plan is 64m x 64m. The structure consists of eight bays, 8 metres each bay.
- The lateral system is a vertical double-layer space structure, and the gravity system is a moment resisting frame connected by pinned joints to the lateral system. Horizontal double-layer space structures and suspended columns were not used in this design in order to analyse the behaviour of the vertical double-layer space structure to the wind load without contribution of the horizontal double-layer space structures.

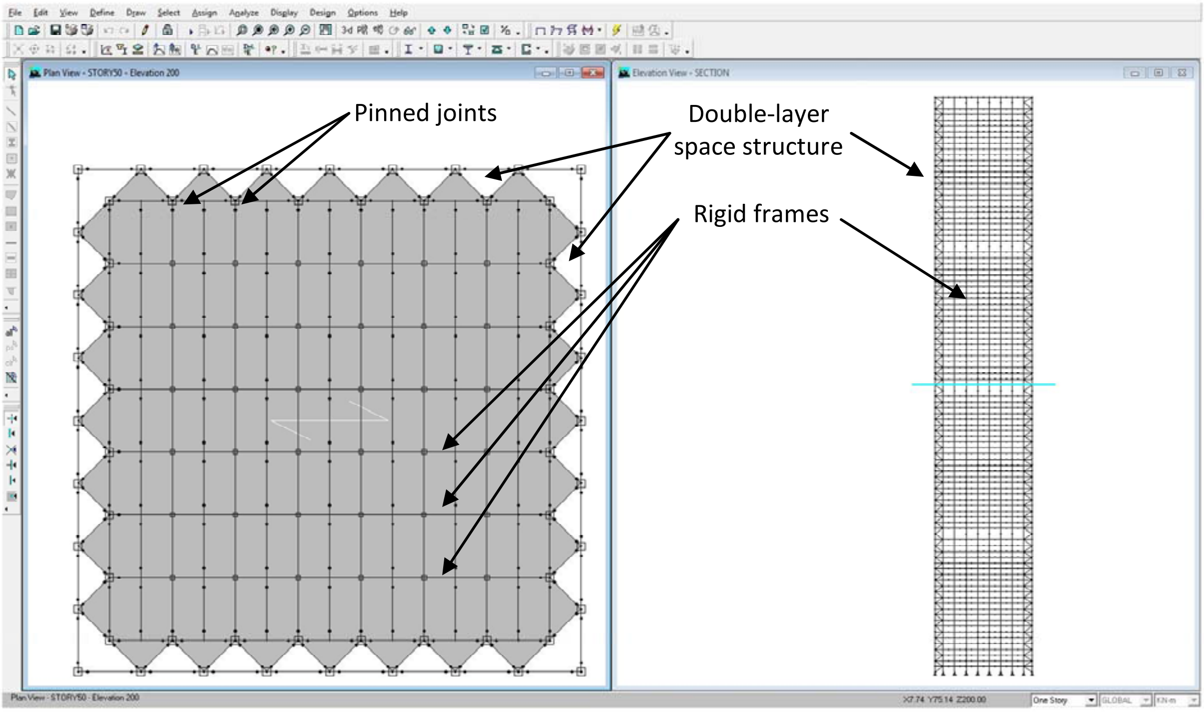


Figure 4.16 Idealization of the six structural models

Five other models were also designed with their structural member sizes and diagonal members' slope varied from the first model as shown in Table 4.18. The external and internal vertical, horizontal, and diagonal members have the same cross-sections for every storey up the building. The variations are as follows:

- Internal vertical members are reduced in cross-sectional area in the second and the third models.
- Diagonal members of the fourth and fifth models use smaller cross-sectional area.
- Diagonal members of the sixth model span two-storeys as compared to the first model which has one-storey high diagonal members.

The six models were analysed using ETABS, and each structural member fulfilled the strength limit. The deflection limit, which is height/500, was not applied because the models were not designed.

Table 4.18 Varied structural components of the six models

MODEL	External vertical members	Internal vertical members	Horizontal members	Diagonal members
1st model: The bench mark	**Box 0.90/0.090 A=0.29 m^2**	**Box 0.90/0.090 A=0.29 m^2**	**Box 0.30/0.030 A=0.032 m^2**	**Box 0.40/0.040 A=0.058 m^2**
2nd model: smaller internal vertical members	Box 0.90/0.090 A=0.29 m^2	Box 0.80/0.080 A=0.023 m^2	Box 0.30/0.030 A=0.032 m^2	Box 0.40/0.040 A=0.058 m^2
3rd model: smaller internal vertical members	Box 0.90/0.090 A=0.29 m^2	Box 0.70/0.070 A=0.18 m^2	Box 0.30/0.030 A=0.032 m^2	Box 0.40/0.040 A=0.058 m^2
4th model: smaller diagonal members	Box 0.90/0.090 A=0.29 m^2	Box 0.90/0.090 A=0.29 m^2	Box 0.30/0.030 A=0.032 m^2	Box 0.35/0.035 A=0.044 m^2
5th model: smaller diagonal members	Box 0.90/0.090 A=0.29 m^2	Box 0.90/0.090 A=0.29 m^2	Box 0.30/0.030 A=0.032 m^2	Box 0.30/0.030 A=0.032 m^2
6th model:	The diagonal members have a different angle and span two-storeys			

4.4.2. Results

The results are summarised in Table 4.19 by showing the lateral deflections and structural weights of the six models. The different deflections between the models are shown in millimetres (column c) and percentages (column d). The different structural weights are shown in kNs (column f) and percentages (column g). The deflections and structural weight percentage differences between the five models and the first model are then compared in δW/δd ratio (column h) as the final result.

The results show that the sixth model, in which the diagonal member angle is changed, has the largest δW/δd ratio, which means a high structural weight reduction, but a low additional lateral deflection. This is the most desirable of the structural changes. The fourth and fifth models, in which diagonal member sizes are varied, have the smallest δW/δd ratio, where structural weight reduction has a significant impact upon lateral deflection. This is an undesirable structural change that should be avoided.

These sensitivity analyses show that changing the angle of the diagonal members has a high sensitivity on structural weight and a low sensitivity on lateral deflection. This is the most desirable condition to enhance structural efficiency.

Table 4.19 The differences in lateral deflection and structural weight of the six models

MODEL	Deflection			Structural weight			δW/δd Ratio
	mm	δd (mm)	δd (%)	kN	δW (kN)	δW (%)	
a	b	c	d	e	f	g	h= g/d
1st model: The bench mark	**756**			**2,177,695**			
2nd model: smaller internal vertical members	781	25	3.31	2,109,370	68,325	3.14	0.95
3rd model: smaller internal vertical members	815	59	7.80	2,062,778	114,917	5.28	0.68
4th model: smaller diagonal members	844	88	11.64	2,093,007	84,688	3.89	0.33
5th model: smaller diagonal members	996	240	31.75	2,022,550	155,145	7.12	0.22
6th model:	773	17	2.25	2,092,091	85,604	3.93	1.75

4.5. Thermal Expansion in Exposed Double-layer Space Structures

This section discusses briefly thermal expansion or contraction, which may cause internal stress in exposed double-layer space structures. The purpose is to examine if thermal expansion caused by different internal and external air temperatures will not significantly affect high-rise double-layer space structures in terms of having acceptable structural deformation. Chapter 6, which discusses architectural integration of double-layer space structures, shows that these structures can be exposed for aesthetic purposes. In exposed structures, different temperatures of external and internal structural members can be significant, and differential thermal movements occur (Schueller, 1990). Internal stress can also occur if the structural components are restrained.

The 100-storey double-layer space structure case study using a 48m x 48m typical floor plan is analysed for different temperatures between external and internal structural members. The analysis uses ETABS and hand-calculation using the following equation (AISC, 2002):

$$\Delta L = 0.0000065 \times L \times \Delta T$$

Where:
- ΔL : deformation (m)
- L : member length (m)
- ΔT : temperature difference in Fahrenheit

Based on various façade types discussed in Chapter 6, thermal expansion and internal stress are analysed in three different exposed structures schemes as follows:

a) Outer vertical members only are exposed.
b) Diagonal and outer vertical members are exposed.
c) All diagonal and double-layer vertical members are exposed (Figure 4.17).

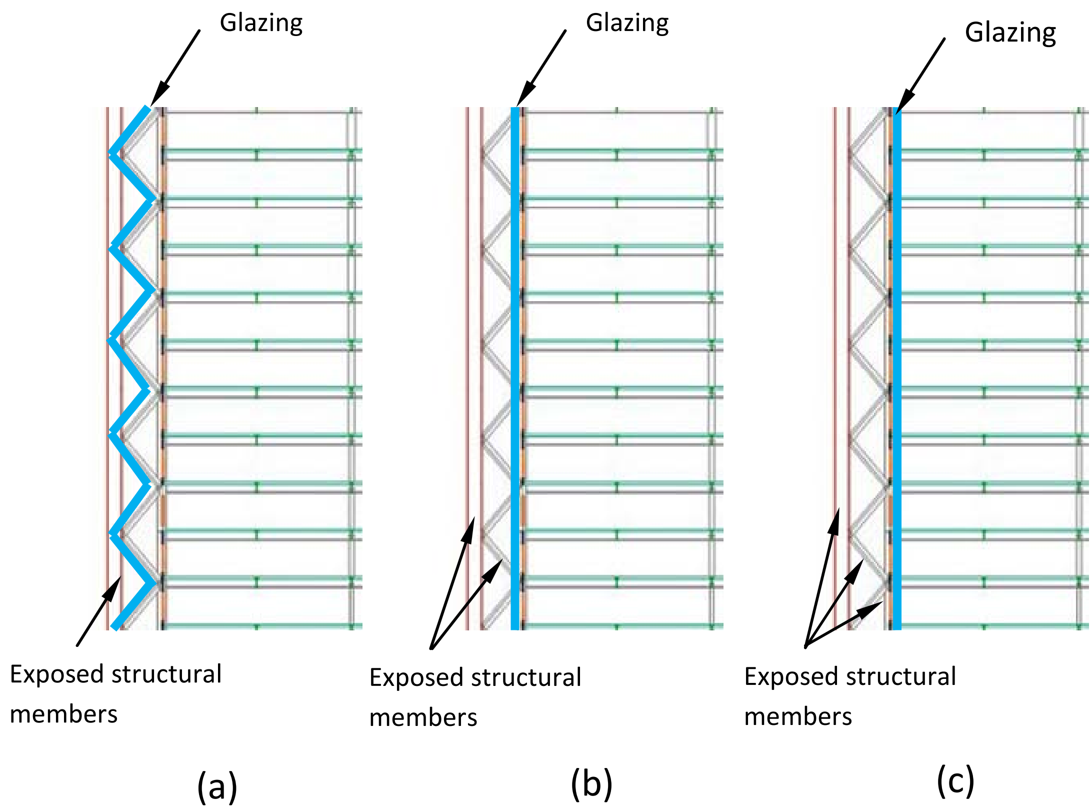


Figure 4.17 Three different schemes of exposed structures

Thermal Expansion

The analysis is conducted based on an assumption that the difference between external and internal temperatures is 20°C (36°F). Internal temperature is assumed 20°C; external air temperature is assumed 40°C on the hottest day and 0°C at the coolest day. This assumption is based on the climate data in Los Angeles city, where temperature differences can be significant compared to other places (NOAA, 2004). The average high of the hottest month in Los Angeles is about 30 °C and the average low of the coolest month is about 10°C. This temperature differences assumed for this research are relatively high and can represent climates in other large cities in the world where many tall buildings are built.

Therefore, the results from the study about thermal expansion in exposed double-layer space structures can be applied generally to other locations in the world.

The results from the case study are as follows:

1. Analysis using ETABS
   a. Outer vertical members only are exposed, Δ L = 48.4 mm
   b. Diagonal and outer vertical members are exposed, Δ L = 82.3 mm
   c. All diagonal and double-layer vertical members are exposed, Δ L = 115.3 mm
2. Analysis using hand-calculation for the scheme of unrestricted vertical members.

$$\Delta L = 0.0000065 \times L \times \Delta T$$
$$= 0.0000065 \times 400 \times 36 = 0.0936 \text{ m} = 93.6 \text{ mm}$$

These calculations show that the third scheme analysed by ETABS has the highest vertical displacement. Figure 4.18 shows the deflected structure of several levels. In this scheme, a significant temperature difference at two end-points of a 16-metre-long beam on storey 52 is 23 mm. For steel beams, the deflection limit under gravity load is l/360 (AISC, 2005) or 44 mm in this case. Since the deflection caused by the temperature difference is lower than the deflection limit, it will not significantly affect operation of moveable interior components such as doors, windows and sliding partitions.

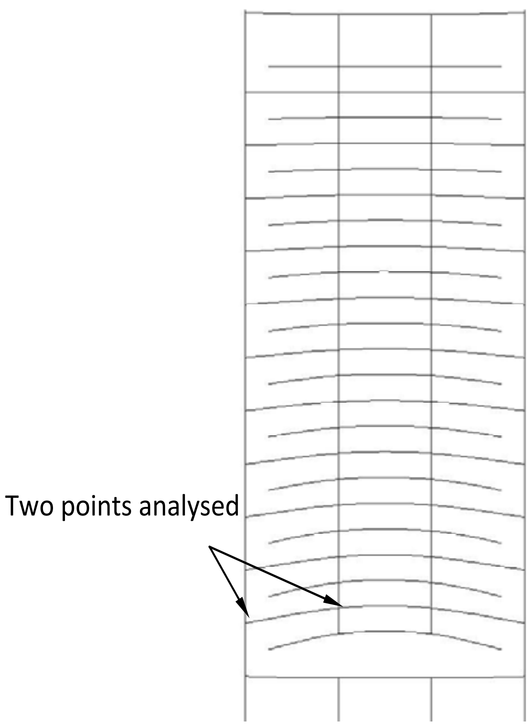


Figure 4.18 Deflected structure caused by differential temperature effects and the two points analysed

This study has provided information about thermal expansion of a building with an assumption that the difference between external and internal temperatures is 20^{o}C, based on the highest ever recorded temperatures in Los Angeles City, which are around 40^{o}C. This temperature difference is relatively high; therefore this extreme value can cover weather conditions of most large cities in the world. For general applications, displacement at critical point analysed in this case study should be calculated especially when the difference between internal and external temperatures is much higher than that assumed in this case study.

Many buildings with exposed structure have structural members covered. For example, steel members in John Hancock Center, Chicago are covered by cladding to hide structural connections (Figure 4.19 (a)). In the HSBC Headquarters, Hong Kong, steel components are fire-protected by an insulation material and cladding (Figure 4.19 (b)). Some buildings, like the Hotel De Las Artes in Barcelona, physically expose their structural members (Figure 4.19 (c)). Structural members of double-layer space structures can be covered by cladding for corrosion protection and fire safety as discussed in Section 5.4, and aesthetic reasons.

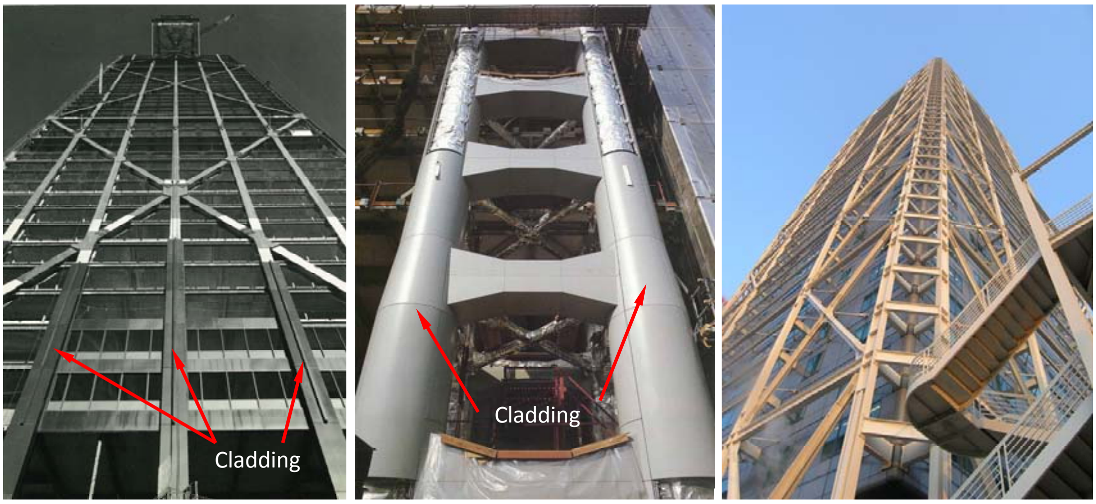


Figure 4.19 (a) Cladding in the John Hancock Center, Chicago (Stoller, 2000, p. 16); (b) Covered steel columns in HSBC Headquarters, Hong Kong (Lambot, 1986, p. 60); (c) Exposed steel structure in Hotel De Las Artes, Barcelona (Source: http://en.structurae.de/)

Internal Stress

Internal stress occurs when thermal expansion is restrained (Schueller, 1990). In double-layer space structures, this problem is minimised by pinning the majority of structural joints. An analysis conducted using ETABS shows that large compression caused by thermal expansion occurs in vertical structural members at lower storeys. This is because thermal expansion of perimeter structural members is restrained by internal structural members. This additional compression is about 10 to 15% of that from gravity loads, but it does not affect the structural design, which is driven by lateral deflection limits.

4.6. Summary

This chapter has investigated the application of double-layer space structures in super-tall buildings from a structural point of view. The findings are summarised as follows:

- Double-layer space structures resist gravity and lateral loads by members in tension and compression rather than bending and shear. As occurred in other tall structural systems, the designs of these structures are driven by the lateral deflection limit.
- Compared to bundled-tubes, braced-tubes, and diagrid structures, vertical double-layer space structures are relatively efficient. Double-layer space structures are slightly heavier than the lightest structures, braced-tubes.
- The four structural systems, vertical double-layer space structures, bundled-tubes, braced-tubes, and diagrids, require less structural weight per unit area in less slender buildings.
- Compared to bundled-tubes, braced-tubes, and diagrid structures, vertical double-layer space structures have relatively smaller components, especially at the upper floors, and reasonable column-to-column spans, which provide an advantage for structural-architectural integration because larger open views can be provided. This is discussed further in Chapter 6. Smaller components at the upper floors are also beneficial for construction as discussed in Chapter 7.
- As in all tall structures, wind load dominates the design of vertical double-layer space structures. In terms of seismic design, the ductility of vertical double-layer space structures is not covered by the building code, ASCE 2005. Further research should be conducted on the ductility of vertical double-layer space structures.
- An investigation of structural sensitivity to wind load showed that changing the angles of diagonal members to make them span two storeys rather than one storey reduces structural weight and has little impact on lateral deflection.
- Different temperatures in exposed double-layer space structures can potentially cause thermal expansion and internal stress. Although their impact is not significant, covering external structural members by cladding can minimise this issue.
- The findings in this chapter can be relevantly applied to double-layer space structures in general high-rise applications in the scope mentioned in Section 3.2 for the reasons outlined in each section of this chapter.

Chapter 5: Building Services

This chapter discusses building services systems integrated with double-layer space structures. In order to answer the research sub-questions about building services in Chapter 3, the study investigates:

- How services systems work within a double-layer space structure building.
- How building services components including fire safety systems integrate with the structural components and the whole building as a system.
- The advantages and disadvantages of this type of structural-services integration.

The discussion covers heating, ventilating and air conditioning (HVAC), vertical transportation, fire safety, approaches to energy efficiency, and building maintenance. Case studies were conducted by designing services systems, like HVAC, stairs and elevators, in order to integrate them with the double-layer space structures designed in Chapter 4. The services systems were designed by applying current technologies that have been commonly used in tall and super-tall buildings. The aim is to investigate if double-layer space structures can accommodate services systems using current technologies. This study also discusses the effect of structural-services integration on the optimisation of usable floor area.

5.1. Heating, Ventilating and Air Conditioning

This section discusses how to integrate HVAC components within a double-layer space structure building. The steps are as follows:

- The design of HVAC systems that represent current services systems that have been commonly used in tall and super-tall buildings
- Testing whether the space required for the plant rooms and the other HVAC components can be accommodated by double-layer space structures in super-tall buildings

The design of HVAC systems depends on the building location and orientation to the sun paths, façade, function, occupants, materials, and many other factors. Double-layer space structure buildings should be able to accommodate various HVAC systems, such as direct refrigerant, all-air, air and water, and all-water systems (Stein, Reynolds, Grondzik, & Kwok, 2006). Large HVAC systems typically have chilled water sets (chillers), water heating units (boilers), cooling towers, and Air Handling Units (AHUs) (Parlour, 1990).

In this research, a case study was designed in order to represent all existing HVAC systems that have been commonly used in high-rise applications. Since the aim of this study is to obtain information about space required for HVAC components, current HVAC systems are classified based on the position of AHUs and vertical distribution systems. They are classified in and represented by three main systems discussed as follow:

- Centralised Air Handling: boilers, chillers, cooling towers, and AHUs are located in central plant rooms. The air is distributed from the central plant rooms through ducts to every floor. The vertical ducts can pass through the space between the internal and external layers of the perimeter structure.
- Localised Air Handling: boilers, chillers, and cooling towers are placed in central plant rooms. Hot and chilled water is distributed from the central plant rooms through pipes to Air Handling Units on every floor. The Air Handling Units can also be installed in the space between the external and internal layers of the space structures. The dimensions of the AHUs should fit the provided space. Positioning several small AHUs at several locations on each floor is useful for zoning the air conditioning.
- A relatively new cooling system, Chilled Beams, is also considered for its possible application in double-layer space structure buildings.

As mentioned above, these three systems were chosen in order to represent various HVAC systems based on the position of AHUs and vertical distribution systems. The first system, Centralised Air Handling, consumes much space in plant rooms but less space in shaft openings; Localised Air Handling has the opposite condition. Chilled Beams are also analysed as a relatively new system that might consume less space in both plant rooms and shaft opening.

These three systems were designed and analysed to test whether they can be integrated with double-layer space structures. Since the main purpose of the HVAC designs in this study is to obtain a clue about the space required for plant rooms and shafts, the findings of this study will not be significantly different for other high-rise buildings with a specific weather condition. The design results provide information on how large the space for HVAC components including duct dimensions and plant room sizes is required. This information is used to ensure the double-layer space structure can accommodate HVAC components.

5.1.1. Design Information

This section provides the information and references for the design. Since the building model was not assumed to be built on a particular area with a specific condition, the HVAC design was just based on the number of people in the building. The three HVAC systems were designed for the 100-storey, 48m x 48m building. The plant room locations and vertical openings for HVAC ducts are shown in Figure 5.1. The design information is as follows:

1. Building height: 400 metres and 100 floors.
2. Occupied one-floor area: 40m x 40m = 1600 m^2.
3. Occupied floors: 100 – (4 plant rooms x 2 floors high each) = 92 floors.
4. Each plant room is two levels high, and 40 x 40 = 1600 m^2 floor area.
5. Plant room levels and serviced floors:
   - Plant room-1 in the basement serves ground floor to the 11th floor.
   - Plant room-2 on level 23 serves the 12th to 36th floor.
   - Plant room-3 on level 48 serves the 37th to 61st floor.
   - Plant room-4 on level 73 serves the 62nd to 86th floor.
   - Plant room-5 on level 98 serves the 87th to 97th floor.

   This case study designs HVAC system for the plant rooms 2, 3 and 4 only because they serve a higher floor number compared to that of the plant rooms-1 and 5. This means that the double-layer space structure will be able to accommodate plant rooms-1 and 5 if the structure can accommodate plant rooms- 2, 3 and 4, which require larger spaces.
6. The vertical openings for HVAC ducts are positioned in two different areas at the building corners as shown in Figure 5.1.
7. Occupancy was assumed at 12m^2/person. The occupied floors were assumed to be 90% of the total area. Normally 80% is used for a standard design (Stein, et al., 2006). A higher percentage is used here because several services components are outside the floor area. Total occupants in one floor, one zone and the total building areas are:

- 90% x 1600 m^2 x 1 floor = 1,440 m^2 per floor.
- 90% x 1600 m^2 x 23 floors = 33,120 m^2 per HVAC zone.
- 90% x 1600 m^2 x 92 floors = 132,480 m^2.

8. Number of people:
   - Per zone = 33,120 m^2 / 12 = 2,760 people.
   - Total = 132,480 m^2 / 12 = 11,040 people.

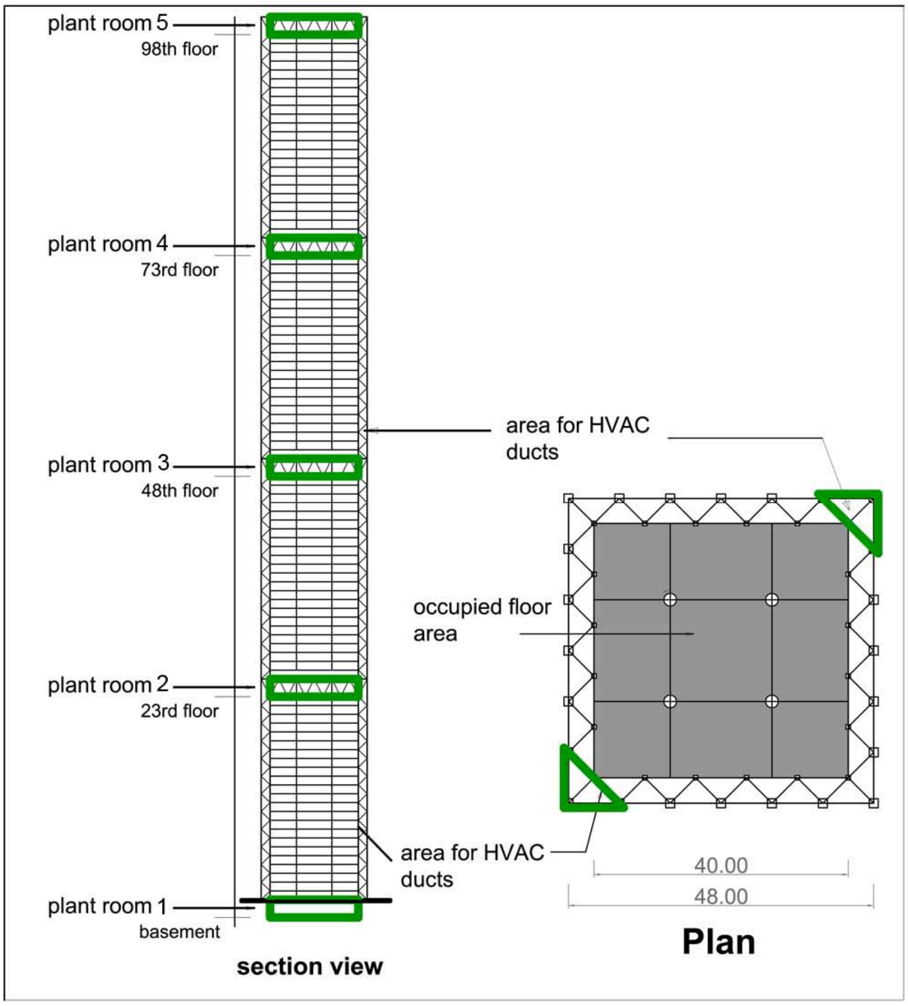


Figure 5.1 The areas for HVAC components

The references used for the design guidelines are "Mechanical and Electrical Equipment for Buildings" (Stein, et al., 2006) and "The Architect's Studio Companion" (Allen & Iano, 2007), as well as online technical brochures by Flakt Woods (2008) about Chilled Beams.

5.1.2. Centralised Air Handling

In the Centralised Air Handling system, each plant room that serves 23 floors was designed to accommodate chillers, boilers, cooling towers, and two AHUs. From Figure 5.2, data for an office building of 33,120 m^2 area is as follows:

- Cooling capacity is 900 tonnes
- Total area for boilers and chilled water plant is 600 m^2.
- Space for a cooling tower is 110 m^2.
- For office buildings 12 floors and 17,280 m^2 area, the required area for an AHU is about 450 m^2. For 11 floors 15,840 m^2 area, the area for another AHU is estimated about 400 m^2.

The total required area for a plant room is 600 + 110 + 450 + 400 = 1,560 m^2. As each building model provides 1,600 m^2 for a plant room, the requirement is achieved.

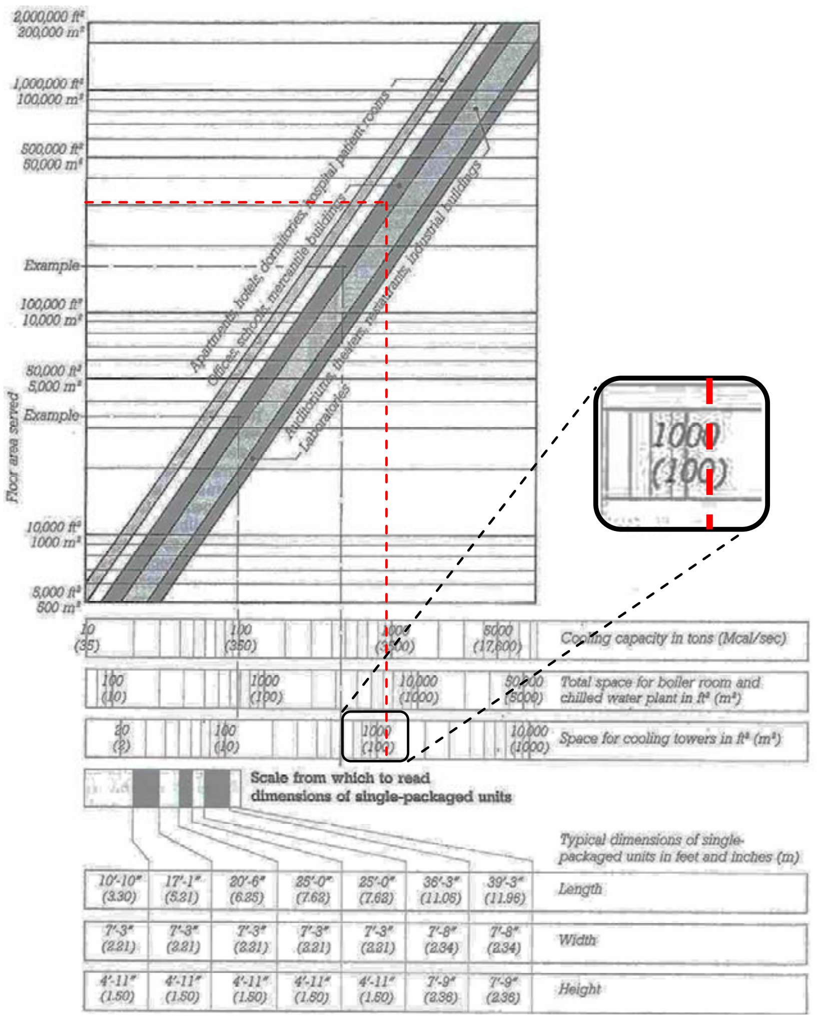


Figure 5.2 Sizing spaces for major heating and cooling equipment (Allen & Iano, 2007, p. 216)

From Figure 5.3, vertical ducts for air supply require about 10 m^2 area. In the double-layer space structure building, two locations within the perimeter structure at the building corners are used for the vertical pipes and ducts. Each location consists of two triangular modules. The minimum net area of each module is about 11 m^2 at the base floor, with the assumption that the structural member sizes at the ground floor were taken from Table 4.2 in Chapter 4. The total area, which is 44 m^2, is sufficient to accommodate all vertical pipes and ducts, such as HVAC and electrical ducts, pipes for plumbing and standpipes. The triangular areas within the perimeter structure are larger at the upper floors because the structural components especially the diagonal members are smaller. Figure 5.4 shows the area to accommodate the vertical pipes and ducts in the building.

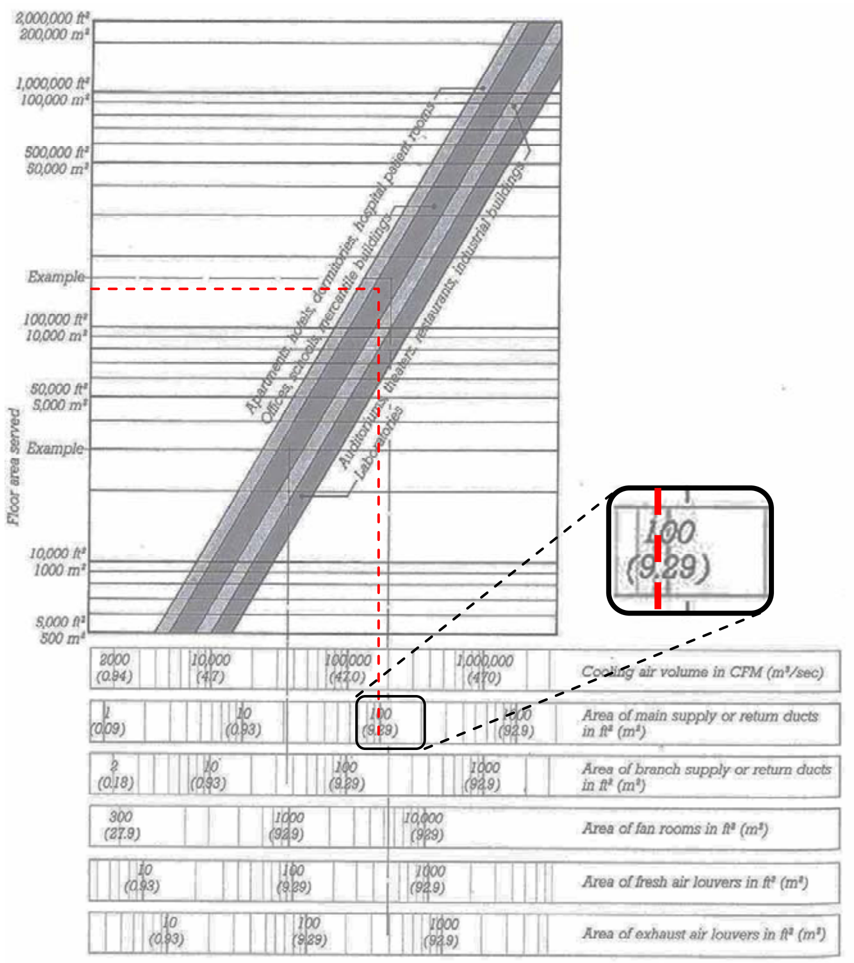


Figure 5.3 Sizing spaces for Air Handling Units (Allen & Iano, 2007, p. 218)

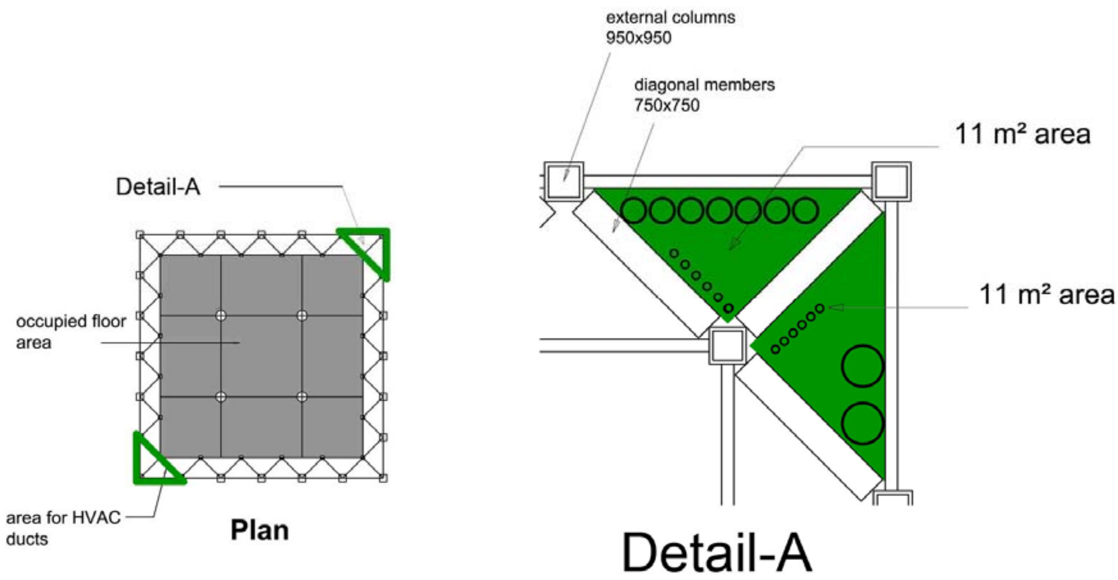


Figure 5.4 The triangular areas for ducts and pipes

5.1.3. Localised Air Handling

In the Localised Air Handling system, an AHU was designed to serve each floor, where chillers, boilers, and cooling towers in a plant room serve 23 floors. Figure 5.2 provides data for office buildings with 42,394 m^2 area for one zone as follows:

- Cooling capacity is 900 tonnes.
- Total area for boilers and chilled water plant is 600 m^2.
- Space for cooling tower is 110 m^2.

The total required area for a plant room is 600 + 110 = 710 m^2. This area is much smaller than the required HVAC area of the Centralised Air Handling Unit system and can be accommodated by the structure.

The Air Handling Units were positioned on each floor. From Figure 5.3, the required area for multi zone AHUs serving 1,440 m^2 is 54 m^2 (Allen & Iano, 2007, p. 218). The AHUs require a minimum of five triangular modules that equal with a total area of 55 m^2. In this case study, the cavity of the double-layer space structure cannot accommodate the AHUs because of the large area required and the fact that diagonal members of the perimeter structure consume considerable space. This means that the AHUs can possibly require a considerable amount of floor area that cannot be occupied. However, this requirement for AHU space is an inherent problem for all super-tall buildings. This indicates that Localised Air Handling system is less suitable for high-rise applications compared to other HVAC systems.

5.1.4. Chilled Beams

Chilled Beams, which are relatively new cooling systems, distribute the cooling by cold water that is supplied by chillers in plant rooms. This system does not use fans or AHUs. Chilled Beams are installed at ceiling levels and controlled by temperature sensors (Mumovic & Santamouris, 2008). The two main systems of Chilled Beams are active and passive systems. The active system operates with induction, mixing about 25% supply air and 75% room air through the coil of the beams. The passive system operates with convection without supply air. Air circulation is based on a chimney effect. The cooler air inside the beam has a higher density than the room air, and this naturally circulates the air. Neither system uses fans or AHUs (Flaktwoods, 2008). An example of passive Chilled Beam in a false ceiling is shown in Figure 5.5.

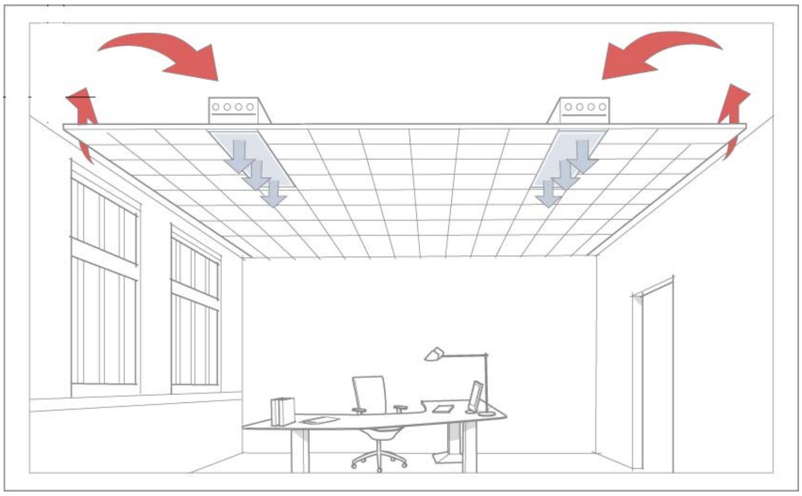


Figure 5.5 Passive chilled beams in a false ceiling (Flaktwoods, 2008, p. 5)

For both heating and cooling systems, heating can be operated by radiators or heating loops in the Chilled Beams and a control valve will manage heating and cooling processes (Flaktwoods, 2008).

For the purpose of this study, a passive Chilled Beams system was analysed to be applied in the double-layer space structure building. Since the system does not require AHUs, the plant rooms have the same area as those in Localised Air Handling system, which is 710 m^2. As mentioned previously, the cooling capacity is 900 tonnes, which equals 3,165 kW, for 23 floors or 137.6 kW /floor. A unit QPBA, a product by Flact Woods (Appendix B) was used as an example, 4.20 m long and 820 W capacity. One floor requires 137.6 / 0.82 = 167 units, and each unit serves 1,440 m^2 / 167 units = 9 m^2.

5.1.5. Analysis

The design of three different air conditioning systems provides the required area for plant rooms and vertical distribution access. Centralised Air Handling and Chilled Beam systems can be accommodated by the double-layer space structure building by integrating the horizontal structures with plant rooms, and the perimeter structure with vertical distribution access. Localised Air Handling systems can also be used in the vertical double-layer space structure building; however the AHUs will require much space if they are placed in the cavity of the structure. Passive Chilled Beams require less area for equipment because AHUs are not used in this system.

In conclusion, double-layer space structures in this case study can accommodate all type HVAC systems, but there are limits to the Localised Air Handling systems which are true for all super-tall buildings.

5.2. Stairs

This section discusses how to integrate stairs within a double-layer space structure building. Stairs, as a part of circulation system, are normally located at the central core in tall and super-tall buildings (Codella, Henn, & Moser, 1981). This strategy can also be easily applied in double-layer space structure buildings. However, this study explores an alternative strategy by positioning stairs at several areas in the cavity of the perimeter double-layer space structure. The aim is to optimise usable floor areas by positioning some of the stairs integrated with the perimeter structure. In order to test this strategy, a case study is conducted as follows.

Stairs were designed for a 100-storey 48m x 48m building using the double-layer space structure designed in Chapter 4. The stairs, as one of the egress systems, were designed based on the example and chart in the book "The Architect's Studio Companion" (Allen & Iano, 2007, pp. 292-293). The design calculation is as follows:

- Building was assumed as an office, category B or business areas (Allen & Iano, 2007, p. 10).
- Gross floor area is 1600 m^2.
- Total occupants = 1600 x 90% / 12 = 120 occupants.

- The building has three sprinkled stairs.
- Each exit is for 120/3= 40 occupants.
- From the Figure 5.6, clear width of stair is less than 36” or 0.90 m. To enhance the safety factor, three 1-metre width stairs are used.

The stairs are located at three different locations; one stair is at the middle core and the other stairs are within two layers of the perimeter structure. Fire rated walls, which can be of concrete construction, are used to protect the stairs from fire. Since the space within the perimeter structure is very limited, the stairs and structural members in those areas must be modified as shown in Figure 5.7:

- The horizontal members are slightly moved inside (from the dashed line) to give a larger stair opening.
- The floor slab can be used as one of two stair landings to optimise the stair opening.

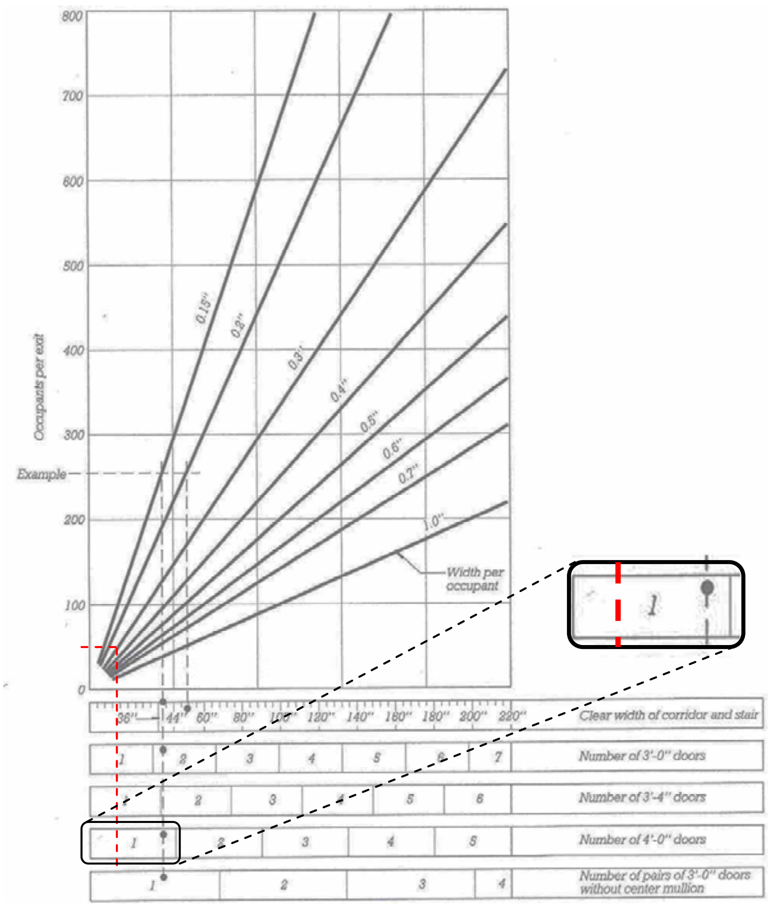


Figure 5.6 Sizing egress (Allen & Iano, 2007, p. 287)

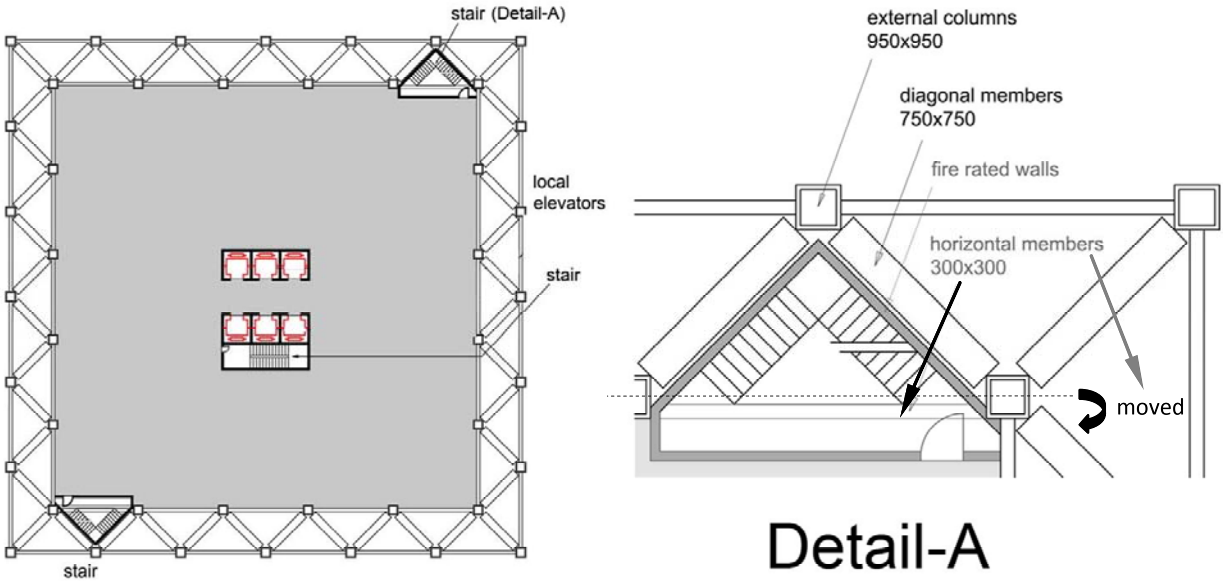


Figure 5.7 Stairwells within the module of perimeter structure

Positioning stairwells at three different locations remote from one another is beneficial to provide more egress, especially for total evacuation. Stairs as an egress system will be discussed further in Section 5.4.2. The plan of the stairwell positions will be shown together with elevator positions in the following section.

5.3. Elevators

This section discusses how to integrate and apply effectively elevators within a double-layer space structure building. This study uses a case study by designing several elevator systems to be integrated with a 100-storey double-layer space structure designed in Chapter 4. The case study was designed by applying current technologies in elevator systems. The aim is to investigate if double-layer space structures can accommodate and integrate with current elevators systems and if this integration leads to some advantages in providing larger usable floor areas.

A literature study has been conducted to obtain information about current elevators systems and their applications in high-rise buildings. Literature identifies that various existing elevator systems in high-rise applications can be classified into three basic types: zoning, double-decking, and sky lobbies (Fortune, 1997). These systems have been applied in current super-tall buildings, such as Willis Tower in Chicago, Petronas Towers in Kuala Lumpur, Empire State Building in New York, Bank of China and Central Plaza in Hong Kong, and Jin Mao in Shanghai and other super-tall buildings. In high-rise applications, elevators are normally located at the central core as a strategic location for services systems (Codella, Henn, & Moser, 1981). This strategy can also be applied in double-layer space structure buildings. However, this study explores an alternative strategy by positioning several elevators at several areas in the cavity of the perimeter double-layer space structure. The aim is to optimise usable floor areas by positioning some of the elevators integrated with the perimeter structure. In order to test this strategy, a case study was conducted as follows.

An exploration of various alternatives using combinations of the three elevator systems, zoning, double-decking, and sky lobbies, has been conducted by design and analysis. The purpose was to obtain an optimal number of elevators and sufficient capacity in this building. Based on this, the required vertical opening for elevators was determined. This is the starting point for an integrated design of structures and elevators by using some of the space between the two structural layers for several elevators.

5.3.1. Design Information

As a case study, elevators for the 100-storey, 48m x 48m building were designed using the following steps:

- Systems selection, such as: zoning, double-decker, and sky lobby systems.
- Estimation of the number of building occupants to be served.
- Estimation of Waiting Interval (WI) and 5 minutes Handling Capacity (HI).
- Providing the elevator schematic diagram.
- Estimation of space for the elevators.
- Estimation of lift motor room and lobby areas.

Three alternative elevator systems using varied zones, single and double-decking, and sky lobbies have been designed to investigate the most effective application.

The elevator design information is as follows:

1. Total occupied floors are 100 – (4 levels x 2 floors deep) = 92 floors.
2. Total gross area (including services area) per floor: 40 x 40 = 1600 m^2.
3. Floor-to-floor height is 4 metres.

4. The building is divided into 4 vertical zones:
   - Zone-1: ground floor to the 23rd floor.
   - Zone-2: 25th floor to the 48th floor.
   - Zone-3: 50th floor to the 73rd floor.
   - Zone-4: 75th floor to the 98th floor.
5. Occupancy is 12 m^2/person (Stein, et al., 2006).
6. Occupied floor area was assumed at 90%, which should be 80% total area for the standard condition (Bowyer, 1979), because part of the services components are outside the floor area:
   - 90% x 1600 m^2 x 1 floor = 1,440 m^2 per floor
   - 90% x 1600 m^2 x 23 floors = 33,120 m^2 per zone
   - 90% x 1600 m^2 x 92 floors = 132,480 m^2
7. Number of people:
   - Per zone = 33,120 m^2 / 12 = 2,760 people
   - Total = 132,480 m^2 / 12 = 11,040 people
8. For the design requirement, two parameters were used as follows:
   - 5-minutes Handling Capacities (HC) were determined minimum 12% and maximum 16% (Stein, et al., 2006). Minimum 16.5% HC can be used for the shuttle elevators, by assuming that all occupants are served within 30 minutes at the peak hour.
   - Waiting Intervals (WI) were determined at 25 seconds minimum and 30 seconds maximum for local elevators (Stein, et al., 2006).

"The Vertical Transportation Handbook" by Strakosch (1998) was used for the design guideline. The elevator design follows several concepts, such as:

- Elevators are near the main entrance.
- Distance from elevator to the furthest office is 45 metres and 60 metres maximum.
- A group of elevators should serve the same floors.
- Skipping stops is useful to enhance time efficiency.
- Standard elevators are used as local elevators and high speed elevators for shuttle elevators.

5.3.2. Elevator Systems

Three alternative elevator systems have been designed, and these systems are discussed and compared.

Alternative-1: Single Decking Elevator Systems

The first alternative applies single-decking for local and shuttle elevators using one main lobby and one sky-lobby. From the main lobby, elevators serve 45 upper floors, which are divided into 4 sub-zones:

1. The first sub-zone, elevators go from the ground floor through the 1st and 12th floors.
2. The second sub-zone, elevators go from the ground floor through the 13th and 22nd floors.
3. The third sub-zone, elevators go from the ground floor through the 25th and 36th floors.
4. The fourth sub-zone, elevators go from the ground floor through the 37th and 47th floors.

These sub-zones are also applied for the upper zone served from the sky-lobby.

Several design calculations have been conducted to provide an optimal system. The design calculation of the local elevators is based on the example from the reference (Strakosch, 1998, pp. 79-81) as shown below:

1. Assumed six 16-passenger elevators, 2.5 m/s speed.
2. From Table 5.1, there are 9 probable stops for 16 passenger lift serving 12 upper floors.
3. Floor height per stop = (12 floors x 4 metres) / 9 stops = 5.3 metres.
4. From Table 5.2, time to open and close for centre-opening lifts 1100 mm width is 4.6 seconds.
5. Using interpolation from Table 5.3, time to run up per 5.3 m stop and 2.5 m/s elevator is 4.9 seconds.
6. Time to run down = (4 metres x 12) / 2.5 m/s + 4.9 seconds = 24.13 seconds. The value 12 is the highest served floor. This value would be different for the elevators serving different zones.
7. From Table 5.4, standing time at lobby for 16-passenger elevators is 14 seconds.

8. Upper floor transfer time = 3 seconds/stop x 9 stops = 27 seconds. This value must be compared with 16 seconds (1 second/passenger x 16 passengers). The large value, which is 27 seconds, is used.
9. Door operation (time to open and close) on the upper floor = 4.6 seconds x (9 seconds + 1 lobby) = 46 seconds.
10. Total time spent at floors or inefficiency was assumed 0%.
11. Total round trip time (RTT) is 44.4 + 24.1 + 87 = 155.5 seconds, based on:
    - Run-up time = 9 stops x 4.9 seconds = 44.4 seconds.
    - Run-down time = 24.1 seconds.
    - Total time spent at floors = 14 seconds (standing time) + 27 seconds (upper floor transfer time) + 46 seconds (door operation) = 87 seconds.
12. The 5-minute Handling Capacity (HC) of six elevators = 16 passengers x 300 / 155.5 seconds = 31 people, which is 31 people x 6 elevators / 1440 people per zone = 12.86%.
13. Waiting Interval (WI) = RTT / number of lifts = 155.5 seconds / 6 = 26 seconds.

The HC and WI are within the range of the recommended.

Table 5.1 Probable stops (Strakosch, 1998, p. 74)

Upper Floors Served	Passengers per Trip														
	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30
30	2	4	5.7	7.6	9.5	10.5	11.7	12.8	13.8	14.8	16.0	17.2	18.0	19.0	19.5
28	2	3.9	5.5	7.2	9.0	10.1	11.6	12.5	13.5	14.6	15.6	16.6	17.6	18.1	18.4
26	2	3.8	5.5	7.0	8.5	9.8	11.2	12.2	13.1	14.1	15.1	16.0	16.8	17.4	17.7
24	2	3.8	5.4	6.9	8.3	9.6	10.8	11.9	12.8	13.8	14.6	15.4	16.1	16.7	17.3
22	2	3.7	5.4	6.8	8.2	9.4	10.5	11.6	12.5	13.3	14.1	14.8	15.4	16.0	17.0
20	2	3.7	5.3	6.7	8.0	9.2	10.3	11.2	12.1	12.8	13.5	14.2	14.7	15.3	16.0
18	2	3.7	5.2	6.6	7.8	8.9	9.9	10.8	11.6	12.3	12.9	13.4	13.9	14.4	15.0
16	2	3.6	5.1	6.5	7.6	8.6	9.5	10.3	11.0	11.6	12.1	12.6	13.0	13.4	13.9
14	2	3.6	5.0	6.3	7.3	8.3	9.0	9.7	10.3	10.8	11.3	11.6	12.0	12.2	12.5
12	2	3.5	4.9	6.0	7.0	7.8	8.5	9.0	9.5	9.9	10.2	10.5	10.8	11.0	11.3
10	2	3.4	4.7	5.8	6.5	7.2	7.7	8.2	8.5	8.8	9.0	9.2	9.4	9.5	9.5
8	2	3.3	4.4	5.3	5.9	6.4	6.8	7.0	7.3	7.5	7.6	7.7	7.8	7.8	8
6	2	3.1	4.0	4.6	5.0	5.3	5.5	5.7	5.8	5.8	5.9	5.9	6	6	6
4	2	2.7	3.3	3.6	3.8	3.9	3.9	4	4	4	4	4	4	4	4
2	1.5	2	2	2	2	2	2	2	2	2	2	2	2	2	2

Table 5.2 Door operating time (Strakosch, 1998, p. 76)

Door Type	Width in. (mm)	Open (sec)	Close (sec)	Total[a] (sec)	Transfer Inefficiency[b] (%)
Single-slide	36 (900)	2.5	3.6	6.6	10
Two-speed	36 (900)	2.1	3.3	5.9	10
Center-opening	36 (900)	1.5	2.1	4.1[c]	8
Single-slide	42 (1100)	2.7	3.8	7.0	7
Two-speed	42 (1100)	2.4	3.7	6.6	7
Center-opening	42 (1100)	1.7	2.4	4.6[c]	5
Two-speed	48 (1200)	2.7	4.5	7.7	2
Center-opening	48 (1200)	1.9	2.9	5.3[c]	0
Two-speed	54 (1400)	3.3	5.0	8.8	2
Center-opening	54 (1400)	2.3	3.2	6.0[c]	0
Two-speed	60 (1600)	3.9	5.5	9.9	2
Center-opening	60 (1600)	2.5	3.5	6.5[c]	0
Two-speed, center-opening	60 (1600)	2.5	3.0	6.0[c]	0

[a]Includes 0.5-sec car start.
[b]Transfer inefficiency: Increase normal standing time inefficiency by this percentage to reflect delay in passengers passing through doors.
[c]When preopening can be used, these values can be reduced by 1 sec.

Table 5.3 Running time (Strakosch, 1998, p. 78)

Floor Heights: Feet	9	10	11	12	13	14	15	20	30	Each Additional 10 ft	Notes
Floor Heights: Meters	2.7	3.0	3.35	3.65	4.0	4.3	4.6	6.1	9.1	Each Additional 3 m	
Elevator speed											
100 fpm (0.5 mps)	7.6	8.2	8.8	9.4	10.0	10.6	11.2	14.2	20.2	6.0	a
150 fpm (0.75 mps)	6.7	7.1	7.5	7.9	8.3	8.7	9.1	11.1	15.1	4.0	
200 fpm (1 mps)	5.8	6.1	6.4	6.7	7.0	7.3	7.6	9.1	12.1	3.0	b
300 fpm (1.5 mps)	5.2	5.4	5.6	5.8	6.0	6.2	6.4	7.4	9.4	2.0	
400 fpm (2 mps)	4.8	5.0	5.1	5.2	5.4	5.6	5.7	6.5	7.0	1.5	
500 fpm (2.5 mps)	—	—	4.3	4.4	4.5	4.6	4.7	5.2	6.4	1.2	
700 fpm (3.5 mps)	—	—	4.3	4.4	4.5	4.6	4.7	5.2	6.1	0.86	
1000 fpm (5 mps)	—	—	4.3	4.4	4.5	4.6	4.7	5.2	5.8	0.6	

[a]Speeds of 100 fpm and 150 fpm include 0.75 sec for leveling.
[b]Speeds of 200 fpm and above include 0.5 sec for leveling.

Table 5.4 Transfer time (Strakosch, 1998, p. 75)

Lobby: Minimum 8 sec plus 0.8 sec per passenger over 8 passengers in, in and out, or out only.

Number of Passengers	8	10	12	14	16	18	20
Lobby Time (sec)	8	10	11	13	14	16	18

Car Calls	Dwell-time	3 sec per stop
	Transfer time	Use 3 sec for first two passengers (dwell-time) + 1 sec per passenger over 2 Example: 4 passengers, 1 stop time = 3 + 2 = 5 sec
Landing Calls	Dwell-time	4 sec per stop*
	Transfer time	Use dwell time + 1 sec per passenger over 1 passenger entering Example: 4 passengers, 1 stop time = 4 + 3 = 7 sec

Using the same steps, local elevators at the other sub-zones are as follow:

- Sub-zone-2: six 16-passenger elevators 2.5 m/s serve 10 floors. The HC is 14.23% and WI is 28 seconds.
- Sub-zone-3: seven 16-passenger elevators 3.5 m/s serve 12 floors. The HC is 13.12% and WI is 25 seconds.
- Sub-zone-4: seven 20-passenger elevators 3.5 m/s serve 11 floors. The HC is 15.23% and WI is 30 seconds.

The shuttle elevators were designed using the same steps as follows:

- Twelve 26-passenger elevators with 10 m/s speed commute from the ground floor to the sky lobby at the 50th floor.
- The HC is 17.91% and WI is 8.3 seconds. The waiting interval time is relatively short because the shuttle elevators only stop at the main and sky lobbies.

Alternative-2: Double Decking Elevator Systems – Two Lobbies

The second alternative applies double-decking for local and shuttle elevators using the same system as the first alternative. The double-deck elevators are applied in conjunction with a dual-loading lobby arrangement as shown in Figure 5.8. The local elevators stop on every two floors.

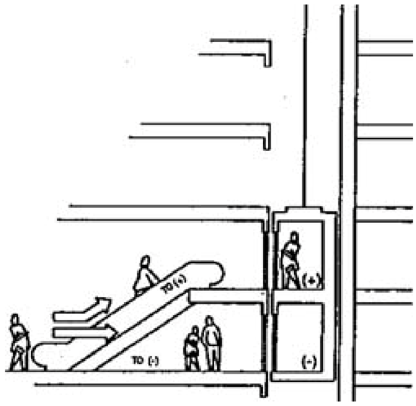


Figure 5.8 A dual-loading lobby and a double-decking elevator (Strakosch, 1998, p. 360)

Using the same steps as those in the first alternative, the assumed inefficiency was 15% for double-deck elevators in terms of consumed time for top and bottom decks ready to depart. Several design calculations have been conducted to get an optimal system and one of those designs has results as follows:

- Sub-zone-1: four double-deck elevators, 2 x 8-passengers and 2.0 m/s, serve 10 floors. The HC is 14.53% and WI is 28 seconds.
- Sub-zone-2: four double-deck elevators, 2 x 10-passengers and 5.0 m/s, serve 10 floors. The HC is 14.75% and WI is 28 seconds.
- Sub-zone-3: five double-deck elevators, 2 x 10-passengers and 3.5 m/s, serve 12 floors. The HC is 15.0% and WI is 28 seconds.
- Sub-zone-4: five double-deck elevators, 2 x 10-passengers and 5.0 m/s, serve 12 floors. The HC is 15.66% and WI is 27 seconds.

The shuttle elevators were designed using the same steps as follows:

- Four double-deck elevators, 2 x 16 passengers 10 m/s speed commute from the ground floor to the sky lobby at the 50th floor.
- The HC is 16.69% and WI is 22 seconds.

Alternative-3: Double Decking Elevator Systems – Four Lobbies

The third alternative applies double-decking for local and shuttle elevators using a different configuration. The building is divided into four main zones that have one main lobby and three sky-lobbies. Local double-deck elevators serve all floors in each zone and stop every two floors.

Several design calculations have been conducted and summarised as follows:

- Local elevators: six double-deck elevators, 2 x 16-passengers and 5 m/s, serve 20 floors. The HC is 14.74% and WI is 27 seconds.
- Shuttle elevators: twelve double-deck elevators, 2 x 10-passengers and 10 m/s, serve the three sky lobbies. The HC is 17.53% and WI is 9 seconds.
- The second alternative for shuttle elevators is six double-deck elevators, 2 x 26-passengers and 10 m/s. The HC is 16.88% and WI is 23 seconds.

Analysis of the Three Elevator System Alternatives

The three elevator systems above are summarised in Table 5.5 and the schematic diagram is shown in Figure 5.9. The second and third alternatives can effectively reduce the number of elevators. The third alternative is preferred when applied in the double-layer space structure building based on the following reasons:

- It requires the least lanes/shafts compared to the other alternatives.
- The elevator cores extend from the base floor to the roof. The continuous core between two layers of the perimeter structure can be used as elevator cores.
- The horizontal double-layer space structures can accommodate lift motor rooms and lift pits.

Table 5.5 Three alternative elevator systems

Alternative-1	**Alternative-2**	**Alternative-3**
2 lobbies	2 lobbies	4 lobbies
Local cars:	Local cars (double-deck):	Local cars (double-deck):
Zone-1: 6 lifts (16 passengers) 2.5 m/s	Zone-1: 4 lifts (2x8 passengers) 2.0 m/s	6 lifts (2x16 passengers) 5.0 m/s
Zone-2: 6 lifts (16 passengers) 2.5 m/s	Zone-2: 4 lifts (2x10 passengers) 5.0 m/s	
Zone-3: 7 lifts (16 passengers) 3.5 m/s	Zone-3: 5 lifts (2x10 passengers) 3.5 m/s	
Zone-4: 7 lifts (20 passengers) 3.5 m/s	Zone-4: 5 lifts (2x10 passengers) 5.0 m/s	
Shuttle cars:	Shuttle cars (double-deck):	Shuttle cars (double-deck):
12 lifts (26 passengers) 10 m/s	4 lifts (2x16 passengers) 10 m/s	12 lifts (2x10 passengers) 10 m/s
Total:	Total:	Total:
26 local cars + 12 shuttle cars	18 local cars (double-deck)+ 4 shuttle cars (double-deck)	6 local cars (double-deck)+ 12 shuttle cars (double-deck)
38 lanes	22 lanes	18 lanes

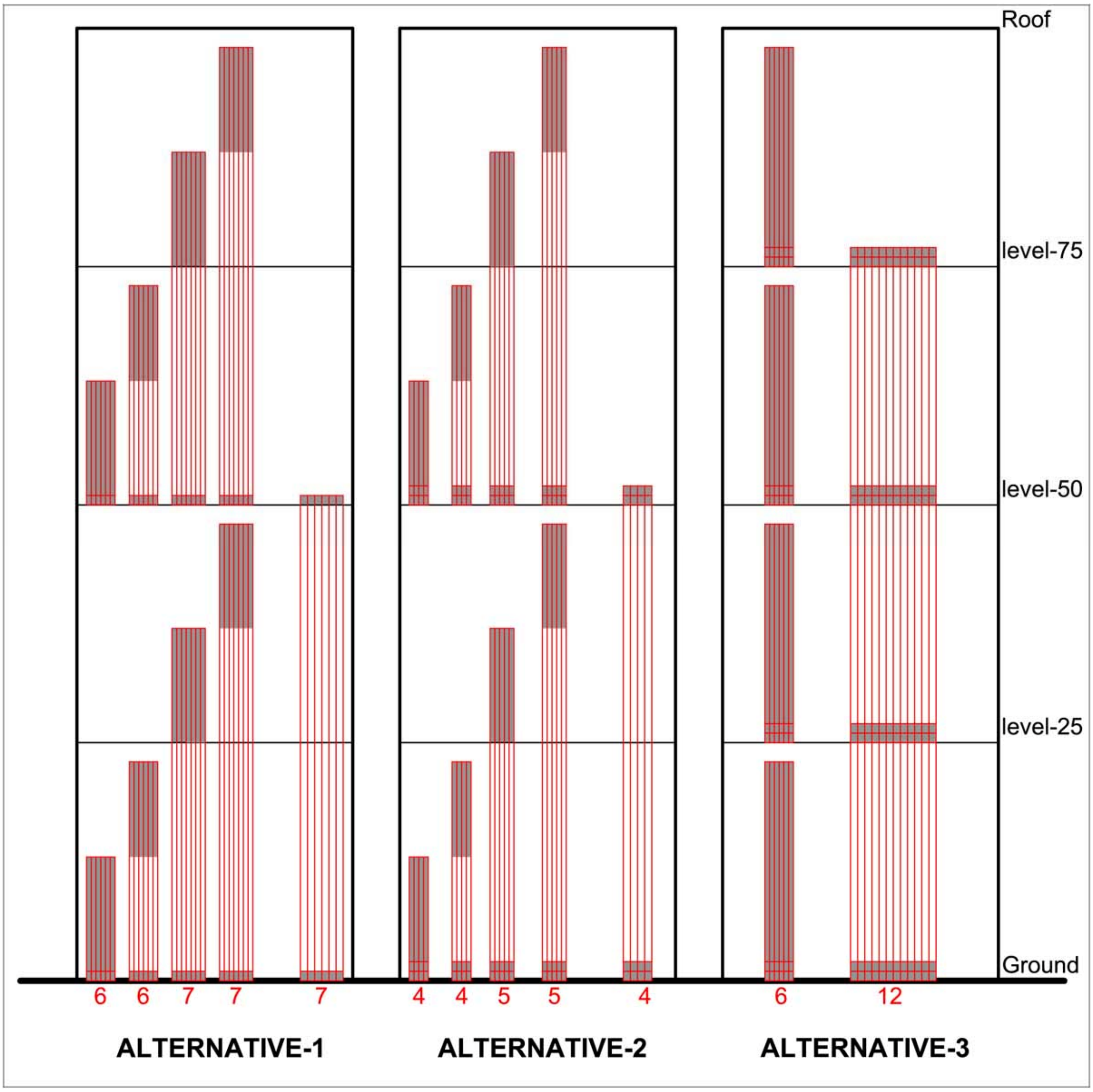


Figure 5.9 Three alternative elevator systems

5.3.3. Elevator Spaces

This section discusses the design of the elevator spaces in the double-layer space structure building by positioning the elevators in both the central core and the cavity of the perimeter structure. The design applies the third elevator system, double-decking with four lobbies, and the calculation follows the examples from the reference (Strakosch, 1998, pp. 175-177) as follows:

1. Local elevators
   - Required area for 16 passengers is 2.9 m^2 from Table 5.6.
   - The inside elevator area was designed W= 2.0 m and D= 1.45 m.

- The clear hoist way is W + (20 in to 24 in) = 2.0 + 0.5 = 2.50 m and D + (25.25 in to 29.25 in) = 1.45 + 0.7 = 2.15 m.

2. Shuttle elevators
   - Required area for 10 passengers is 1.9 m^2 using Table 5.6.
   - The observatory elevators should be specially designed to fit the area provided by the space between two layers of the perimeter vertical structure. Additional space for the hoist-way is 20 in (0.5 m) and 0.7 m for the counterweight.

Table 5.6 Elevator capacity and inside area (Strakosch, 1998, p. 175)

Rated Load (mass) (kg)	Maximum Available Car Area (see note) (m^2)	Maximum Number of Passengers	Rated Load (mass) (kg)	Maximum Available Car area (see note) (m^2)	Maximum Number of Passengers
100	0.40	1	975	2.35	13
180	0.50	2	1000	2.40	13
225	0.70	3	1050	2.50	14
300	0.90	4	1125	2.65	15
375	1.10	5	1200	2.80	16
400	1.17	5	1250	2.90	16
450	1.30	6	1275	2.95	17
525	1.45	7	1350	3.10	18
600	1.60	8	1425	3.25	19
630	1.66	8	1500	3.40	20
675	1.75	9	1600	3.56	21
750	1.90	10	1800	3.88	24
800	2.00	10	2100	4.36	28
825	2.05	11	2500	5.00	33
900	2.20	12			
Beyond 2500 kg, add 0.16 m^2 for each 100 kg extra.					

Figure 5.10 shows the dimensions of local elevators in the centre core, and shuttle elevators integrated with the perimeter structure.

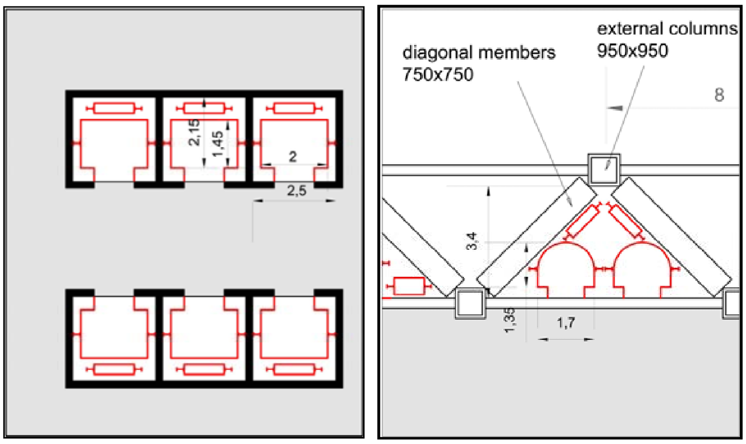


Figure 5.10 (a) Six local double-deck elevators; (b) Two double-deck shuttle elevators in one structural module

5.3.4. Motor Rooms and Pit Spaces

This section discusses whether the motor rooms and the pits of the local elevators can be placed at the plant rooms integrated with the horizontal double-layer space structures. This strategy does not apply to shuttle elevators because the motor rooms are placed on level 77, while the pits are located on the ground floor (see Figure 5.9). Super-tall buildings normally have two-floor deep plant rooms that can sufficiently accommodate the elevator motor room of the lower zone and the elevator pit of the upper zone in one area. This type of arrangement is also applied in the Burj Khalifa, Dubai, shown in Figure 5.11.

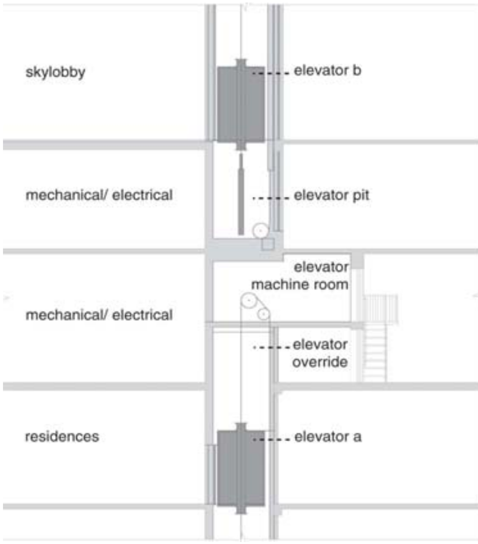


Figure 5.11 The elevator pit and machine room in the Burj Khalifa, Dubai (Weismantle, Smith, & Sheriff, 2007, p. 341)

In the case study of the 100-storey double-layer space structure, the area for the machine rooms and the pits of the local elevators was designed based on (Strakosch, 1998, pp. 183-187):

- The pit depth is 3 metres for 5 m/s elevators.
- Total overhead is 5 metres.
- The machine room height is 3 metres.

Figure 5.12 demonstrates that the elevator motor room and pits can be located in the space between the top and bottom layers of the horizontal space structure in the case study building.

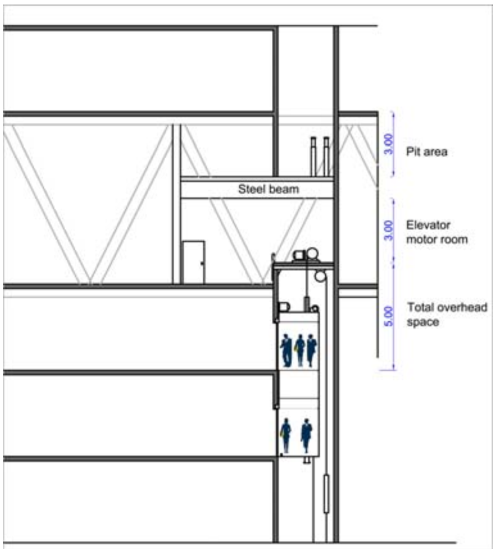


Figure 5.12 The upper zone pit area and the lower zone elevator machine room within the horizontal double-layer space structure

5.3.5. Analysis

Three alternative elevator systems have been compared. The third alternative is the most effective because it optimises advanced elevator technologies consisting of zoning, double-decking, and sky lobby systems. These technologies have been applied in several current super-tall buildings. Table 5.7 shows that super-tall buildings built after the 1960s have applied the sky lobby system and some of these buildings have double-decking elevators.

Table 5.7 Elevator systems of current super-tall buildings (Fortune, 1997, p. 134)

HEIGHT RANK	BUILDING	PASSENGER ELEVATOR DESIGNS			COMMENTS
		SKY LOBBY(S)	SHUTTLES	LOCALS	
7	EMPIRE STATE BUILDING	-	-	SINGLE DECKS	CONVENTIONAL, MULTI-ZONE (6 ZONES) SINGLE-DECK ELEVATORING; HIGH-RISE ZONE FEEDS TOWER/OBSERVATION ELEVATORS
9	BANK OF CHINA TOWER	ONE (43rd)	SINGLE DECKS (1600kg)	SINGLE DECKS	CONVENTIONAL TOP/UP SHUTTLE ELEVATORING
8	CENTRAL PLAZA	ONE (46th)	SINGLE DECKS (2050kg)	SINGLE DECKS	CONVENTIONAL TOP/UP SHUTTLE ELEVATORING
5&6	WORLD TRADE CENTER 1&2	TWO (44th & 78th)	SINGLE DECKS (4500kg)	SINGLE DECKS SINGLE DECKS	CONVENTIONAL TOP/UP SHUTTLE ELEVATORING 2 INTERZONE, SKY LOBBY SHUTTLES SEPARATE SINGLE-DECK OBSERVATION SHUTTLES
4	JIN MAO	ONE (54th)	SINGLE DECKS (1600kg)	SINGLE DECKS SINGLE DECKS	CONVENTION TOP/UP HOTEL SHUTTLE ELEVATORING SEPARATE SINGLE-DECK OBSERVATION SHUTTLES
10	T & C TOWER	TWO (12th & 39th)	SINGLE DECKS (OFFICE 1800kg) (HOTEL 2040kg)	SINGLE DECKS	CONVENTION TOP/UP OFFICE & HOTEL SHUTTLE ELEVATORING SEPARATE SINGLE-DECK OBSERVATION SHUTTLES
3	SEARS TOWER	TWO (33rd & 34th, 66th & 67th)	DOUBLE DECKS (2250kg/2250kg)	SINGLE DECKS	SPLIT-LEVEL TOP/UP SHUTTLE ELEVATORING HIGH ZONE SHUTTLES CAN STOP @ BOTH SKY LOBBIES SEPARATE SINGLE-DECK OBSERVATION SHUTTLES (CONVERTING TO DOUBLE DECKS)
1&2	PETRONAS TOWERS	ONE (41st & 42nd)	DOUBLE DECKS (2100kg/2100kg)	DOUBLE DECKS	SPLIT-LEVEL TOP/UP SHUTTLE ELEVATORING
PLANNING STAGE BUILDINGS					
WOULD BE #4 (435m)	MILLENNIUM TOWER LONDON, ENGLAND	TWO	DOUBLE DECKS (2250kg/2250kg)	DOUBLE DECKS	SPLIT-LEVEL TOP/DOWN SHUTTLE ELEVATORING HIGH ZONE SHUTTLES CAN STOP @ BOTH SKY LOBBIES SEPARATE DOUBLE-DECK OBSERVATION SHUTTLES
WOULD BE #1 (460m)	INTERNATIONAL WORLD FINANCIAL CENTER SHANGHAI, CHINA	ONE	DOUBLE DECKS (1500kg/1500kg)	DOUBLE DECKS	SPLIT-LEVEL TOP/UP SHUTTLE ELEVATORING

The shuttle elevators in this model were designed for 10 m/s speed. This speed is reasonable compared to the suggested 9 m/s speed for elevators for over 60-floor buildings (Strakosch, 1998). The current fastest elevator, with 16 m/s speed, is in Taipei 101 (Eisenstein, 2004). High-speed elevators have a problem with wind noise. Aerodynamic capsules have been used in Taipei 101 to reduce the noise level (Mizuguchi, Nakagawa, & Fujita, 2005). These elevators are also equipped with twin air pressure control systems to reduce the air pressure when the elevators descend (Eisenstein, 2004).

The local elevators are located in the centre core, and shuttle elevators around the building perimeter. The elevator and stairwell positions are shown in Figure 5.13 and discussed as follows:

- At the sky lobbies, large floor areas are used for circulation because the elevators and stairs are positioned in three different locations remote from one another. About 40% of the building perimeter does not have open views because of the shuttle elevators and stairs.

- At the typical floors, the main vertical transportation is in the centre of the floor. Only 10% of areas at the building perimeter are used for stairs and the other areas can obtain natural light. However, the rooms with external walls located at the shuttle elevator lanes will not have an open view due to the regular elevator movement. Frosted glass can be used to allow natural light to penetrate into the interior space.

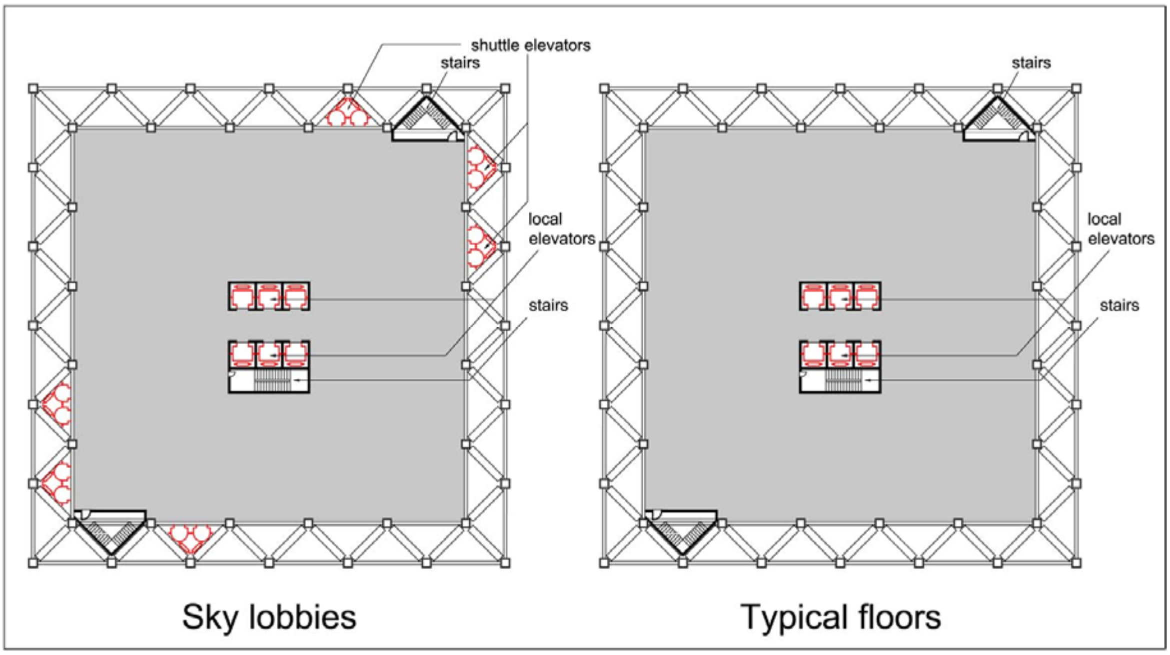


Figure 5.13 Elevators and stairwells at the sky lobbies and typical floors

Figure 5.13 demonstrates an alternative strategy by positioning elevators in three different locations remote from one another. For general applications, this strategy can be applied with some variations by positioning elevators in the cavity of the structure in different locations, which depend on building functions and other requirements. This study has offered a different strategy of positioning elevators than that normally used in general super-tall buildings. This strategy can also be used in general high-rise buildings that have other structural systems, but the elevators will consume some usable floor areas. This condition is different to double-layer space structure buildings, where the cavity of the perimeter structure can be used for elevators.

The integration of the stairs, elevators, and double-layer space structure will be discussed in another section. The stairs and elevators as egress system will be discussed further in Section 5.4.2.

5.4. Fire Safety

As a part of the discussion of structural-services integration, this section investigates the fire safety of double-layer space structure buildings in order to answer the research sub-question in Chapter 3. The discussion, which has been mentioned briefly in Section 3.4, covers fire safety systems, egress, steel protection, and structural stability in fire. The aim is to analyse the potential of a double-layer space structure to integrate with fire safety and egress systems, and investigate its structural characteristics during fire. This research applies qualitative and quantitative approaches to investigate the fire safety aspect.

A qualitative approach was conducted by reviewing fire safety systems applied in recent super-tall buildings, and learning from the collapse of the World Trade Center (WTC), New York, as well as briefly discussing several recommendations from related agencies that investigated the WTC collapse like FEMA (2002) and NIST (2005). The purpose is to test if double-layer space structures can accommodate fire safety and egress systems that have been commonly used in tall and super-tall buildings. The collapse of the WTC and recommendations from related agencies also provide important lessons and advice for improving and enhancing fire safety of the future super-tall buildings. This study tries to adopt the lessons and advice to double-layer space structure super-tall buildings.

A quantitative approach is also used for the analysis of the structural stability during fire. A case study using a structural model of a 100-storey double-layer space structure imitated the damage condition of the WTC New York. This model was analysed using ETABS (*ETABS version 9*, 2005) to see the capacity of each structural member in that condition. The aim is to analyse if the structure can still stand.

Both approaches can be used to investigate the fire safety of double-layer space structures in general high-rise applications by testing the structures with both general and extreme conditions that have been happened in real life.

5.4.1. Fire Safety Systems

The integration of fire safety systems within the double-layer space structure is discussed here. Current fire safety systems that have been commonly used in tall and super-tall buildings are analysed to determine if they can integrate well with double-layer space structures in super-tall buildings. The discussion is not only about integration, but also the redundancy of fire safety systems during a fatal disaster like that of the World Trade Center, New York.

Fire Safety in the World Trade Center

As buildings rise higher, fire protection becomes more difficult and the safety risk is higher. To provide fire safety systems in tall buildings, current fire safety engineering approaches such as providing sprinklers, fire alarms, smoke detectors, and hydrants have developed. The possibility of failed fire safety systems in serious fire and fatal disasters, like in the World Trade Center, has to be minimised.

FEMA (2002) explains that the World Trade Center in New York was equipped by the fire safety systems, such as automatic fire sprinklers, standpipes, smoke sensors, fire alarm, emergency voice, and alarm speakers. The fire safety systems complied with criteria from the local building code in the 1960s. Unfortunately, these fire safety systems were damaged during the fire caused by the aircraft attacks. The piping supplying the water for the automatic sprinklers had been broken, and the water was flowing down the stairwells.

Like typical floors of other tall buildings, the services area of the World Trade Center was located at the building core, which was damaged by the impact of the aircraft. This caused six core columns to be severed and three to be heavily damaged in Tower 1. Ten core columns were severed and one was heavily damaged in Tower 2 (NIST, 2005). Water pipes and other equipment for fire safety systems in the building cores were also damaged, so they did not work during the fire.

Based on this condition, NIST (2005) recommended redundancy of active fire safety systems, such as sprinklers, standpipes/hoses fire alarms, and smoke management systems. These systems are expected to be able to work under severe conditions when a fire is large.

Redundancy of Fire Safety Systems in Double-layer Space Structure Buildings

Fire safety systems have been designed to be integrated within the double-layer space structure, and to still work during severe conditions. Figure 5.14 demonstrates a strategy for positioning fire safety systems, including water storage tanks in the plant rooms and vertical water pipes to supply the storage tanks and the sprinklers, in double-layer space structure buildings. The location of fire safety equipment in the vertical double-layer space structure differs from that in typical high-rise buildings where services are located in a central core. In general applications of high-rise double-layer space structures, the positions of plant rooms and vertical pipes can be varied. However, this case study offers a strategic location, where plant rooms are located at the top floor of the served zones and vertical fire safety pipes are positioned remote from one another, in order to optimise the redundancy of fire safety systems as discussed below.

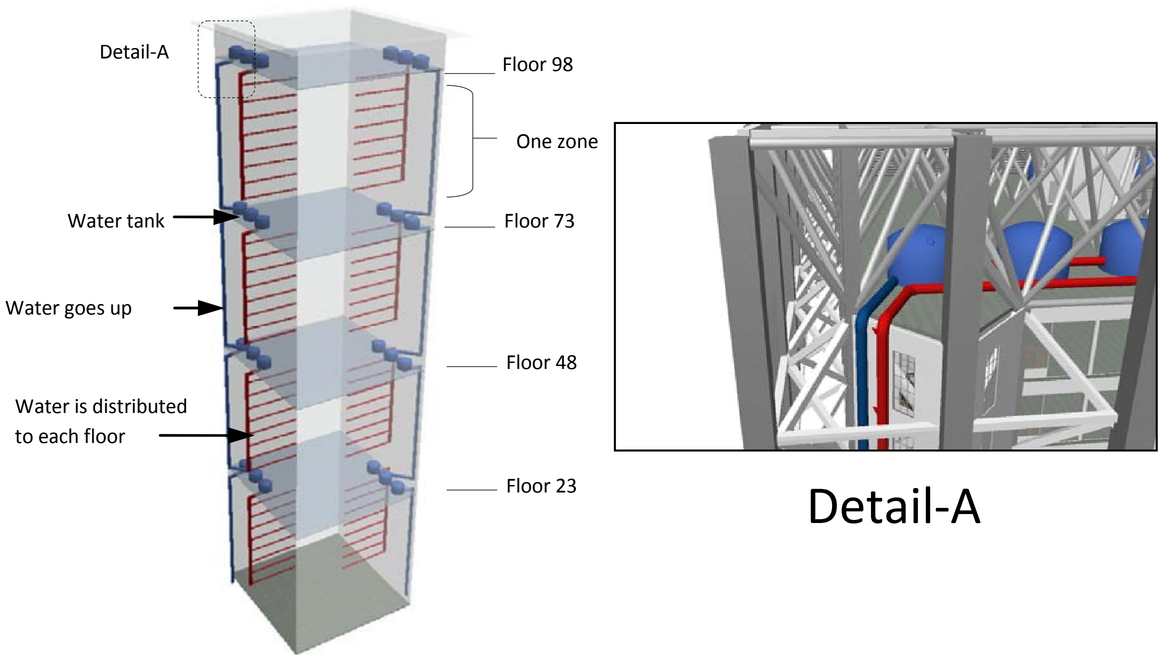


Figure 5.14 Schematic diagram of the water distribution for fire safety and Detail-A showing the water storage tanks and the vertical water pipes within the structure

As mentioned in Section 5.1.1, plant rooms are proposed within the horizontal double-layer space structures at four different levels, floors 23, 48, 73, and 98. These plant rooms accommodate water storage tanks and water pumps for sprinklers and fire hydrants. Water is pumped to the storage tanks on floor 23. From this level, water is then pumped to the storage tanks on floor 48. This process continues up to the storage tanks on floor 98 as shown in Figure 5.14. In terms of fire safety systems, the plant rooms are located on strategic floors because water storage tanks in each plant room serve sprinklers at the zone of the lower floors using gravity pressure.

Water pipes have two vertical points of access to supply the water storage tanks in each plant room. From the plant room, water is distributed down to each floor through two separated lanes. These access points, which pass through the perimeter structure, are located far apart from each other as shown in Figure 5.14. It is unlikely that both main pipes could be damaged at the same time; this strategy is totally different to that applied in the WTC New York, where the fire safety systems did not work during the fire because they were located together at the building core (FEMA, 2002).

In conclusion, the strategic position of fire safety systems in double-layer space structures buildings as demonstrated in this case study is a strategy for the redundancy of fire safety systems in general applications of super-tall double-layer space structure buildings to fulfil the recommendation from NIST (2005).

5.4.2. Egress

This section discusses how to integrate egresses with double-layer space structures in super-tall buildings and how to maintain the egresses for a total evacuation. Egresses in high-rise buildings are reviewed. This review leads to an analysis using a case study to test if double-layer space structures buildings can accommodate egresses and possibly offer better strategies for egresses. Strategies in this case study are presented as guidance for designing egresses in multi-storey double-layer space structures in general applications.

Egress in High-rise Buildings

As buildings get taller, partial and especially total evacuations take longer. Evacuation systems in high-rise buildings including stairs, elevators, and refuge floors have developed over the years.

Stairs as a conventional egress system are still commonly used for tall buildings because elevators are often unsafe during fire and are usually used for the fire-fighting operation.

In tall buildings, emergency stairs become ineffective in terms of evacuation time because of people's fatigue, especially in a total evacuation. Elevators, which have been commonly used for fire-fighting access in buildings during fire, have been recently proposed as a more sophisticated evacuation system (Lay, 2008).

Another evacuation system that has been recently developed for tall buildings is refuge floors. Refuge floors are very important for occupants to have a temporary rest while they wait for a rescue in terms of the long journey going down out of the building. Refuge floors have been used in recent super-tall buildings, such as the Jin Mao Building, the Petronas Towers, John Hancock, and the Burj Khalifa. A relatively old building like the Willis Tower does not provide refuge floors for evacuation (Evenson & Vanney, 2008). High-rise buildings exceeding 25 storeys in height have recently been required to provide refuge floors by the Hong-Kong local government (Chow & Chow, 2009). Bukowski (2008) has recommended that refuge floors should be provided every 20 to 25 floors, and they could be on mechanical floors.

Egress in Existing Super-tall Buildings

In typical high-rise buildings, stairs and elevators are usually located in the building centre. In 1981 the Council on Tall Buildings and Urban Habitat (CTBUH) recommended that strategic locations for cores should be in the building centre for structural and mechanical needs (Codella, Henn, & Moser, 1981). This has been applied in many existing super-tall buildings, especially those built before the collapse of the World Trade Center, New York.

The John Hancock Center and the the Willis Tower, both in Chicago, were constructed in the 1970s. These buildings have cores for egress in the building centre. Figure 5.15 (a) shows how the John Hancock Center has three stairs and several elevators located in the middle of the building. The Willis Tower has four stairs in two different locations that are far apart. As a bundled-tube system is applied in this building, the stairs and elevators are located in 5 of the total 9 tubes as shown in the ground floor plan in Figure 5.15 (b). The number of stairs and elevators decrease as the number of tubes decrease for the upper floors.

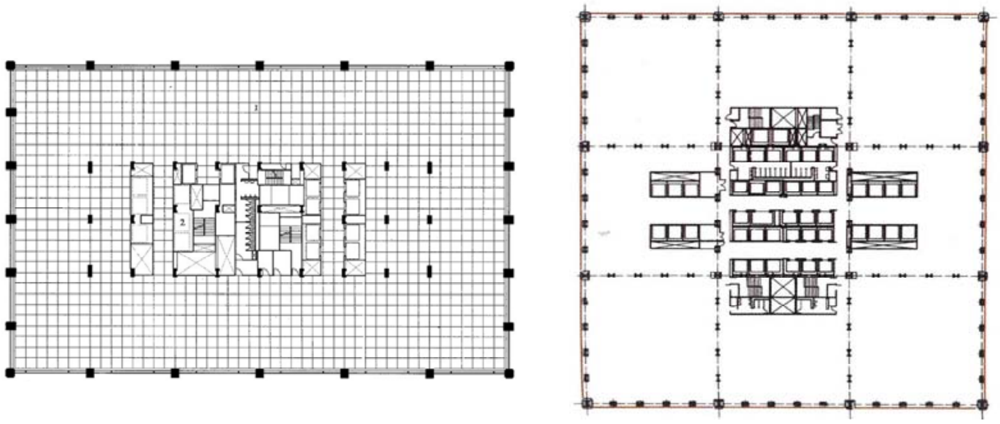


Figure 5.15 (a) Ground floor plan of John Hancock Center, Chicago; (b) Ground floor plan of the Willis Tower, Chicago (Binder & CTBUH, 2006, p. 32)

The Petronas Towers in Kuala Lumpur, Malaysia, were completed in 2004. Figure 5.16 (a) shows three stairwells at each tower, two located in the middle core and the third in the extended round area serving floors 43 and below. The twin towers are linked together by a sky-bridge. After the collapse of the World Trade Center in New York, evacuation procedures were developed for minor and major event cases. The egress in the Petronas Towers consists of stairs, shuttle lifts, and the sky-bridge (Ariff, 2003).

Another super-tall building, the Taipei World Financial Center, also known as Taipei 101, has stairwells and elevators in the middle core (Figure 5.16 (b)).

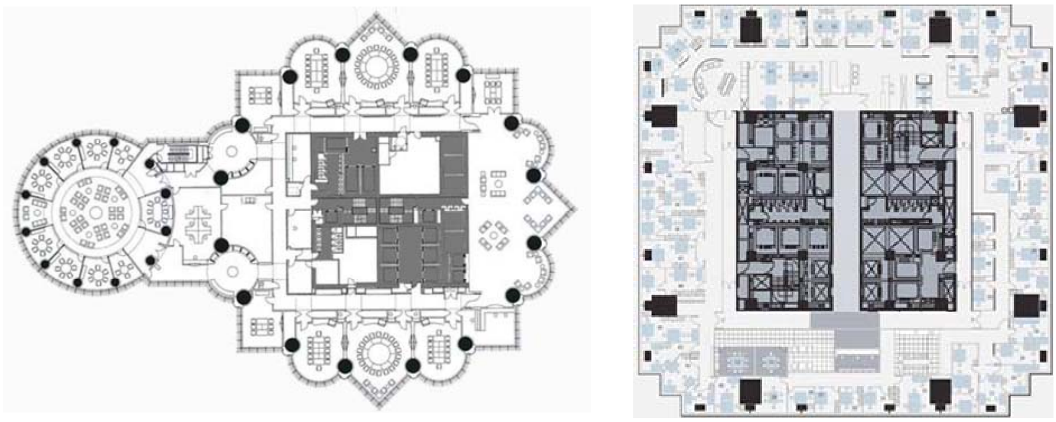


Figure 5.16 (a) Ground floor plan of the Petronas Tower, Kuala Lumpur (Pelli & Crosbie, 2001, p. 90); (b) Ground floor plan of the Taipei World Financial Center, Taipei ("Taipei 101," 2011)

These examples show that the location for building services and vertical transportation, which is normally used for building egress, in the typical floors of super-tall buildings is at the building centre. As a result, the stairs and elevators are located close to each other.

After the collapse of the World Trade Center, this layout has been reviewed. For example, Lorenz (2006) recommends that stairwells should be located farther apart. The Shanghai World Financial Center, which was completed in 2008, has egress at the building core. After the September 11 tragedy, the designers put more attention to building safety and added a third fire stair as well as corner elevators at two different locations (Chen, 2009). Figure 5.17 shows the egress on the 7th and 77th floors, such an egress layout would have been helpful for total evacuation from buildings like the World Trade Center that is discussed further in the following section.

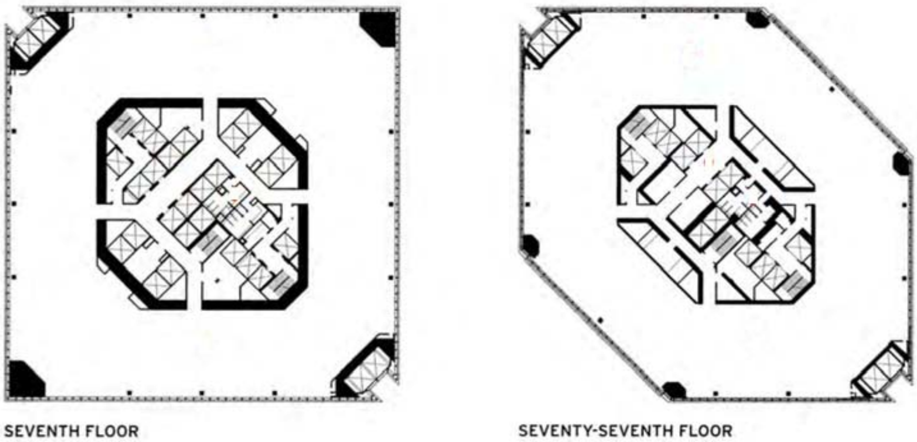


Figure 5.17 (a) The 7th floor plan of Shanghai World Financial Center, Shanghai (Chen, 2009, p. 186); (b) The 77th floor of the building (Chen, 2009, p. 186)

Egress in the World Trade Center

The following discussion about egress in the World Trade Center, New York, is summarised from the NIST final report on the collapse of the Twin Towers (NIST, 2005).

Egress in the World Trade Center was provided by stairwells and elevators in the central core. Three stairwells extended to nearly the full height of the tower (Figure 5.18). The stairwells at upper floors did not descend continuously to the lobby, but rather to horizontal corridors and then to other stairwells beneath.

Evacuations in WTC 1 and 2 had different conditions and timings. In WTC 1 the aircraft caused damage over half the width of the building on 6 floors from 93rd floor to 99th floor. The evacuation took more than one and a half hours. People who were on or above the 92nd floor could not be rescued. The aircraft had destroyed all egress paths downward. A door to the roof could not be opened and helicopters could not land on the roof because of the smoke.

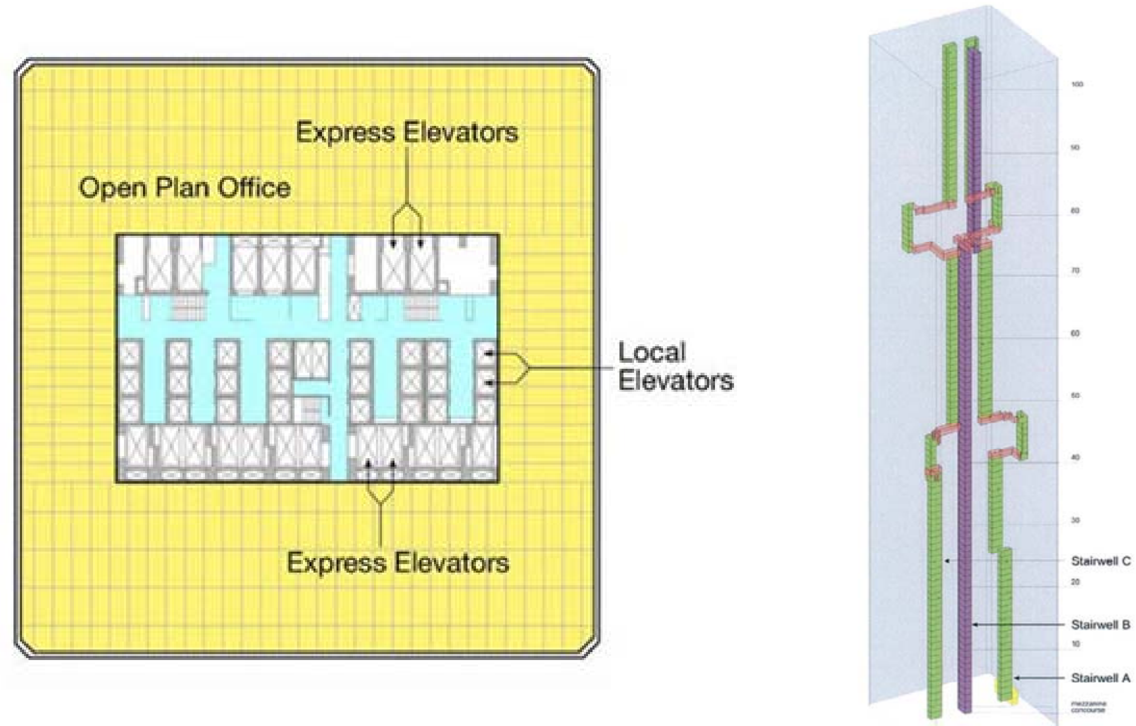


Figure 5.18 (a) The typical floor of the WTC (Source: Wikimedia.org); (b) The schematic diagram of the stairwells in the towers (NIST, 2005)

In WTC 2, some occupants had moved down before the aircraft attack. About one-sixth used the elevators and the remainder divided themselves among the three stairwells. After the aircraft attack, a quarter of those on or above the impact floors could not be rescued. Some of them could not find the egress routes.

This information shows that stairwells and elevators in the World Trade Center provided enough egress paths for total evacuation. However, when the egresses were cut, evacuation of the people above was impossible.

Continuous stairwells from the top floor to the ground floor are better than stairwells connected by horizontal routes like those in the World Trade Center (NIST, 2005). This avoids confusing people who can panic during fire.

Egress in Double-layer Space Structure Buildings

Egresses in the vertical double-layer space structure building can be designed using a different strategy than those normally used in existing super-tall buildings. Several modules of the perimeter structure with space between the external and internal vertical members can be integrated with building services systems including the fire escape stairs. As a result, the egress system consisting of stairwells and elevators can be located in three different locations far apart from each other as shown in Figure 5.48 and discussed in Section 5.8. This has benefits as follows:

- The occupants have more than one route of egress when the fire occurs in a certain location.
- In a case of a fatal condition like an aircraft destroying one vertical egress, at least one other vertical lane is expected to still remain open for total evacuation.

The stairwells extend continuously from the ground to the top floor. This condition helps people get accustomed to using the stairwells because they are at the same location on every floor. In addition, when people panic, it is not difficult to find the exit because they have used the stairwells many times. For visitors, inductions explaining the evacuation routes would be easily understood.

There are two types of elevators in the vertical double-layer space structure buildings, local and shuttle elevators. The local elevators are located at the building centre, while the shuttle elevators are at the building perimeter. The local elevators go to each floor in one zone, but shuttle elevators stop at the main and sky lobbies only. This makes the occupants descend by the local elevators to the closest sky lobby, and then continue to the main lobby by shuttle elevators. The plant rooms, which are located under the sky lobbies, can be used as refuge floors for the occupants to have a temporary rest in terms of the long journey going down out of the building (Bukowski, 2008).

A scenario of a fire occurring in two floors of the double-layer space structure building is shown in Figure 5.19. Since the shuttle elevators do not have landing doors at each floor, it is safe to evacuate the occupants above the fire floors. The occupants can go up to the upper sky lobby through fire stairs, but those who are below the fire floors can go down to the lower sky lobby through fire stairs, and then go down to the ground floor by the shuttle elevators. The local elevators in the zone of fire should not be used to avoid fire spread to the elevators. In terms of the fire-fighting operation, one elevator and one stair can be dedicated for fire-fighter access. A building safety management system is needed to control egress for evacuation and access for fire-fighters.

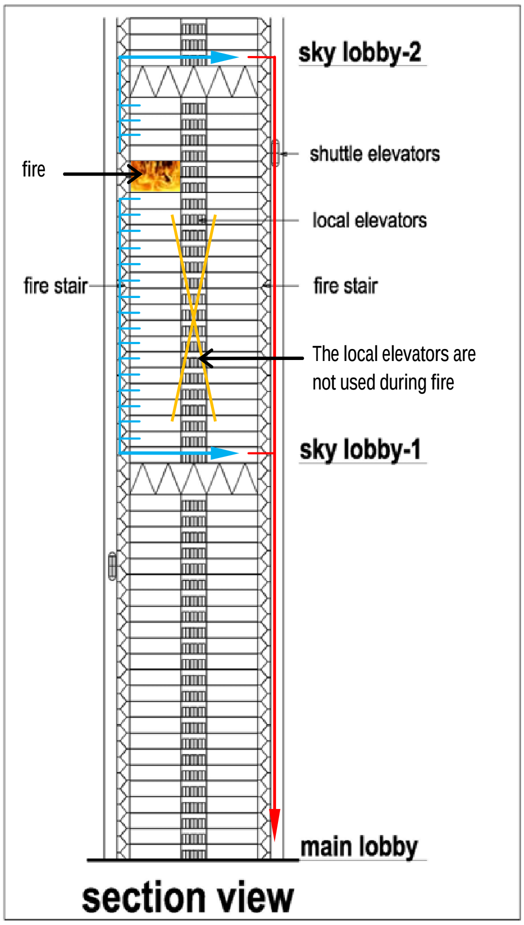


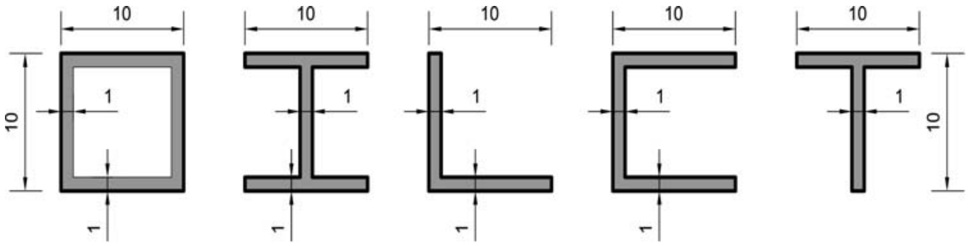
Figure 5.19 An evacuation scheme in the double-layer space structure building

5.4.3. Steel Protection against Fire

Steel structures are very susceptible in fire. Steel double-layer space structures have to be fully fire protected. Buchanan (2001) notes that the section factor H_p/A has an impact on the temperature rate, where H_p is heated perimeter and A is the cross section area. This section discusses briefly current fire protection methods that could be used in steel double-layer space structures. It also analyses H_p/A values of various steel profiles in order to obtain the most suitable profile that requires less fire protection. This analysis can be used for general multi-storey double-layer space structures.

Table 5.8 compares H_p/A values of different structural sections where thicknesses are assumed as width/10. Compared to other structural section, such as I, L, C and T sections, box sections have the least H_p/A values. Since steel structures have to be protected, box or tube profiles are suitable for double-layer space structures. The two main reasons are lesser H_p/A values for fire protection and less possibility for buckling. Several methods can be used to protect steel double-layer space structures, such as: concrete encasement, board systems, spray-on systems, concrete filling, and water filling (Buchanan, 2001a).

Table 5.8 H_p/A ratios of five different steel profiles



Section	Box	I	L	C	T
H_p	40	58	40	58	40
A	36	28	19	28	19
H_p/A	1.11	2.07	2.11	2.07	2.11

This analysis shows that box sections are the most efficient profiles among various profiles normally used in steel construction, because of fewer surfaces for fire protection and less possibility for buckling. The result of this analysis can be used to determine the efficient structural member profiles for double-layer space structures from fire protection perspective. These structural profiles are also discussed in Chapter 7 in from construction perspective. This result is applicable generally for vertical double-layer space structures.

5.4.4. Fire in the Double-skin Facade

Section 5.5.2 discusses several approaches to energy efficiency including the potential of a double-skin façade for the double-layer space structure. This section analyses the effect of fire on double-skin façade in double-layer space structure buildings and how to cover it. This is because double-skin façade can be a media for heat and smoke transfer, which can endanger the building occupants.

The space within the double-skin façade allows heat and smoke to transfer from a fire source vertically and horizontally to other rooms that have openings connected to it. A study on smoke movement in a double-skin façade using various cavity depths has shown its effect on glass damage (Chow & Hung, 2006; Chow, Hung, Gao, Zou, & Dong, 2007). Several techniques to minimise this problem are discussed below:

- A heat and smoke management system has an important role to control the heat and smoke in emergencies. A study on smoke control and natural ventilation in a double-skin façade has shown that smoke spread can be prevented with a suitable arrangement of openings. Natural ventilation and smoke control rely on the stack effect in the cavity. Heat and smoke is exhausted from the top opening and fresh air is taken from an atrium on the other side of the rooms (Ding & Hasemi, 2006). This system can also be applied in the double-layer space structure building. Fans can also be installed at inlet and outlet openings to quickly release the smoke from the cavity during fire as shown in Figure 5.21 .
- When fire occurs in a part of the perimeter structure, it can easily spread to the upper and lower floors through the cavity. Vertical or horizontal sprinklers, known as drenchers, can be placed in the space between the two layers to douse the fire (Figure 5.21).

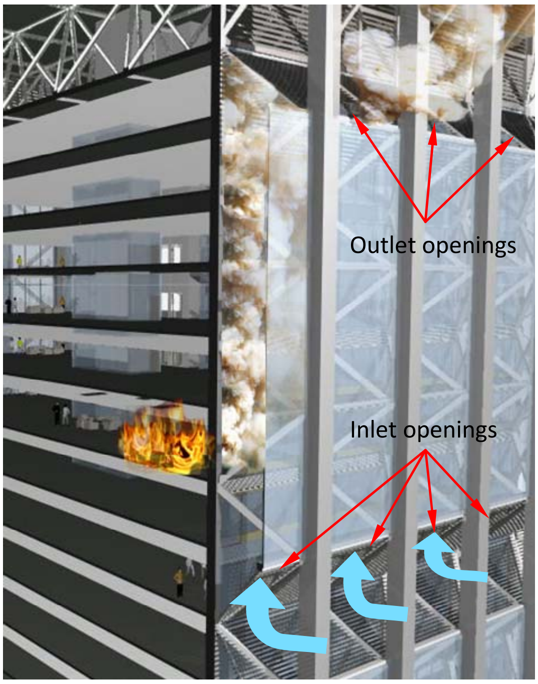


Figure 5.20 A scheme of the heat and smoke control in the double-layer space structure building

Figure 5.21 Sprinklers in the space between the two layers

These techniques have been presented as a strategy to minimise the effect of fire in double-layer space structure buildings that use double-skin façades. This strategy can be applied generally to double-skin façades of double-layer space structure buildings.

5.4.5. Structural Stability in Fire

In order to answer the research sub-question explained in Section 3.3, this section investigates the stability of double-layer space structures under fire or under fatal attack damaging several main structural members. This investigation begins with reviewing structural stability in current super-tall buildings and the collapse of the World Trade Center, New York, as well as NIST recommendations for increasing structural integrity. Based on this review, a case study is conducted using structural model with a scenario imitating the damaged condition of the WTC New York.

NIST recommends increasing structural integrity, preventing conditions that could result in progressive collapse of tall buildings. An important note from NIST (NIST, 2005, p. 206) mentions that “Progressive collapse should be prevented in buildings. The primary structural systems should provide alternate paths for carrying loads in case certain components fail”.

A case study model using a scenario imitating the damaged condition of the WTC New York is analysed using ETABS (*ETABS version 9*, 2005) to see the capacity of each structural member in that condition. The aim is to analyse if the structural system meets the NIST recommendation. The finding in this case study shows the stability of double-layer space structures in general and extreme conditions that have been happened in real life. Therefore, it can be applied for general super-tall double-layer space structure buildings.

Structural Stability in Super-tall Buildings

Structural systems of recent super-tall buildings are relatively efficient. For example, the World Trade Center, New York, used a framed-tube system (Gunel & Ilgin, 2006). However, when several structural members were heavily damaged, the main structure could not survive. NIST (2005) reports that sagging of the floor structure at the position of the aircraft impact caused pull-in forces on several perimeter columns that bowed the columns which had a reduced capacity to carry loads. Figure 5.22 shows the sequence of the structure collapse (Usmani, Chung, & Torero, 2003). The framed tube relied on a collaboration of the perimeter structure, the core structure and the floor system. Failure of one element weakened the whole structure. As a result, a progressive collapse could not be avoided.

Another example of structural redundancy is in the structural design of the 492-meter Shanghai World Financial Center. The structure consists of large perimeter columns, concrete shear walls, diagonal members, and belt trusses (Katz, Robertson, & See, 2008). Leslie E. Robertson, structural designer of this building and the World Trade Center, mentions that the structure was designed to remain stable in the condition where several structural members, which could be small perimeter columns, perimeter belt truss members, and service core members, are destroyed (Robertson & See, 2007).

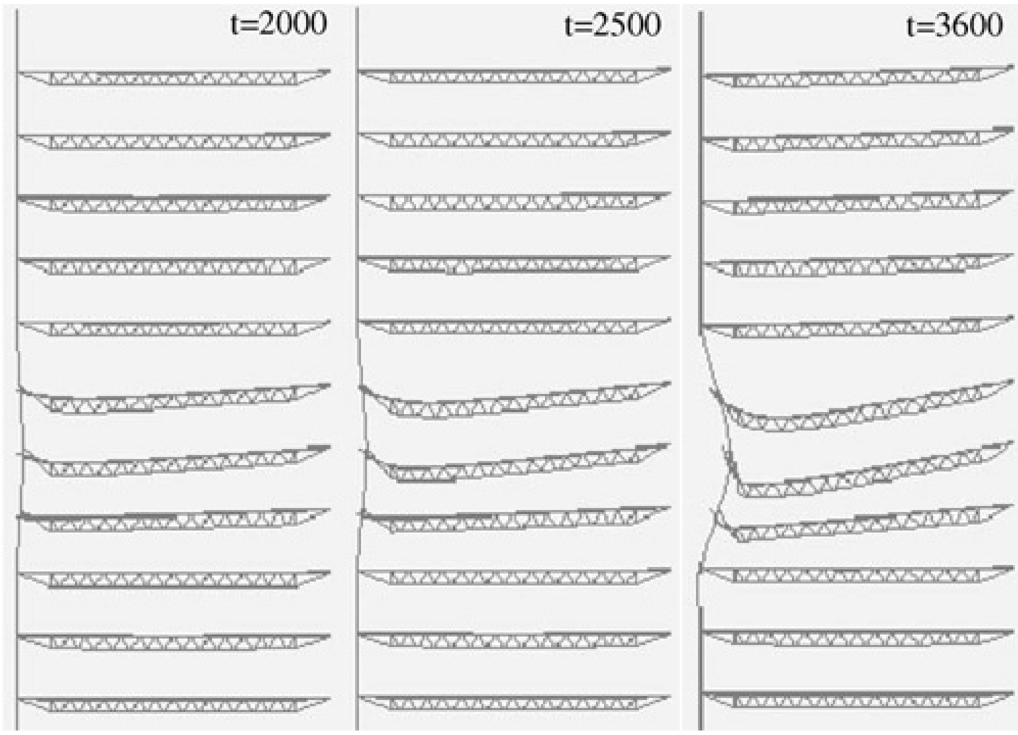


Figure 5.22 The sequence of the floor collapse pulling-in the perimeter columns in different time periods (Usmani, Chung, & Torero, 2003, p. 523)

Structural Stability in Double-layer Space Structure Buildings

The vertical double-layer space structure is a free standing structure. The structure can stand alone without being braced by the floor system. This is in contrast to the World Trade Center and other structural systems where bracing from the floors is necessary to prevent buckling of the columns. In the World Trade Center, relatively light-weight trusses susceptible to fire supported the floors.

Connecting the vertical perimeter structure with the horizontal double-layer space structure makes the structure even more stable. Figure 5.23 shows a case when several structural members of the perimeter structure fail. The structure has been analysed using ETABS (*ETABS version 9*, 2005). The result shows that the demand/capacity ratios of the other structural members are less than one. This means that the vertical double-layer space structure is still stable when several structural members fail in this case study. This is because the gravity and lateral loads working in the perimeter structure are transferred through the diagonal members to other structural members nearby because redundancy.

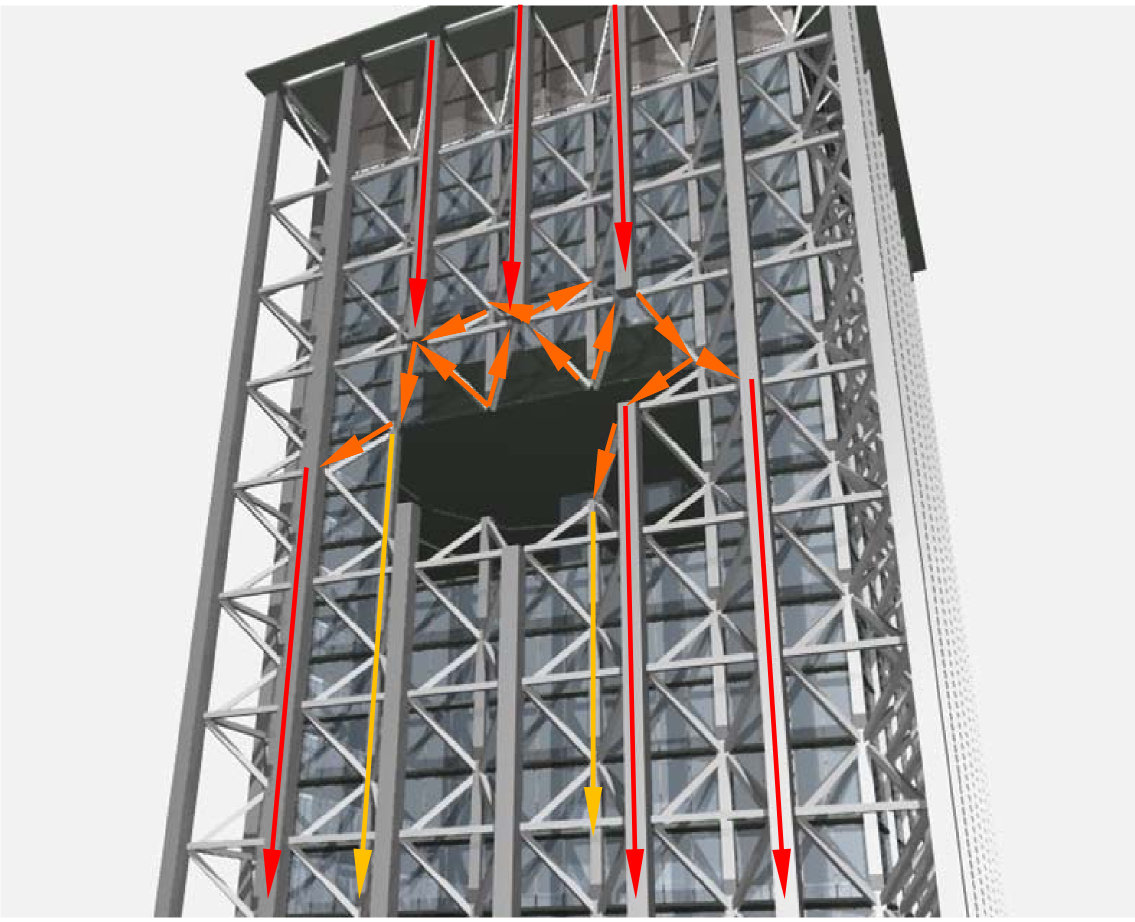


Figure 5.23 The loads in the perimeter structure are transferred through the other members to the ground when several members are damaged

Figure 5.24 shows another case when two floors collapse. The perimeter structure is still able to stand up because it is a free-standing structure. The internal gravity columns can be designed continuously extended from the ground floor or lower horizontal double-layer space structure to the upper one. The purpose is to avoid a progressive collapse of the gravity system. In case the gravity columns in several floors collapse, columns on the upper floor would hang from the upper horizontal double-layer space structure, while those in the lower floor are expected to still remain. Figure 5.24 also shows the gravity loads of the upper collapsed floors are transferred up to the upper horizontal double layer space structure and those of the lower collapsed floors go down to the foundation or the lower horizontal double-layer space structure. However, since the vertical double-layer space structure is a steel structure, fire protection is necessary.

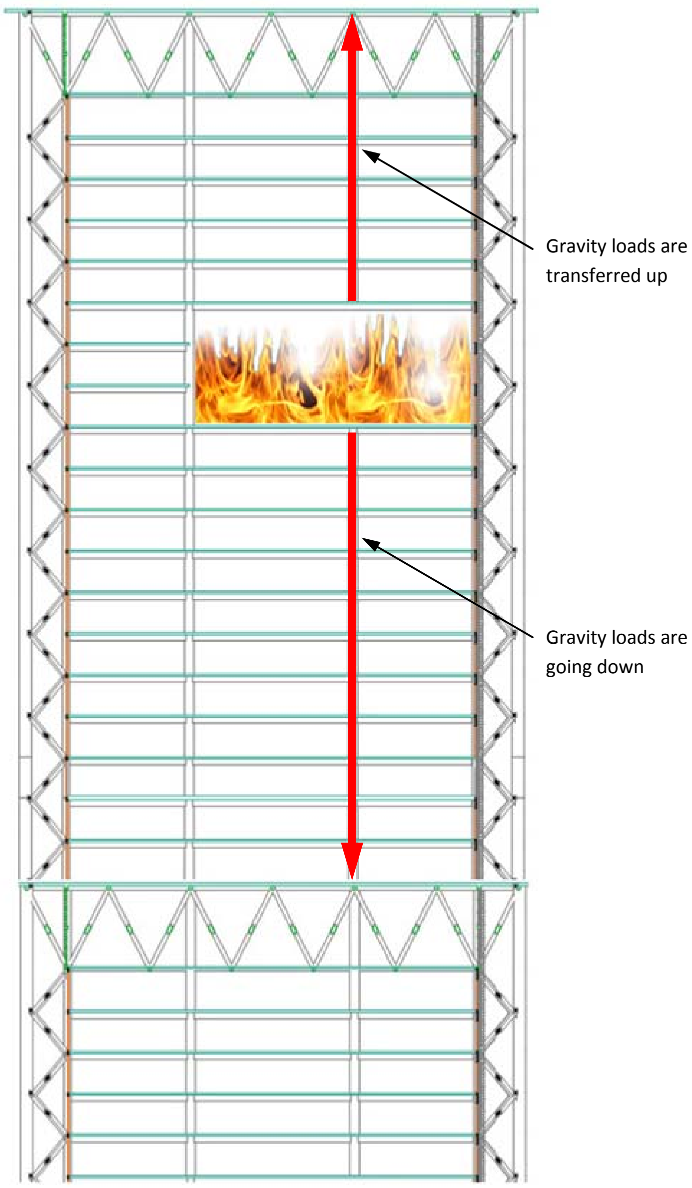


Figure 5.24 A scenario when two floors collapse. Gravity loads are transferred to the upper and lower horizontal double-layer space structures

The findings of this analysis can be used for double-layer space structures in general high-rise applications because the case study is based on general and the most extreme conditions that have happened in real life.

5.4.6. Discussion

Double-layer space structure buildings provide opportunities for integrated fire safety and egress systems as well as ensuring structural stability in the event of localised failure. Compared to typical high-rise buildings that use different structural systems and normally have fire safety and egress systems in the central core, systems integration in high-rise double-layer space structures provides several advantages that can be summarised as follows:

- The geometry of a vertical double-layer space structure enables structural integration with fire safety and evacuation systems by providing strategic positions for fire safety, which is improvement for existing super-tall buildings.
- Positioning fire safety systems within the perimeter structure at two different locations, far apart from each other, enable one system to work when the other fails.
- Locating egress into three different locations that are far apart minimises the possibility of occupants being trapped by fire. In the case of an aircraft attack, at least one egress still remains. All three egresses can only fail when the whole structure collapses.
- As three-dimensional structures, double-layer space structures are free standing structures that can stand alone without being braced by floors. Their loads can be transferred through other structural components to the ground in the event several structural members collapsing.

The findings of this study including the summarised advantages are applied generally to multi-storey double-layer space structures.

5.5. Energy Efficiency

This section discusses approaches to energy efficiency by looking at the inherent capability of double-layer space structures and their integration with other building systems as mentioned briefly in Section 3.4. The purpose is to analyse if this structural system can be compatible with energy efficient design concept to be found in the current literature. The discussion begins with common perceptions about the sustainability of tall buildings and several approaches to the sustainability of tall structures in general. Based on this discussion, several approaches to energy efficiency are explored by integrating double-layer space structures with several devices explained further in Section 5.5.2. Using various case studies, computer models show several examples of possible energy efficiency approaches in double-layer space structures for general high-rise applications.

5.5.1. Energy Efficient Double-layer Space Structure Buildings

This section discusses the inherent capability of vertical double-layer space structures to approach energy conservation in super-tall buildings. The discussion is based on common perceptions about sustainability of tall buildings in the current literature.

Literature indicates that people have different opinions about energy efficiency in tall buildings. For example, tall buildings have been perceived to be inefficient in terms of energy consumption (Elnimeiri & Gupta, 2008). This is because of the large amount of natural resources used in the construction as well as the operational energy consumed. Tall buildings also require large quantities of mechanical equipment, such as elevators, pumps, pipes and ducts, which also consume significant energy. However, other people argue that tall buildings can also achieve a degree of energy conservation by optimisation of limited land resources (Ali & Armstrong, 2006).

Another opinion by Elnimeiri (2008) states that sustainability of tall structures can be enhanced by developing several strategies, such as:

- New efficient structural systems in order to reduce structural weight by developing new structural materials and advance constructability.
- Structural geometries that integrate with architectural building forms.
- Structural materials that can be recycled or reinstalled.
- Energy conservation strategies by enhancing thermal performance of building envelopes, designing exposed structures for sun shading, atriums for the use of solar/wind spaces, and installation of wind turbines.

These strategies lead to a discussion about the inherent capability of vertical double-layer space structures to approach energy efficiency in super-tall buildings as follows:

- Efficient structures

  Chapter 4 shows the material efficiency of double-layer space structures when compared to current tall structural systems (diagrid, bundled-tube, and braced-tube). It has a significant effect on overall structural costs.

- Recycled materials

  Steel is suitable for vertical double-layer space structures because of its strength, ductility, and lesser weight where compared to reinforced concrete. Steel also provides constructional benefits, such as improved construction speed and relatively easy installation compared to in-situ concrete construction. When steel buildings are demolished, waste materials can be minimised because steel can reused or recycled. Recycled steel is used in Taipei 101 and Random House Tower in New York (Tamboli, Joseph, Vadnere, & Xu, 2008).

- Structural expression

  Chapter 6 shows various façade alternatives by integrating façades with the perimeter structure. This integration optimises vertical double-layer space structures to perform structurally and architecturally. As a result, decorative elements and non-functional materials can be minimised.

- Sun shading

  Chapter 6 discussed several alternatives for exposing the structural members of double-layer space structures. This enables sun shading by the existence of the structural members at the external layer. Therefore the cooling load of the building can be minimised.

5.5.2. Approaches to Energy Efficiency

This section discusses how to integrate double-layer space structure with several devices using current technologies in order to approach energy efficiency. The purpose is to analyse if current technologies that have been developed for the purpose of energy efficiency can be accommodated by the structural system. The discussion covers four systems including sun shading devices, double-skin façades, wind turbines, and Building-Integrated Photovoltaics (BIPV); these systems are found from a literature study and presented as an example of energy efficiency approaches using current technologies.

Sun Shading Devices

Tall buildings normally have glazed façades to allow natural light. However, when direct sunlight penetrates the buildings, solar radiation increases the internal temperature. As a result, ventilating and air conditioning systems consume more energy to achieve thermal comfort. Sun shading devices like louvers and integrated sunshades are commonly used to reduce direct sunshine penetrating the buildings in order to minimise energy consumed for cooling.

An application of a louver system can be seen in Durr Systems Stuttgart (Feireiss, 2003). Figure 5.25 (a) shows the façade when the louvers are pulled-up; in Figure 5.25 (b) the louvers are totally covering the façade. A motorised louver system is also used in Nikken Sekkei Building in Tokyo (Baird, 2010), as shown in Figure 5.26 (a) and (b).

Figure 5.25 (a) The louvers are pulled-up (Feireiss, 2003, p. 64); (b) Deployed louvers in the Durr Systems Stuttgart (Feireiss, 2003, p. 70)

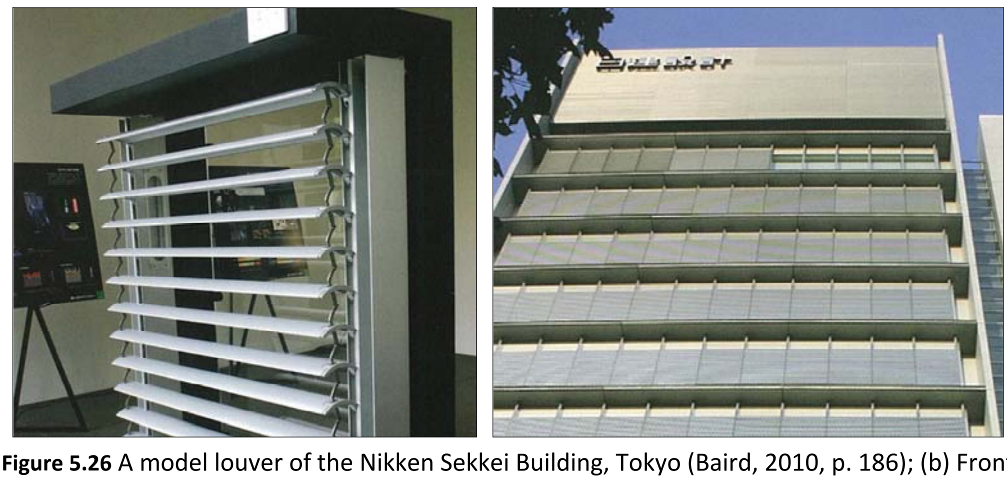


Figure 5.26 A model louver of the Nikken Sekkei Building, Tokyo (Baird, 2010, p. 186); (b) Front view of the building (Baird, 2010, p. 185)

An example of sunshades integrated with the façade can be seen in the Sinosteel International Plaza, Tianjin, China. It has a unique façade system whose irregular honeycomb patterns are designed to achieve energy efficiency by mapping the different air flows and solar path across the site (Welch & Iomholt, 2010). The façade also performs as the building structure (Figure 5.27 (a) and (b)).

Figure 5.27 (a) Irregular honeycomb patterns in the façade of the Sinosteel International Plaza in Tianjing (Welch & Iomholt, 2010); (b) Shading inside the building caused by the façade pattern (Welch & Iomholt, 2010)

In double-layer space structure buildings, a design of sun shading is naturally performed by the external layer of the structural elements. The shade areas vary for different floors because of differing structural element sizes. Figure 5.28 shows less shade at the upper floors from the smaller structural components compared to those at the lower floors.

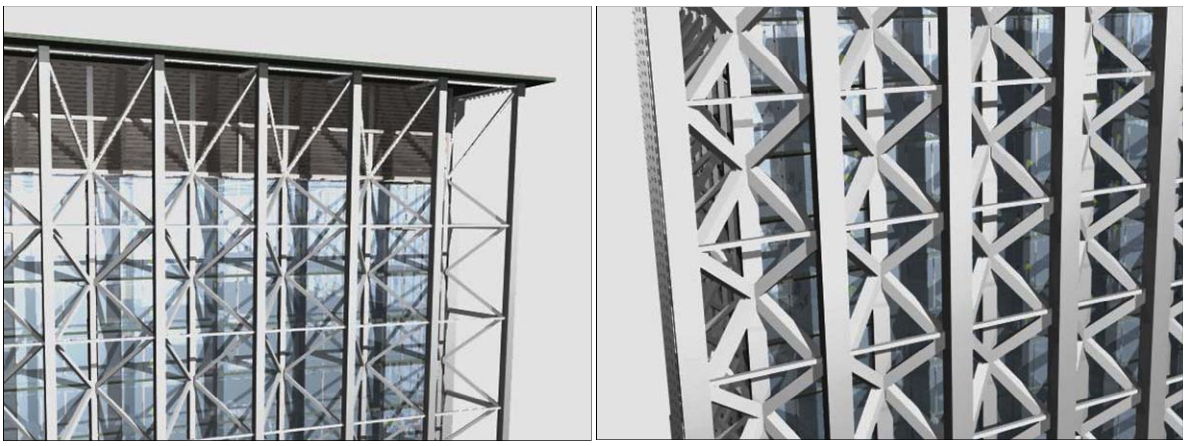


Figure 5.28 (a) Very limited sun shading by small structural members at the top floors; (b) Significant sun shading at the lower floors

Horizontal structural members provide some sun shading. However, they have small profiles compared to the diagonal and vertical members. To optimise the performance of the horizontal structural components, mechanical solar screens can be installed and attached to them. The solar screens can be designed to be adjustable by centralised control to provide optimal shading in relation to the solar path. Figure 5.29 shows an example of possible mechanical solar screens using louvers to shade the building. The louvers can be designed to be mechanically pulled-up, stretched-down, and rotated to adjust the amount of sunlight radiation reaching the inner layer of the façade. They should be applied in conjunction with the double-skin façade system. In countries with warm climates during sunny summer days, the temperature in the space between the two layers can significantly increase because of the solar gains (Gratia & Herde, 2004). To solve this problem, Baldinelli (2009) suggests a shading system integrated with the external layer of the façade. The shading system is adjustable to optimise both winter and summer energy performance. In the vertical double-layer space structure, the horizontal structural elements can be used for structural support of the external glass and the louvers. By positioning the solar screens behind the external skin of the façade, solar radiation is blocked before it can reach the internal skin.

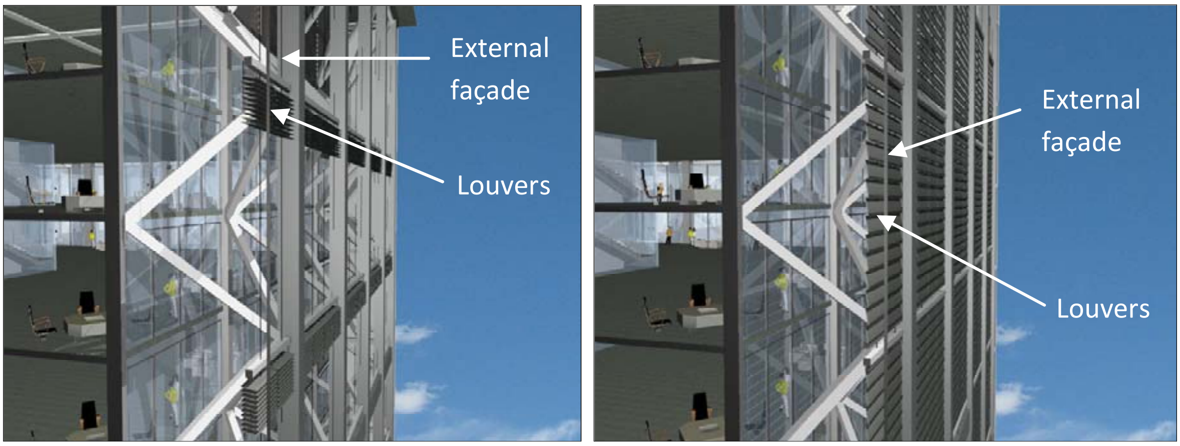


Figure 5.29 (a) Louvers are raised; (b) Louvers are fully deployed

Chapter 6 discusses that double-layer space structures can also accommodate balconies. Louvers can also be applied to the balconies of double-layer space structure buildings in order to reduce the sunshine penetrating the building. Louvers can shade the balconies and can be installed permanently without being rotatable or deployable (Figure 5.30).

This section has demonstrated that double-layer space structures buildings with glazing façades or balconies can accommodate sun shading devices in order to reduce energy.

Figure 5.30 Louvers in the vertical double-layer space structure building with balconies

Double-skin Façades

Double-skin façades have been used in buildings for sound and thermal insulation. In tall buildings, this façade system also has the benefit of reducing the gust of external wind pressure (Oesterle, 2001). In addition, the double-skin façade system provides an alternative of providing natural ventilation in tall buildings (Etheridge & Ford, 2008). This section discusses the integration of vertical double-layer space structures and double-skin façades; the purpose is to analyse if natural ventilation can be provided in double-layer space structure buildings using the technology of double-skin façades.

Vertical double-layer space structures have the potential to accommodate double-skin façades by virtue of their geometries. The construction of the double-skin façade in these structures will be discussed in Section 7.3.2. Each structural layer, consisting of vertical and horizontal elements provides frames for the glass. Common glass materials used in double-skin façades are thermal insulating double or triple glazing for the internal skin, and toughened single glass for the external skin (Poirazis, 2004).

Several different systems of double-skin façades are possible in multi-storey façades; the gap between the two layers of multi-storey façades can be continuous up the height of the building. Natural ventilation occurs by the air circulation from openings near the ground floor and the roof. Air circulation can be driven naturally by stack effect, which will be discussed later, or by mechanical devices. Multi-storey double-skin façades are also suitable to minimise external noise levels. However, the rooms behind have to be mechanically ventilated, and the façade can be used as a joint air duct (Oesterle, 2001). This system is applied in Victoria Ensemble in Sachsenring, Germany (Figure 5.31).

Figure 5.31 Multi-storey façade in the Victoria Ensemble, Sachsenring (Oesterle, 2001, p. 25)

Double-skin façades can be used in double-layer space structure buildings. Figure 5.32 shows an application of multi-storey façade in a double-layer space structure building. The space between the two layers is extended vertically for a certain height and the openings at the top and bottom allow air circulation through them. The air inlet and outlet devices must be adjustable. Opening should be reduced or closed in winter.

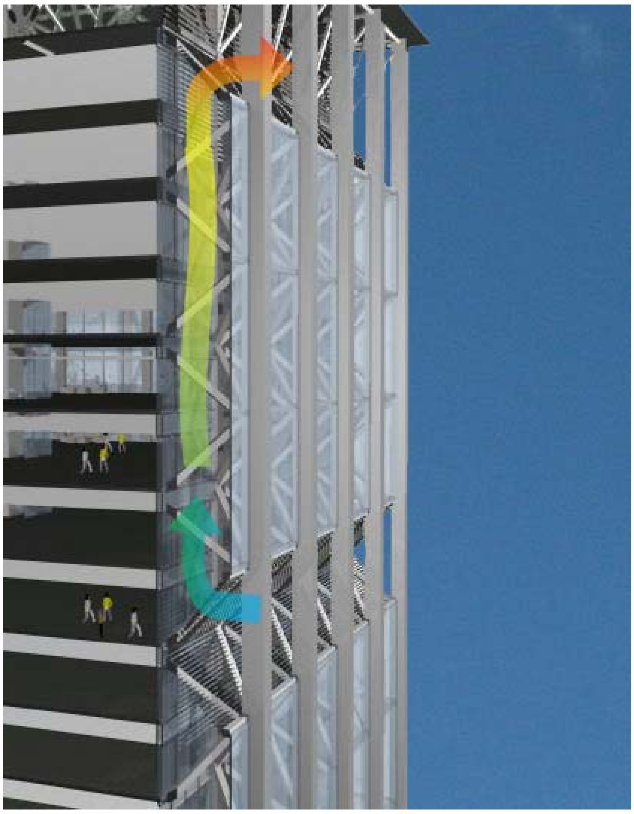


Figure 5.32 Air circulated through the space gap within the double-skin façade

Another double-skin façade system is corridor façades where corridors at each floor are placed within the cavity. Air is circulated through openings at the floor and ceiling each level as shown in Figure 5.33 (a). A corridor façade can be seen in the City Gate in Dusseldorf (Figure 5.33 (b)), where windows can be opened to enable air circulation in the building (Oesterle, 2001).

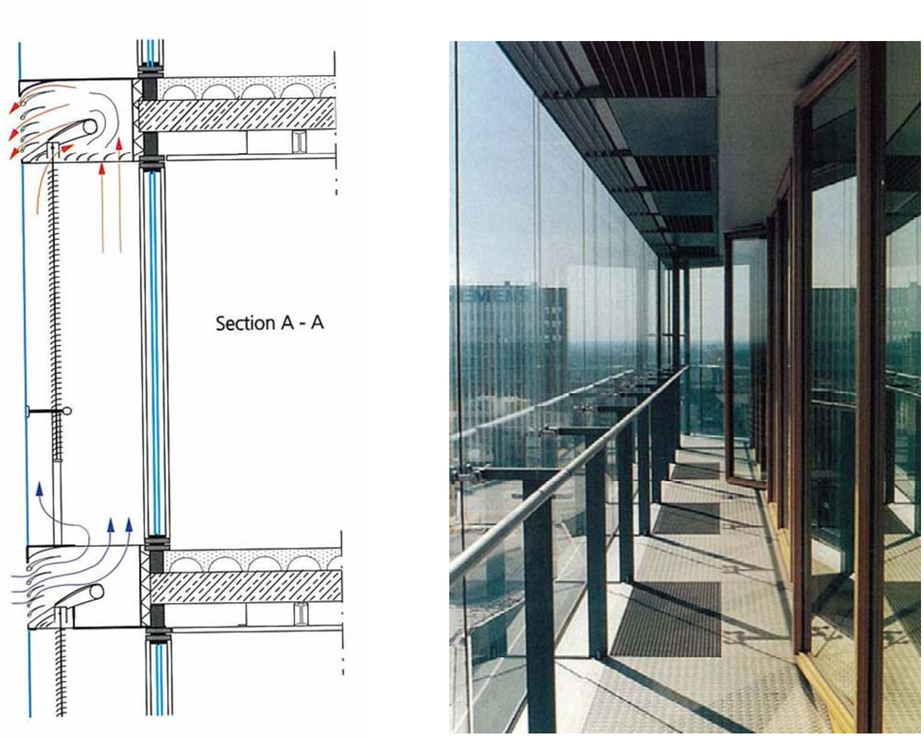


Figure 5.32 (a) Air circulation in corridor façades (Oesterle, 2001, p. 22); (b) A corridor façade in the City Gate, Dusseldorf (Oesterle, 2001, p. 22)

This façade system can be used in the double-layer space structure building with a little modification. The application of the corridor façade system is combined with balconies in double-layer space structure building. This is because the diagonal structural members do not allow a continuous corridor within the two layers. The air-intake and extract openings at the external layer are located between the ceiling of the lower storey and the floor of the upper storey. The air is diagonally circulated from the bottom air-intake opening to the top air-extract openings at the next bay as shown in Figure 5.34 to prevent air recontamination. Either single or double glazing can be used for the internal skin of the façade. Double glazing is normally used for buildings in cold-temperature climates. During summer, windows can be opened to enable air circulation in the building.

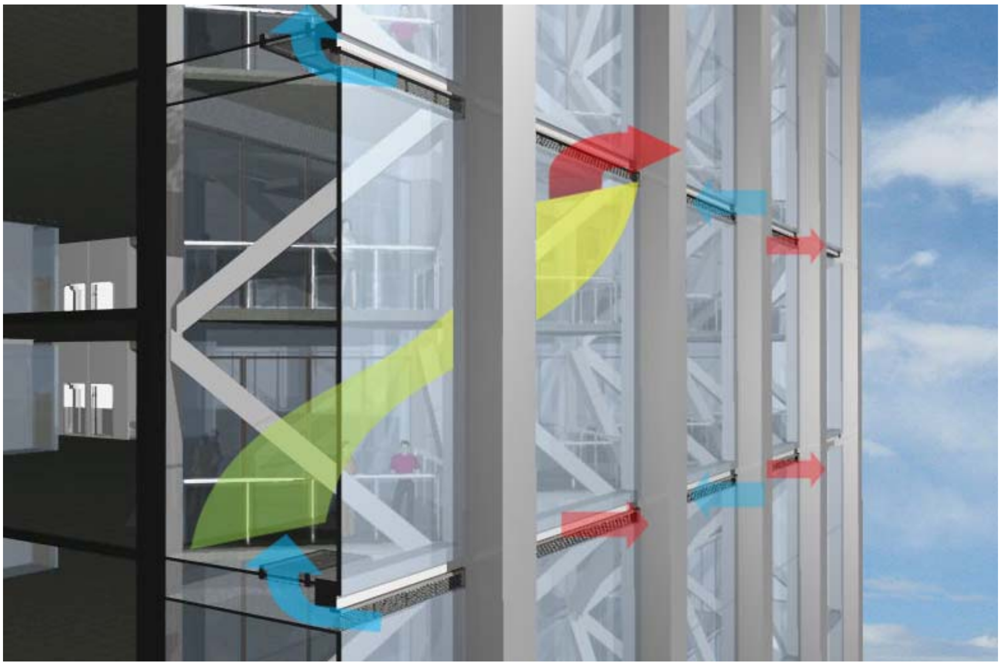


Figure 5.33 Air circulation in corridor façade of the double-layer space structure building

This section has shown that natural air ventilation can be provided in double-layer space structure buildings using the technology of double-skin façades. Two types of double-skin façades referred from current literature can be accommodated by the structural system; each has different air circulation system. These types of double-skin façades have been discussed as alternative applications to approach energy efficiency in high-rise double-layer space structure buildings.

Wind Turbines

This section discusses the integration of double-layer space structures with wind turbines as an approach to generate energy for the building. The aim is to provide an alternative application of wind turbines in high-rise double-layer space structure buildings. The reason for using wind turbines as a generator for building energy is discussed below.

As building height increases, so does the potential to generate wind energy by installing wind turbines in high-rise buildings (Irwin, Kilpatrick, Robinson, & Frisque, 2008). Several factors should be considered in order to achieve long-term environmental benefits of these applications. High wind speed and low turbulence are the desired factors for wind turbines, but these factors do not always occur in tall buildings. For example, tall buildings are sometimes surrounded by other buildings of similar heights because of height restrictions set by local governments. This has a significant impact to reduce the wind speed. Another way to optimise the wind turbine performance is to adjust building shapes. For example, Bahrain World Trade Center in Manama, Bahrain has turbines installed between its two towers (Figure 5.35 (a)) that channel the wind (Smith & Killa, 2007). Wind turbines are also installed in Pearl River Tower in Guangzhou as shown in Figure 5.35 (b). The building shape is designed to allow air flow through the four openings within the façade at its mechanical plant floors (Boyer & Dang, 2007).

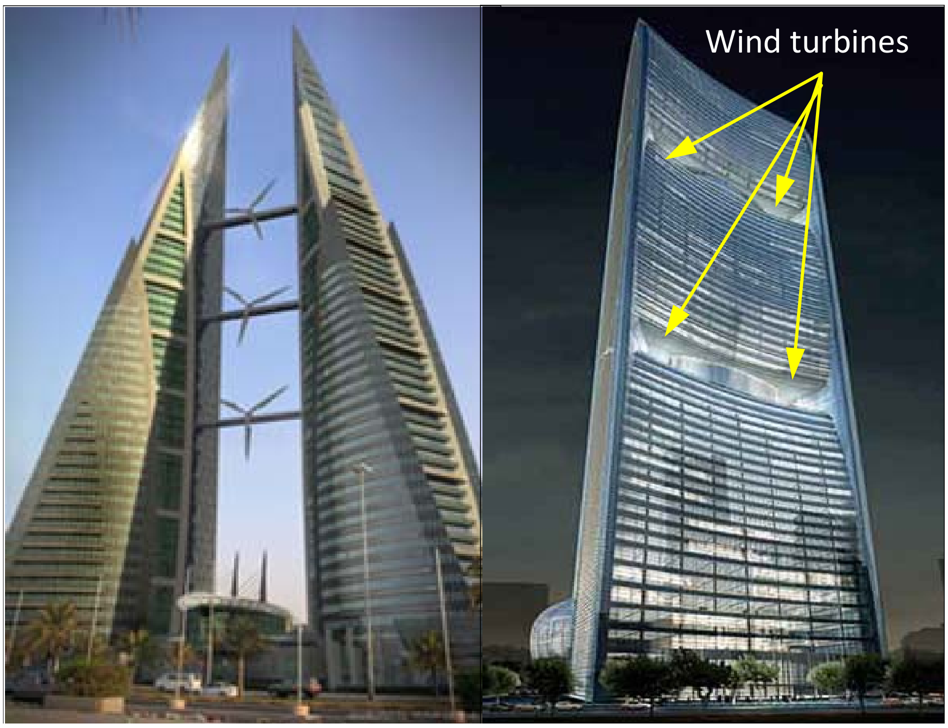


Figure 5.34 (a) Bahrain World Trade Center, Manama (Kaczynska, 2007); (b) Pearl River Tower, Guangzhou (Denoon, et al., 2008, p. 324)

Vertical double-layer space structures have the potential to accommodate wind turbines because the majority of the structure can be located outside the façades. Therefore, many structural members at the building perimeter have a direct contact with wind. However, the façade shapes have to be designed so they channel the wind to the turbines. Figure 5.36 (a) shows a simplified sketch of wind acting on a tall building. Positive wind pressure occurs on the windward face and negative wind pressure on the side and leeward faces (Denoon, et al., 2008). Based on the predominant wind orientation, wind turbines are placed at building corners and thereby integrated with the vertical double-layer space structure. The corners of the façade need to be chamfered to orientate wind to the turbines (Figure 5.36 (b)).

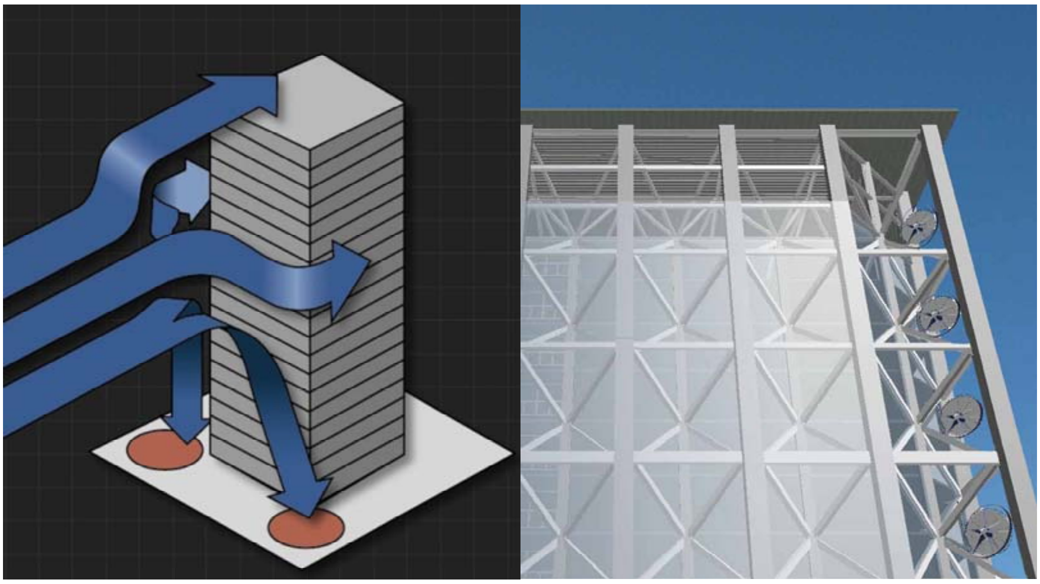


Figure 5.36 (a) Wind in a tall building (Denoon, Cochran, Banks, & Wood, 2008, p. 323); Wind turbines in a double-layer space structure building

Designs of building-integrated wind turbines need to consider several issues, such as noise from blades and generators, blade loss, bird strike, maintenance and other factors. Safety, Availability, Reliability and Maintainability (SARM) analysis by Ramboll and team (Smith & Killa, 2007), who have addressed these issues, can be used in the design of wind turbines. The disadvantage of applying wind turbines in double-layer space structure buildings is view obstruction in the location where the wind turbines are installed.

This section has discussed an alternative application of wind turbines in high-rise double-layer space structure buildings in order to generate building energy. This discussion, which also covers some potential problem of using wind turbines, can be useful information for designing wind turbines in high-rise double-layer space structure buildings in general.

Building-Integrated Photovoltaics

This chapter discusses the integration of double-layer space structures with photovoltaics in order to gain solar energy. The aim is to provide examples of integrating photovoltaics with double-layer space structures. The reason for considering photovoltaics as an alternative to generate energy for the building is based from current literature as discussed below.

Photovoltaics have been developed and used in buildings to generate electricity from sunlight. These solar panels produce Direct Current (DC) electricity, which is then convert to

Alternate Current (AC) power by an inverter. The intensity of solar radiation and its orientation are important factors for generating solar power. This power generating system is suitable for tall buildings with a large façade surface. Solar panels installed and integrated with building envelopes, are known as Building-Integrated Photovoltaics (BIPV) (Hammonds, 2001).

An application of BIPV can be seen in the Co-operative Insurance Tower built in 1962 in Manchester, England (Hudson, 2007). The tower, 118 metres high, is covered by 3,972 m^2 of photovoltaic cells ("CIS 'Solar Tower'," 2010). Figure 5.37 (a) shows its photovoltaic panels. BIPV is also installed on the façade and roof of the Samsung Institute of Engineering and Construction Technology in Gihung, Korea. BIPV not only produces electricity, but also performs as a shading device in order to reduce cooling loads in the building (Yoo & Lee, 2002). In Pearl River Tower in Guangzhou, solar panels are integrated into the façade of the mechanical rooms where views are not required and on the glass roof of the upper level to reduce solar heat gain (Boyer & Dang, 2007). In the Hong Kong Science Park, a double-skin façade is combined with BIPV (Figure 5.37 (b)). The solar panels also perform as solar screens for the building ("Hong Kong Science Park," 2005).

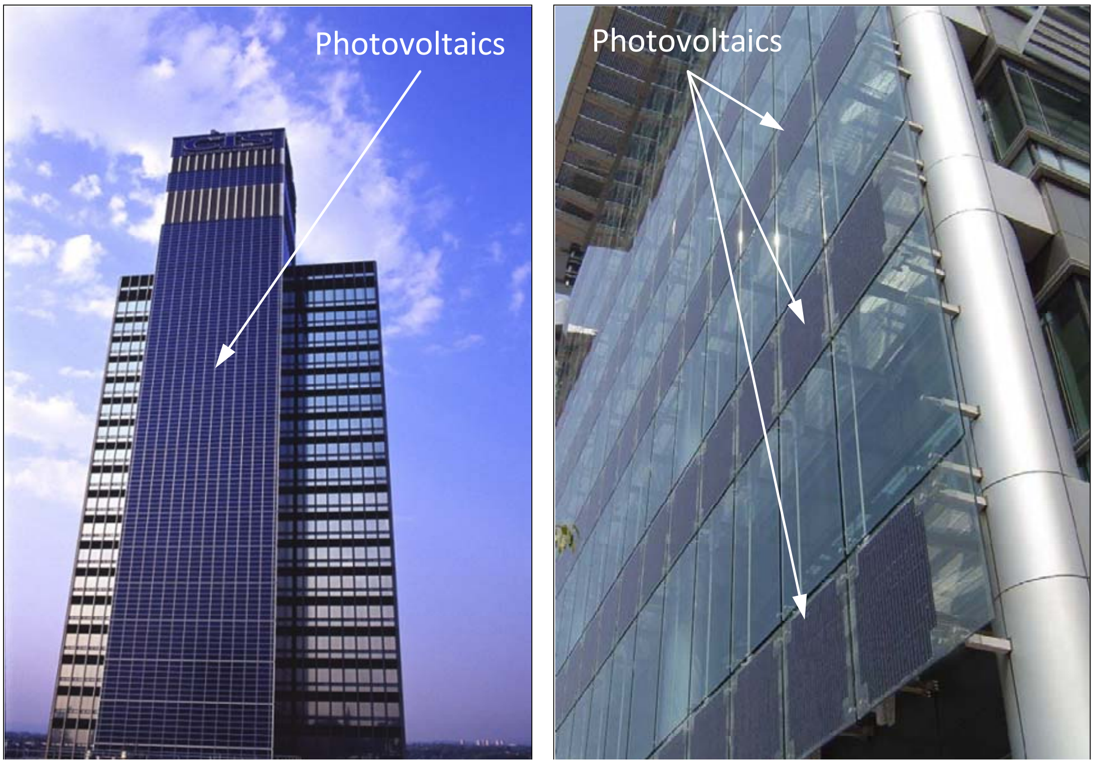


Figure 5.35 (a) Co-operative Insurance Tower, Manchester, England ("The Co-operative Insurance Tower," 2010); (b) BIPV in the Hong Kong Science Park ("Hong Kong Science Park," 2005)

In the double-layer space structure building, the majority of the perimeter structural components can be exposed. Since most external structural members receive a large amount of solar radiation, they are suitable to accommodate BIPV. Figure 5.36 (a) shows an example of BIPV on the structure. The sloped solar panels are attached to the horizontal structural components with the purpose of gaining more solar radiation. BIPV should not be installed on diagonal members and the internal layer of the structure because of the sun shading from the external structure will render the BIPV less efficient.

BIPV can also be integrated with double-skin façades. A theoretical study of these façades with BIPV and motorised blinds was conducted by Charron and Athienitis (2006) to analyse their thermal-electric efficiencies. The study considered two configurations. The first locates Photovoltaics at the external layer, and in the second Photovoltaics are located in the cavity. The motorised blinds of both configurations are in the cavity. This approach can lead to a combined thermal-electric efficiency of over 60%. This system can also be applied to double-layer space structure buildings shown in Figure 5.36 (b).

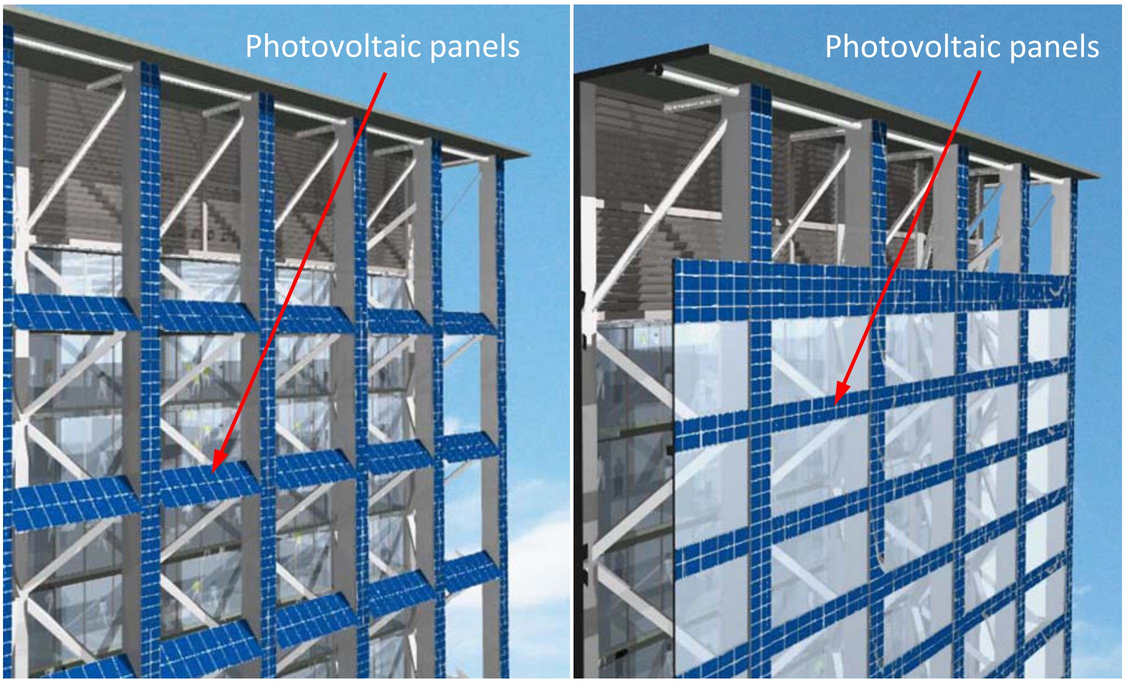


Figure 5.36 (a) BIPV on the double-layer space structure; (b) BIPV on the double-skin façade and the structure

In these two examples, factors like building orientation to the sun, BIPV sloped, long-term cost-benefit analysis and installation details have to be considered in the design of BIPV.

However, these examples and discussion in this section have provided useful information for developing design strategies of BIPV in high-rise double-layer space structure buildings.

5.5.3. Discussion

This has shown how vertical double-layer space structures can integrate with other building systems for approaching to energy efficiency. Since these structures have two layers of components at the building perimeter, the external structural layer can be exposed, in direct contact with the external environment. This condition provides opportunities to exploit natural resources as well as to provide some protection from external environmental conditions. The systems including sun shading devices, wind turbines, and Building-Integrated Photovoltaics (BIPV) can be applied to several façade forms discussed in Chapter 6, but might not be suitable for complex façade forms.

This study does not investigate the energy efficiency of these approaches, but they are presented as examples. Future research should be conducted in order to calculate energy efficiency of these approaches. Other approaches using different systems and strategies can also be explored in future research.

5.6. Façade Maintenance

This section discusses façade maintenance of multi-storey double-layer space structure buildings. This study is important because various façade geometries discussed in Chapter 6 can be relatively complex for maintenance. The discussion covers several techniques of façade maintenance that have been commonly used in existing tall buildings and considers some possibilities that could be applied to multi-storey double-layer space structure buildings using various façade shapes.

5.6.1. Technology in Façade Maintenance

As in other super-tall buildings, the façade of a multi-storey double-layer space structure building must be maintained. The design of façade access equipment is determined by safety, climate, façade complexity, building height, architecture, and code requirements (Herzog, 2008).

Building façades are normally maintained manually through vertical access from the roof. Façade access equipment sits on a rail along the perimeter of a building roof to enable access to the façade. A work platform is suspended from the façade access equipment as shown in Figure 5.39.

Figure 5.39 Conventional façade access equipment ("Facade Elevator with Fix Cantilever," 2011)

One technique of façade cleaning uses an automated robot; this system has been researched, applied, and developed in several countries. In Japan, Urakami (2008) developed a robot for various applications such as abrasive blasting, metal surface polishing and window cleaning. In Germany, Schraft, Brauning, Orlowski, and Hornemann (2000) developed a robot to fully clean a glass façade. The cleaning robot, which is detachable from the building and portable, cleans the outside of the windows on a façade with vertical jambs and horizontal bars as shown in Figure 5.37. This cleaning robot works faster, safer, and is cheaper as compared to manual cleaning.

Figure 5.37 (a) Window cleaning robot in Germany (Schraft, Brauning, Orlowski, & Hornemann, 2000, p. 496); (b) Inside view of the robot (Schraft, et al., 2000, p. 497)

Another cleaning robot has been developed in Hong Kong by Sun, Zhu, Lai, and Tso (2004). The robot climbs and moves with a translation mechanism rotating a flexible waist. A CCD camera and two laser diodes are used for a visual sensor to measure the robot's position and orientation to the window frames (Figure 5.41).

Figure 5.38 A window cleaning robot in Hong Kong (Sun, Zhu, Lai, & Tso, 2004, p. 1093)

5.6.2. Façade Maintenance Systems

A multi-storey vertical double-layer space structure can accommodate various façade forms that will be discussed in Chapter 6. These façades can be classified into flat façades, which comprises double-skin façades, and recessed façades, which cover the exposed structures, vertical and horizontal folded façades, as shown in Figure 5.39.

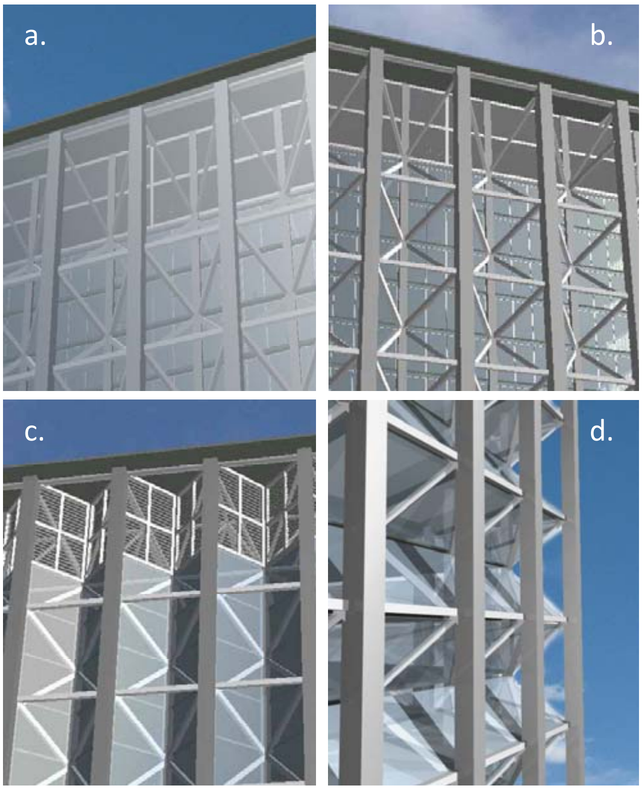


Figure 5.39 (a) Double-skin façade; (b) Exposed structure; (c) Vertical folded façade; (d) Horizontal folded façade

In the flat façade, the surface is flat because the glass is attached to the external sides of the external structural members. Either conventional façade access equipment or window cleaning robots can be used for its maintenance.

In the recessed façade, the glass can either be attached to the diagonal structural members or internal structural members. A special window cleaning device using a platform that allows access to a recessed window can be used for this type of façade. This device requires a significant counter weight to stabilise its position Figure 5.43 shows the application of a recessed façade cleaning device.

The crane of a façade cleaning device can be installed in the plant rooms. Since the double-layer space structure building has plant rooms at four different levels, each plant room can have façade cleaning equipment to serve the façade of the floors below.

Figure 5.40 A recessed façade cleaning device (Herzog, 2008, p. 406)

The main issue of the façade maintenance system in a multi-storey double-layer space structure is in the horizontal movement of its façade cleaning device. The device cannot move horizontally because the crane of the façade cleaning device will hit the structural members around the building perimeter. To solve this problem, the crane's arm must be designed using a telescopic system that can be lengthened or shortened like the façade cleaning device in the Petronas Towers, Kuala Lumpur. The cranes of the façade cleaning device in that building, which has multiple setbacks, can be adjusted as shown in Figure 5.41.

Figure 5.41 The cranes of façade cleaning devices of the Petronas Tower, Kuala Lumpur (Herzog, 2008, p. 405)

The discussion above has shown that current maintenance technology can be used in double-layer space structure buildings with flat or recessed façades, although the maintenance system is relatively complex.

5.7. Structural-Services Integration

This section discusses the integration of double-layer space structures and services systems by looking at the categories and levels of integration introduced in the literature review in Chapter 2. Double-layer space structures were applied vertically and horizontally in the structural model discussed in Chapter 4. The concept was to optimise the space within the structures for services components.

Vertical Double-layer Space Structure

A vertical double-layer space structure is located at the building perimeter. As discussed in the previous sections, services components including ducts, pipes, elevators, and stairs are located at two building corners, within the depth of the vertical double-layer space structure. Physical integration at the meshed level (physical integration levels have been briefly explained in Section 2.3.2) has been achieved because the structural and services components share space by occupying the same volume. Figure 5.42 shows a building section illustrating the application of structural-services integration.

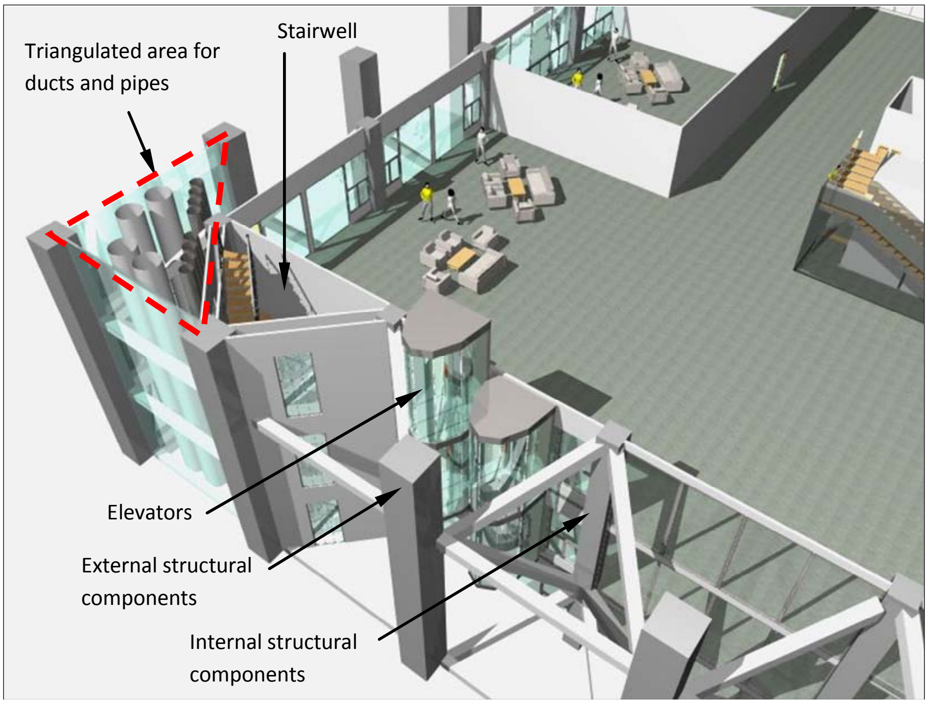


Figure 5.42 Structural-services integration in the vertical double-layer space structure

Horizontal Double-layer Space Structure

Horizontal double-layer space structures are located at levels 23, 48, 73, and 98. Since these structures are two-storeys deep, the spaces within them can be used for plant rooms. The plant rooms can accommodate:

- HVAC components: AHUs, chillers, boilers, water pumps, and cooling towers.
- Elevator components: motor room and pit.
- The cranes for façade maintenance devices.

Again, physical integration at the meshed level is achieved because the horizontal double-layer space structures and services components occupy the same space as shown in Figure 5.46.

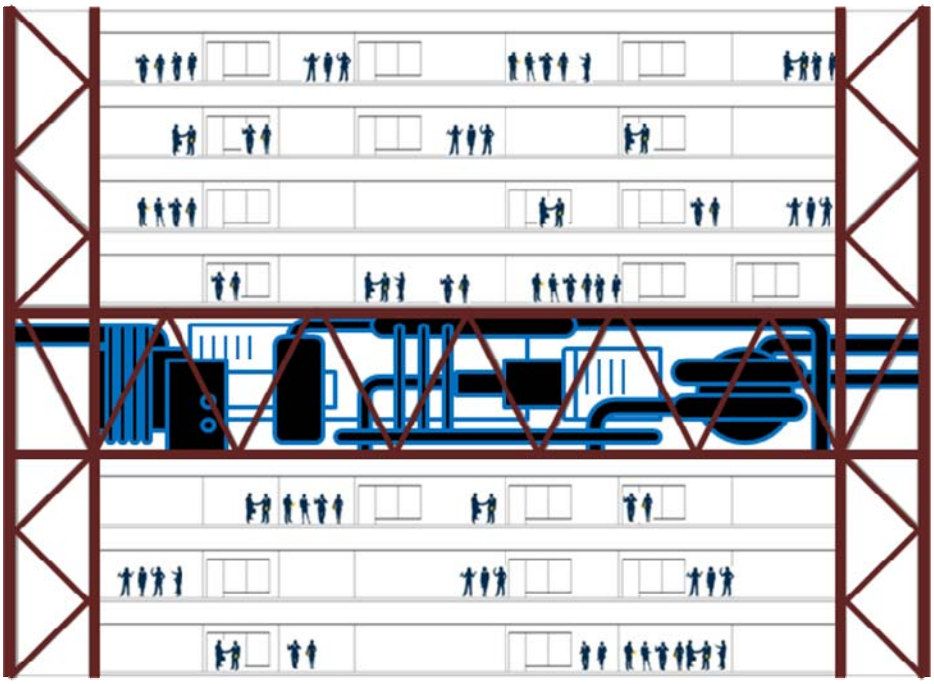


Figure 5.43 Structural-services integration in the horizontal double-layer space structure

5.8. Usable Floor Area

This section discusses the advantage of structural-services integration in providing a larger usable area than in conventional high-rise buildings. The integration concept of the vertical double-layer space structure in this case study is to locate the majority of structural and services components at the building perimeter and a small proportion in the building centre. This approach is totally different to typical tall buildings where the strategic location of services components is in the centre core; this provides the shortest distance to any occupied areas (Codella, Henn, & Moser, 1981). However, taller buildings require a very large area for the services, especially elevators. As a result, the usable floor area decreases due to the increase of the services area. In contrast, in a double-layer space structure building, a larger usable floor area can be achieved because services components are located outside the floor areas.

Two buildings that have 40m x 40m gross floor areas were compared. The first building has a centre services core like typical tall buildings. The second building using a double-layer space structure has stairs and elevators as shown in Figure 5.44. The elevator areas of the double-layer space structure building have been discussed in Section 5.3.3. Using the same steps, the elevator areas of a typical tall building are as follows:

1. Local elevators
    - Required area for 16 passengers is 2.9 m^2, the inside elevator area was designed W= 2.0 m and D= 1.45 m.
    - The clear hoist way is W + (20 in to 24 in) = 2.0 + 0.5 = 2.50 m and D + (25.25 in to 29.25 in) = 1.45 + 0.7 = 2.15 m.
2. Shuttle elevators
    - Required area for 10 passengers is 1.9 m^2, the inside elevator area was designed W= 1.5 m and D= 1.25 m.
    - The clear hoist way is W + (20 in to 24 in) = 1.5 + 0.5 = 2.00 m and D + (25.25 in to 29.25 in) = 1.25 + 0.7 = 1.95 m.

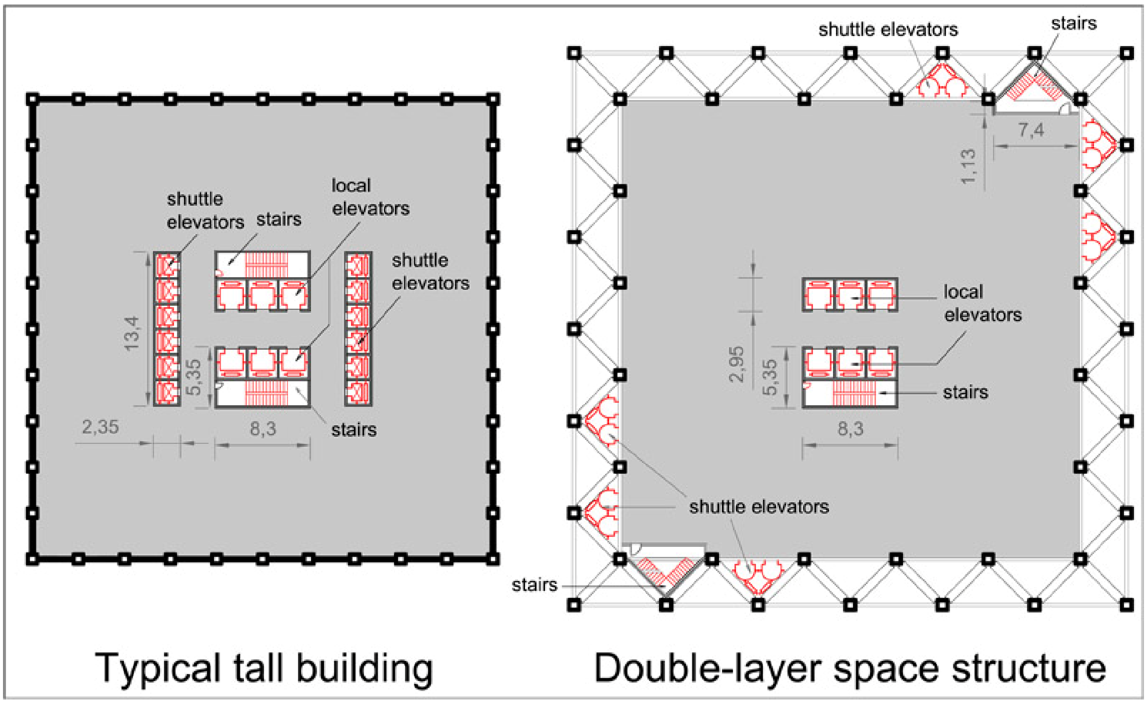


Figure 5.44 Usable areas of a typical tall building and double-layer space structure building

In a typical tall building, two stairs are located at the centre of the building. The double-layer space structure building has two stairs located out of the floor area and a stair in the building centre. This integration concept is also applied in Centre Pompidou, Paris ("Architecture of the Building," 2011), where several stairs, pipes, ducts and structural members are located out of the floor area (Figure 5.48).

Figure 5.48 Structural and services components in the Centre Pompidou, Paris, are located out of the floor area (Source: www.centrepompidou.fr)

The usable floor areas of a typical tall building and the double-layer space structure building are compared in Table 5.9. It shows that the central cores for stairs and elevators of the typical tall building are about twice those of the double-layer space structure building. The gross floor areas of the two buildings are 40m x 40m = 1,600 m^2, measured between the external walls. Usable floor area is measured as the area between the major vertical penetrations including common areas (ANSI/BOMA, 1996). In this case study, the usable floor area is the area difference between the gross floor area and the internal core including vertical structural members.

Table 5.9 The area comparison of a typical tall building and a double-layer space structure building

Typical tall building			**Double-layer space structure**		
2 stairs + 6 local elevators	89	m^2	1 stair + 3 local elevators	44	m^2
12 shuttle elevators	63	m^2	3 local elevators	24	m^2
			The landings of the perimeter stairs	8	m^2
Total stair & elevator areas =	**152**	**m^2**	**Total stair & elevator areas =**	**77**	**m^2**
Total gross floor area	1,600	m^2	Total gross floor area	1,600	m^2
Total usable floor area	1,448	m^2	Total usable floor area	1,523	m^2
Total usable 92 floor area	**133,235**	**m^2**	**Total usable 92 floor area**	**140,093**	**m^2**
Building foot print area	**1,600**	**m^2**	**Building foot print area**	**2,304**	**m^2**

The advantage of the double-layer space structure is that a larger area can be provided for the building occupants. The disadvantage of this concept is that a larger ground area is required. However, the required additional land area is outweighed by the additional available usable floor area, which is multiplied by the total number of storeys. The difference of the foot print areas of the two buildings is 2,304 – 1,600 = 704 m^2, but the difference of the total usable floor area is 140,093 – 133,235 = 6,857 m^2. Normally, super-tall buildings require a ground area that is larger than the tower area. The area outside the tower is normally used for a podium, garden, and car park. In addition, a certain distance to neighbouring buildings is often required to provide manageable construction areas and to minimise shading to the neighbours.

The result of this comparison is limited to the following conditions:

- In double-layer space structure buildings, the major proportion of services components like pipes, ducts, stairs and elevators are located within the cavity of the structure at the building perimeter, out of the floor area.
- In typical high-rise buildings, all of the services components are located at the building centre.

5.9. Summary

This chapter has discussed the application of services systems in a multi-storey double-layer space structure building. The study shows how HVAC, stair, elevator, fire safety and façade maintenance systems can integrate with double-layer space structures in super-tall buildings, not only for the designed case studies but also for general high-rise applications. However, these applications are limited to the scope of this study mentioned in Section 3.2, and the strategies explained in this study. Physical integration is achieved because the structural and services components occupy the same space. An advantage of this type of integration is that larger usable areas can be provided compared to the floor areas of typical super-tall buildings. This is because the majority of structural and services components are positioned at the building perimeter.

Chapter 6: Architectural Integration

This chapter discusses structural-architectural integration of vertical double-layer space structures in super-tall buildings in order to answer the research sub-questions in Chapter 3, which require strategies for structural-architectural integration including their advantages and disadvantages. The discussion covers the integration between the structures and architectural components like façades, entrances, lobbies, interior space, and building geometry.

This part of the research is conducted using a qualitative approach. The study begins with the review of several existing tall and super-tall buildings that have high-level and significant structural-architectural integration. Positive and negative aspects of their structural-architectural integration are analysed. Based on these reviews and analysis, the study explores various architectural integration possibilities of vertical double-layer space structures using computer models. The computer models are used as a medium to demonstrate alternative strategies for multi-storey double-layer space structures to integrate with façades, entrances, lobbies, interior space, and building geometry, discussed in each section of this chapter. The strategies for the structural-architectural integration are then summarised by showing their advantages and disadvantages that can be used as guidance for the integrated design of double-layer space structures in general high-rise applications.

6.1. Building Façade

This section discusses the integration of a double-layer space structure and building façades. Since the majority of the structural members are at the building perimeter, this can have an impact on the aesthetics of the façade. The structure-façade integration in several super-tall buildings that have perimeter structures is reviewed and several façade configurations that are suited to double-layer space structures are explored.

6.1.1. Structural-façade Integration in Existing tall and Super-tall Buildings

Integration between perimeter structures and building façades can be seen in several tall and super-tall buildings. For example, in the John Hancock Center, Chicago, the structural braces are exposed as part of the building façade as shown in Figure 6.1. The braced-tube system, which consists of perimeter beams and columns connected with large diagonal braces, is used in this building because of its efficiency in reducing the amount of steel. At the same time, the integrity of the structure-architectural expression is enhanced by the pattern of the diagonal braces (Khan, 1983).

Figure 6.1 (a) Structural expression of the diagonal braces of the John Hancock Center, Chicago (Source: som.com)

Diagonal bracing is commonly used in tall buildings. The system relies on large perimeter diagonal members that connect corner columns to each other. The aim is to create vertical truss action that is relatively rigid in resisting lateral loads. Structure-façade integration using a bracing system can be seen in Bank of China in Hong Kong, completed in 1990, as shown in Figure 6.2. Here, I. M. Pei, the architect applies bamboo symbolism where four triangular sticks of different lengths provide architectural inspiration (Blake, 1991). Since Hong Kong is in a wind and earthquake prone area, the building must resist considerable lateral loads. Leslie Robertson, the structural engineer, uses a space-truss concept in order to provide a rigid structure and integrate the structure with the architectural form (Blake,

Figure 6.2 Bank of China, Hong Kong (photo by Hendry Y Sutjiadi)

1985). Another application of this style of bracing system can be seen in the 780 Third Avenue Building, New York. Bracing-façade integration is achieved by blocking several windows with structural components forming diagonal patterns as shown in Figure 6.3.

Figure 6.3 780 Third Avenue Building, New York (Source: 780third.com)

Diagrid structures, recently developed as a new structural system of tall buildings, also have diagonal members on the building perimeter (Moon, Connor, & Fernandez, 2007). Building designers express the diagonal pattern of the structure and integrate it with the building façade. As a result, this integration can achieve an elegant façade. Integration of diagrid structures and building façades is applied in the Hearst Tower in New York and the Swiss Re Building in London as shown in Figure 6.4.

Figure 6.4 (a) The Hearst Tower, New York (Source: Wikimedia.org); (b) The Swiss Re Building, London (photo by Andrew W. Charleson)

These examples show how integration between structural and façade systems in tall buildings can be achieved by expressing the structural form as a part of the building façade itself. This concept will be applied to vertical double-layer space structures as an integral part of the façade systems, which is discussed in the following section.

6.1.2. Integration of Glazing Façade and the Double-layer Space Structure

Glazed façades have been widely used in many tall buildings. Alternatives for integration of glazed façades and double-layer space structures are as follows:

1. Double-skin façades

   Double-skin façades, which consist of two layers of glazing separated by an intermediate space (Shameri, Alghoul, Sopian, Zain, & Elayeb, 2011), can be integrated with the structure by attaching the layers of the façade to the layers of the space structure as shown in Figure 6.5 (a). This system can provide natural ventilation by allowing air circulation through the space between the layers. It can also provide high-quality sound and thermal insulation to the building (Etheridge & Ford, 2008).

2. Exposed structures

   Exposed structures can be another alternative for structure-façade integration. Either single or double glazing can be attached to the internal layer of the space structure. As a result, the diagonal, horizontal, and external vertical members are architecturally exposed as shown in Figure 6.5 (b). Colour combinations of the structural members together with suitable coloured glazing can be specified by the architects.

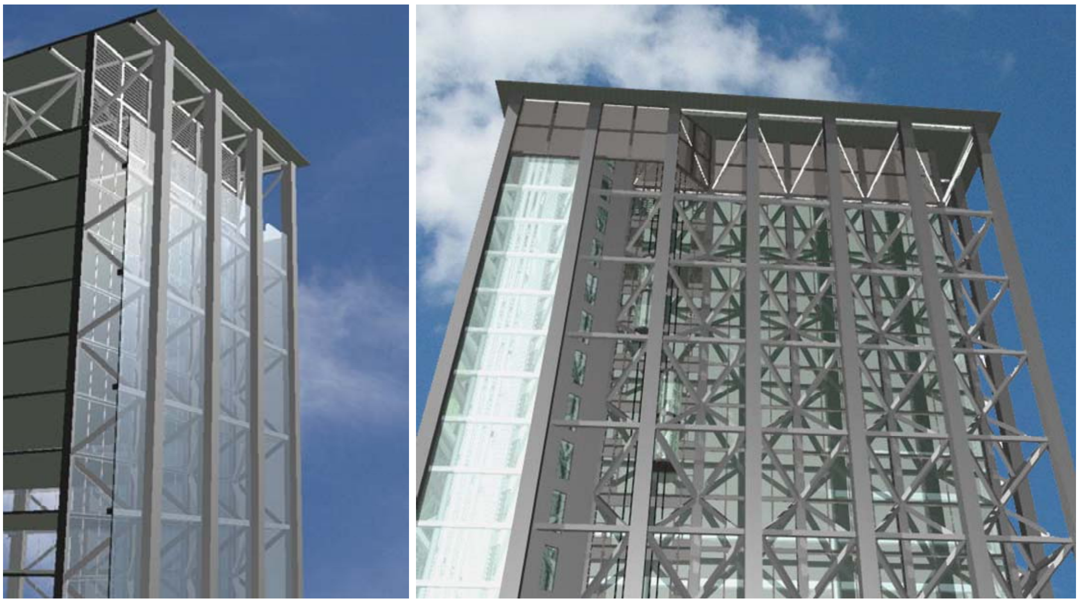


Figure 6.5 (a) Double-skin façade; (b) Exposed structure

3. Vertical and horizontal folded façades.

   Glazed façades can be attached to the diagonal members of the vertical double-layer space structure by following the diagonal pattern either vertically or horizontally. Floor areas using these two different façade systems are different. Figure 6.6 (a) shows the application of a horizontal folded façade. A horizontal folded façade building has two floor plan types with different areas. The smaller floor area is bordered by the internal columns while the larger floor area is bordered by the external columns. Each-storey glazing spans diagonally between the smaller floor border and the larger floor border. In a vertical folded façade building, the floors are framed by the diagonal members. The glazing is attached to diagonal members in the same plane as the columns and resulting zigzag façade as shown in Figure 6.6 (b).

Figure 6.6 (a) Horizontal folded façade; (b) Vertical folded façade

4. Combinations

   The façade alternatives above can be combined providing several alternatives:

   a. A combination of double-skin and the horizontal folded façades is shown in Figure 6.7 (a). This façade system expresses an irregular pattern of the structural modules. The idea is to make the building form more interesting by minimising a repetitive pattern.

   b. A combination of the double-skin and the exposed façades forming curved external glazing is shown in Figure 6.7 (b). A curved shape is generated with the straight lines of the structural components to provide a curving sense among the straight lines from the structural expression.

c. A combination of the double-skin façade and the exposed structure is shown in Figure 6.8 (a). This combination can be applied to the buildings where their internal spaces require different types of façade. For example, where a double-skin façade is required for a specific area but not for the rest of the building/floor.
d. The prismatic façade is a combination of the horizontal and vertical folded façades as shown in Figure 6.8 (b). This façade system explores the diagonal pattern of the double-layer space structure by integrating the glazing surface and the diagonal structural members.

Figure 6.7 (a) A combination of double-skin and horizontal folded façade; (b) Curved external façade

Figure 6.8 (a) A combination of double-skin façade and exposed structure; (b) Prismatic façade

The above examples show structural integration of various glazing façade geometries. The following section discusses façades with various balconies integrated with double-layer space structures.

6.1.3. Balconies in Double-layer Space Structure Buildings

Balconies are very desirable in hotels and apartments because occupants can have open views and fresh air. Two alternatives of integrating balconies with vertical double-layer space structures are discussed in this section.

In the first alternative, an external wall is placed in line with the internal layer of the perimeter structure. Separator walls between apartments are placed perpendicular to the first external wall. The balcony is the triangulated area between the first external wall and the separator wall as shown in Figure 6.9. The edge of the balcony is positioned in line with the diagonal structural members.

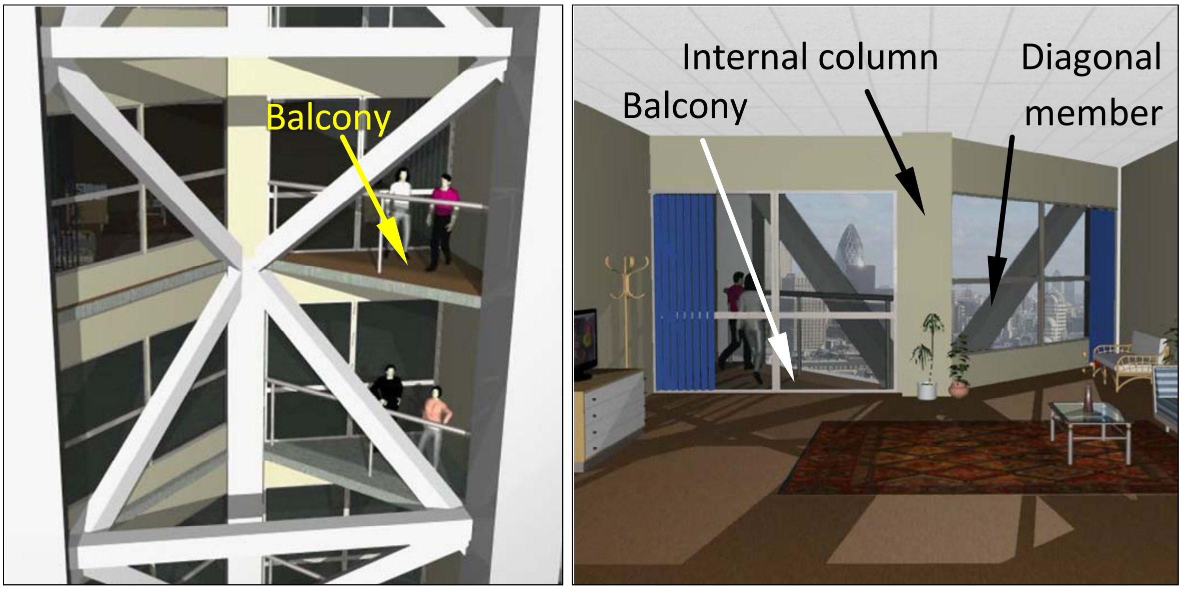


Figure 6.9 (a) The first alternative balcony in the double-layer space structure building; (b) Interior view

In the second alternative, the external walls are placed in line with the diagonal members. Balconies are placed outside the external walls as shown on the left of the Figure 6.10 (a). Since the balcony is positioned between two columns and two diagonal members, people standing on the balconies will have an open view. Alternatively, one structural module can accommodate two balconies separated by a wall as shown in the Figure 6.10 (b). This is suitable for small apartment units.

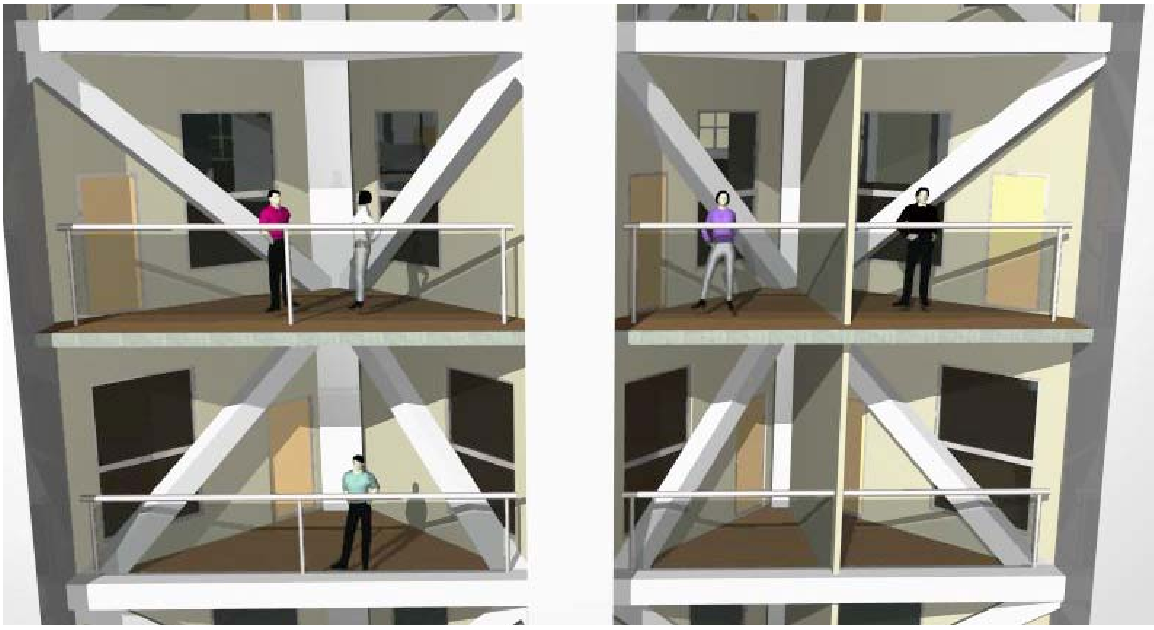


Figure 6.10 (a) One-structural module balconies; (b) Half-structural module balconies

Two alternatives of façade designs integrated with the vertical double-layer space structure are shown above. The design concept is to optimise the uniqueness of structural expression. Unlike conventional vertical structures that mainly consist of horizontal and vertical components, vertical double-layer space structure features consisting of vertical, horizontal, and diagonal components as well as the dual layers system can provide many integrated design alternatives.

6.2. Entrances and Lobbies

This section discusses the integration of entrances and lobbies with the structure. Like in some other perimeter structures, placing entrances in double-layer space structures is not an easy task. The following sections discuss entrances of tall buildings with perimeter structures and explore possible integration of entrances and lobbies with double-layer space structures.

6.2.1. Integration of Entrances and Lobbies with the Structure

Entrances and lobbies are essential areas in buildings to welcome visitors and users. As primary public spaces, entrances are often large-in-scale. Lobbies express the activities and qualities of the building's users and reveal the building's geometry (Phillips, 1991).

Providing a wide entrance in a building with perimeter structure can be a challenge. For example, the World Trade Center in New York, with a framed-tube as its structural system, had only 0.65 metres net distance between two columns. Columns on the lower floors merged to provide enough area for the entrance as shown in Figure 6.11.

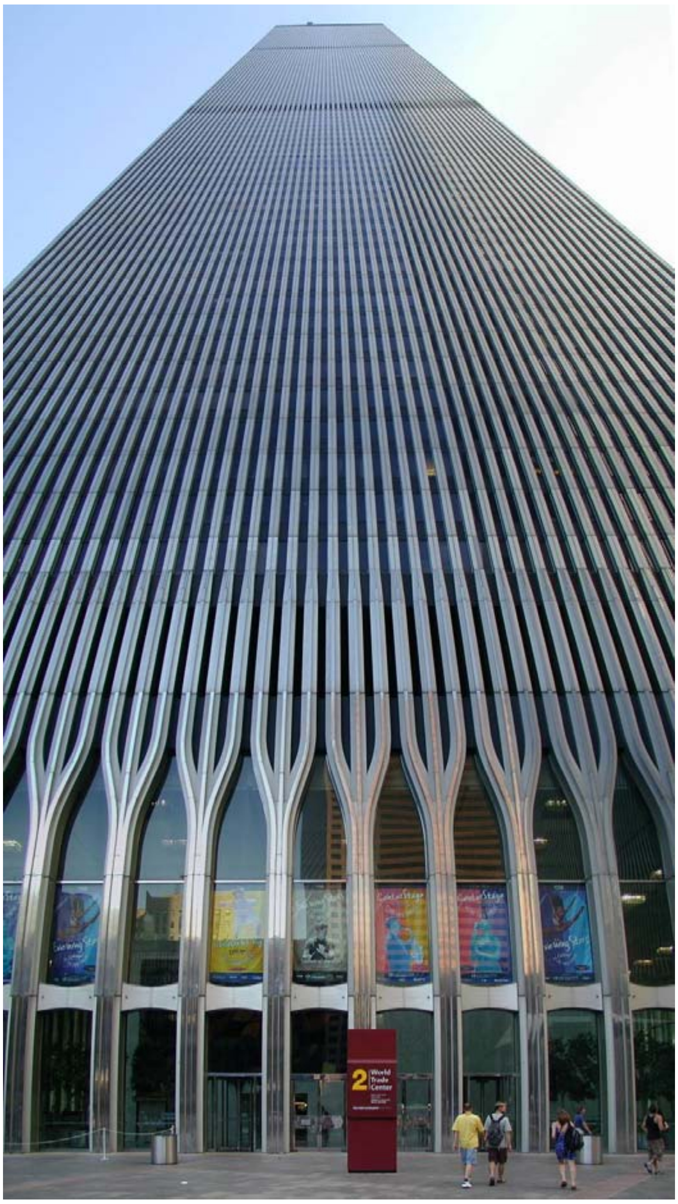


Figure 6.11 The entrance of the World Trade Centre, New York (Source: Imageshack.us)

In other cases, structural components are also integrated with building entrances. In the Swiss Re building, London, glazing in several structural modules on the bottom floors are omitted to provide a terrace and a unique entrance as shown in Figure 6.12 (a). The entrance of this building is also fully integrated with the building façade and benefits from structural expression. Another example of structure-entrance integration can be seen in Fleet Place House in London. The ground floor columns in this building diverge and merge forming groups of diagonal components. The architect created an entrance by using the space between two groups of columns in the middle of the building as shown in Figure 6.12

(b). As a result, an elegant entrance is formed by the expression of the ground-floor structural components.

Figure 6.12 (a) The entrance of Swiss Re, London (Source: Flickr.com); (b) The entrance of the Fleet Place, London (Photo by: Andrew W Charleson)

Integration between structural components and the building entrance and lobby can also be seen at The Center, Hong Kong, constructed in 1998. K-braces at the ground floor form striking building components in the lobby as shown in Figure 6.13 (a). This concept is also applied in the Hearst Tower in New York completed in 2006, where columns and diagonal structural components contribute a stylish appearance to the lobby as shown in Figure 6.13 (b). The expression of diagonal structural components in the lobbies of these buildings contributes to the architectural characteristics of these spaces.

Figure 6.13 (a) An entrance of The Center, Hong Kong (photo by: Hendry Y Sutjiadi); (b) The lobby of the Hearst Tower, New York (Source: International-highrise-award.com)

These examples show how a building entrance can incorporate perimeter structural components. An elegant entrance can be designed by integrating exposed diagonal structural components.

6.2.2. Entrances and Lobbies in Double-layer Space Structure Buildings

Positioning an entrance in a vertical double-layer space structure building creates a challenge because of the short distance between vertical members. In addition, the 45-degree diagonal members make the space for access even narrower. To minimise these problems, several design approaches are discussed below:

- The slope of the diagonal members at ground floor should be increased by designing the ground floor columns to be two floors high. As a result, unusable space around the columns can be minimised by reducing the area where people might bump into the diagonal members.
- The entrance can be located in a podium attached to the outside of the building. This position is discussed further by showing an example.
- Removing a vertical external structural component at the entrance position and placing it with two large diagonal members to transfer the load from the upper columns to the foundation.

Several alternatives for entrances and lobbies in a vertical double-layer space structure building are as follows:

1. The building entrance can be positioned at the building corner, on the same plane as diagonal members as shown in Figure 6.14 (a). The disadvantage of this is that not the whole space between the columns can be used for the entrance. Due to the diagonal braces, only 50% of the space can be used for the entrance. This type of entrance suits buildings with a façade located at the external columns.
2. For buildings with façades fixed to the internal structural layer, the entrance can be located between two columns of the internal layer as shown in Figure 6.14 (b). Since diagonal members do not cross the entrance, its design can be more flexible and the entire space between the two columns can be used for the entrance.

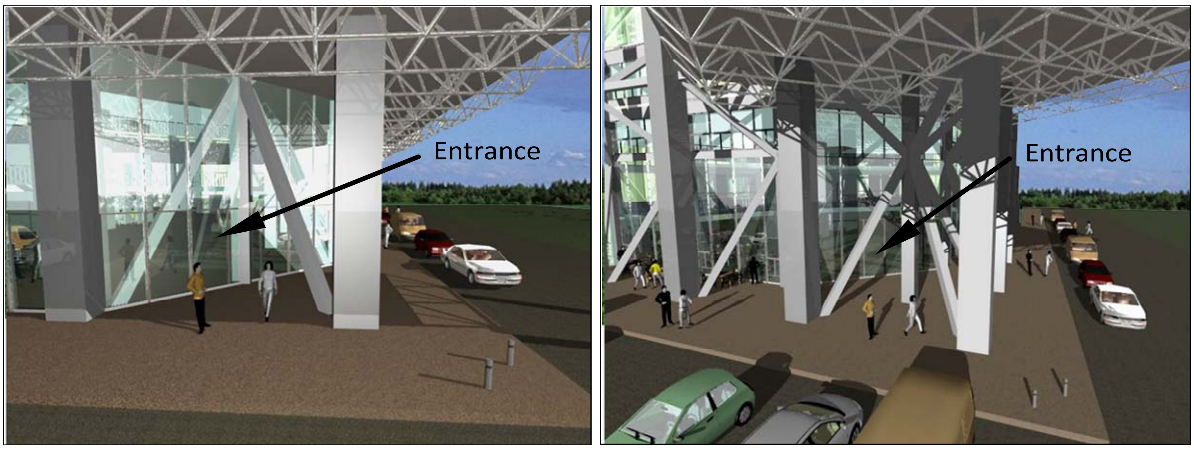


Figure 6.14. (a) An entrance for a building with the external façade; (b) An entrance for a building with the internal façade

3. A podium can be attached to a vertical double-layer space structure building to provide entrances and a lobby (Figure 6.15). In this example, the podium is three floors high. Entrances can be placed anywhere at the perimeter of the podium. The vertical double-layer space structure components separate the interior of the podium and the tower.

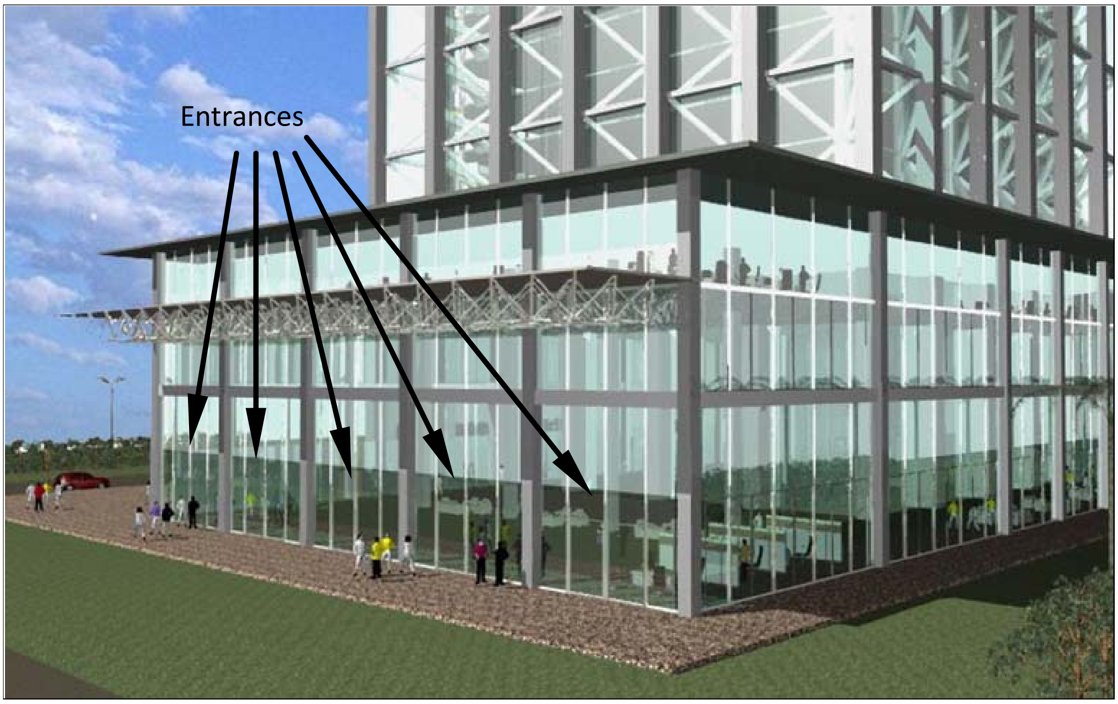


Figure 6.15 A podium attached to a vertical double-layer space structure building

4. A relatively wide entrance can be made by bifurcating one of the external columns as in Figure 6.16. By removing the ground floor column, the space in front of the entrance is larger. The large diagonal members transfer the axial loads from the upper column to

the foundation. In addition, the large diagonal members will clearly express the building entry.

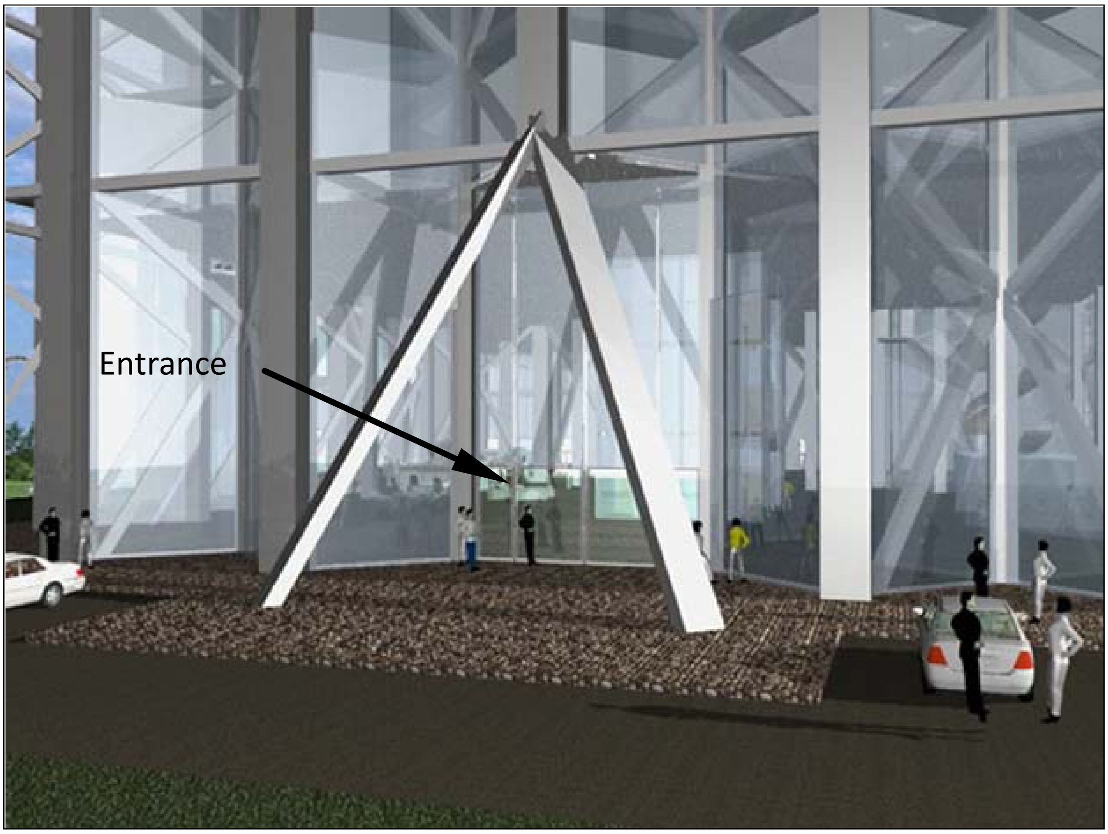


Figure 6.16 Two large diagonal members as a part of a building entrance

6.3. Interior Space

This section discusses how to integrate the diagonal members of vertical double-layer space structures within interior space. Several buildings that have diagonal members are reviewed first.

6.3.1. Integration of Diagonal Structural Members and Interior Space

Diagonal members can be exposed as feature building components and as part of interiors. For example, a column and two diagonal structural members contribute to the architectural character of a room in the John Hancock Center, Chicago, shown in Figure 6.17 (a). Another example is shown in the Hearst Tower, New York. The integration of the diagonal structural members with building façade and lighting devices increase the aesthetic quality of a lounge as shown in Figure 6.17 (b).

Figure 6.17 (a) Interior of the John Hancock Center, Chicago (Lepik, 2004, p. 88); (b) Interior of the Hearst Tower, New York (Source: News.cnet.com)

However, diagonal structural members can also disrupt interior space (Charleson, 2005). For example, diagonal tension members in 125 Alban Gate, London, interrupt circulation space and endanger people passing by as shown in Figure 6.18 (a). In the design process of the Hong Kong and Shanghai Bank Headquarters, a full-scale mock-up of diagonal members was placed in Foster's office to see if people could live with it as shown in Figure 6.18 (b), but it was shown to be unacceptable (Williams, 1989). These examples are a reminder of how diagonal members must be integrated within interior space without endangering public circulation.

Figure 6.18 (a) 125 Alban Gate, London (Charleson, 2005, p. 99); (b) Full-scale mock-up in Foster's office for the HSBC design (Williams, 1989, p. 105)

A good strategy for positioning diagonal members in buildings can be seen in Century Tower in Tokyo, also designed by Foster Associates (Shuppan, 1995). In this building, the diagonal members are positioned as a separator of two different areas. The main structure, consisting of deep beams, columns, and large diagonal members, is placed between the work space and atrium as shown in Figure 6.19. As a result, the existence of the structure does not interrupt internal spaces. In addition, the structural system is expressed architecturally as a part of the building interior.

Figure 6.19 Diagonal structural components as a part of the interior architectural expression in Century Tower, Tokyo (Shuppan, 1995, p. 103)

These examples show that the existence of diagonal components in interior space can be desirable if they are located in suitable places and provide particular functions.

6.3.2. Integration of Double-layer Space Structures and Interior Space

Providing usable interior space within three-dimensional diagonal members is not an easy task. Learning from the lessons of diagonal member applications at 125 Alban Gate and the HSBC as discussed previously, three design approaches are suggested:

1. Ground floor columns are lengthened to eight metres high, compared to four metre long columns of upper typical floors. By lengthening these columns, the angle of the diagonal members increase and the spaces around the columns are more usable. The space around columns and diagonal members on the ground floor can then be used for a lounge as shown in Figure 6.20 (a).

2. The façade is located in the same plane as the diagonal members. The aim is to avoid unusable space below the diagonal members. This approach is applied to vertical and horizontal folded façades shown in Figure 6.6 and discussed in the first section of this chapter. Diagonal members attached to the vertical folded façade provide enough space for seating without a space interruption from the diagonal members as shown in Figure 6.20 (b). However, the diagonal members interrupt views. This also occurs in the interiors of the John Hancock and Hearst Tower buildings discussed above.

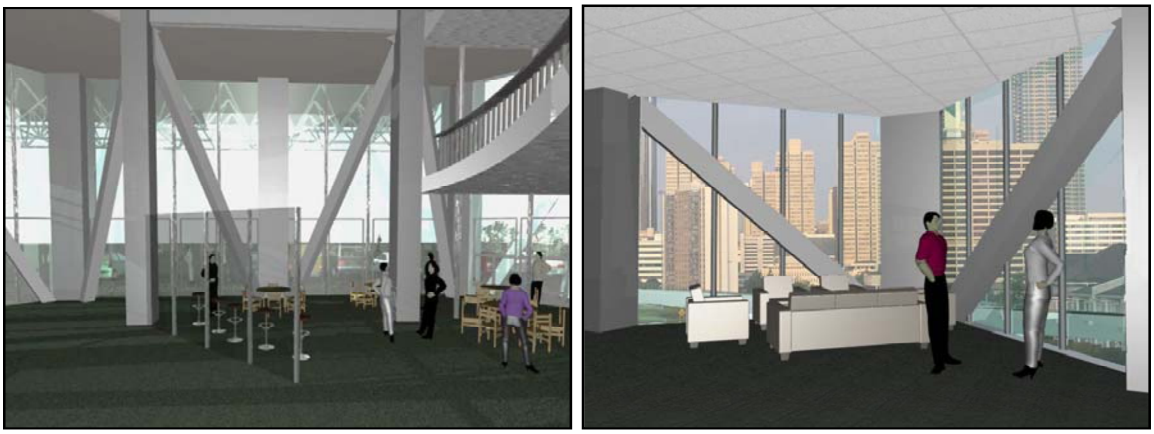


Figure 6.20 (a) Diagonal structural members integrated with a lounge on the ground floor; (b) Interior space of the building using the vertical folded façade system

3. The façade is attached to the diagonal members horizontally as discussed in the first section of this chapter, shown in Figure 6.6 (a). The integration of the diagonal members and horizontal folded façade provide good views through the 45 degree glazing. Two types of interior space result from the horizontal folded façade system. In the first type, the perimeter structure does not disrupt the interior space, but the floor area is limited to the internal layer of the structure as shown in Figure 6.21 (a). The second interior type has larger floor area than the first type. However, a certain distance from the façade along the perimeter of the floor cannot be used effectively because of the façade slope. Several interior components like miniature interior gardens, HVAC diffusers, lighting devices, and a handrail can be placed at that space as shown in Figure 6.21 (b). An example of sloped façade can be seen in the City Hall, London, shown in Figure 6.22. A handrail is placed inside the façade, so the occupants cannot bump into the sloped glazing. At this area, grills for air circulation are placed in the floor (Baird, 2010).

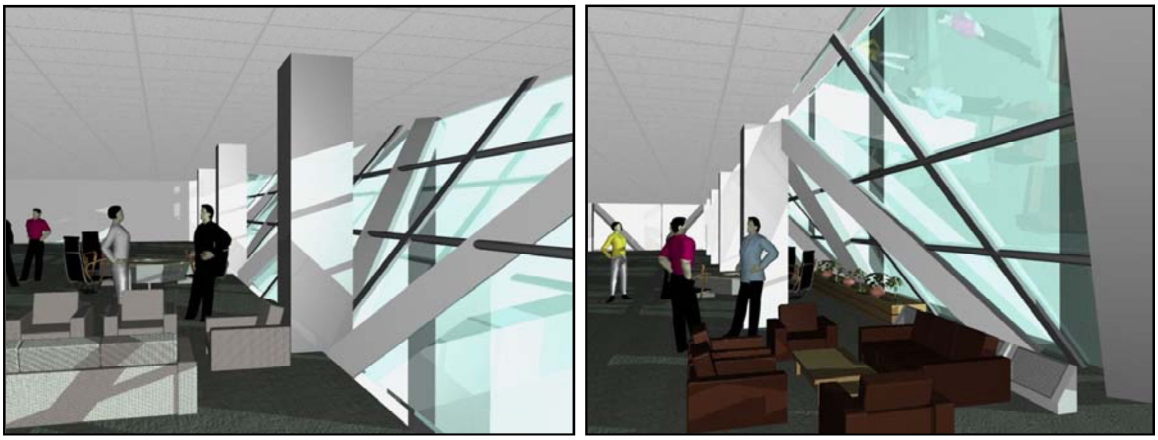


Figure 6.21 (a) The first interior space of the horizontal folded façade; (b) The second interior space has larger floor area

Figure 6.22 The sloped façade in the City Hall, London (Baird, 2010, pp. 122-123)

6.4. Open Views

This section discusses open views through the façade of double-layer space structure buildings. Since the majority of the structural members are at the building perimeter, they potentially obstruct open views through the façade. Several tall buildings that have perimeter structures are reviewed. The open view obstruction caused by the structural members is discussed, as well as other factors that influence obstructions of the view.

6.4.1. Open Views in Perimeter Structure Tall Buildings

Perimeter structural systems are particularly efficient in resisting lateral loads in tall buildings. However, they limit open views through their façades because large structural components are located at the building perimeter.

Figure 6.23 Diagonal braces in Onterie Center, Chicago (Source: Wikimedia.org)

A braced-tube building, for example, has large diagonal components that block several areas of the façade. In the Onterie Center, Chicago, a large number of windows are blocked by concrete walls, which are located at different positions to form a pattern of diagonal bracing (Figure 6.23). This also occurs in John Hancock Center, Chicago, which has large steel braces. Figure 6.24 shows that the large diagonal members significantly obstruct open views through the façade. However, this condition occurs only in several areas at the building perimeter where the diagonal members are positioned.

Figure 6.24 Large diagonal members that obstruct open views in the John Hancock Center, Chicago (Stoller, 2000, pp. 62, 63 & 67)

In the World Trade Center, New York, the clear span between the columns was only 0.65 metres. The two buildings used a framed-tube system that had a large number and size of beams and columns at the building perimeter. Figure 6.25 shows the view from a restaurant in the World Trade Center before it was destroyed. It shows how open views around the entire building perimeter were obstructed by the large columns.

Figure 6.25 Large columns that obstructed open views in the World Trade Center, New York (Source: Forum.skyscraperpage.com)

Another perimeter structural system is diagrid structure. This structure has diagonal structural members around the whole area of the façade. Although the diagonal components are not as large as those in a braced-tube, they still obstruct open views. Figure 6.26 shows how the open view is obstructed by the diagonal structural components in the Swiss Re Building, London.

These examples show that large structural members of perimeter structures potentially obstruct views through the façade. The following section discusses the view obstruction in double-layer space structure buildings.

Figure 6.26 A view from the Swiss Re Building, London (Source: fosterandpartners.com)

6.4.2. Open Views in Double-layer Space Structure Buildings

A multi-storey double-layer space structure has a large number of structural components at the building perimeter. In addition, the dual layer of structural components also contributes to obstruction of open views. The view obstruction is mainly caused by the large vertical and diagonal members. The horizontal components at the floors levels are relatively small and they do not block the views significantly.

The obstructed view areas are different for different floor levels and different types of façades. The different sizes of the structural components at the lower and upper floors have a significant impact on open views at those floors. Larger open views can be provided at the upper floors because the structural members are relatively small. Various types of façades also provide different open view areas because the façade positions relative to the structure differ.

In exposed structure façades, a view through the glazing between columns is obstructed mainly by the diagonal and external vertical members as shown in Figure 6.27 (a). More open views can be provided at the upper floors at the building with the same façade as shown in Figure 6.27 (b).

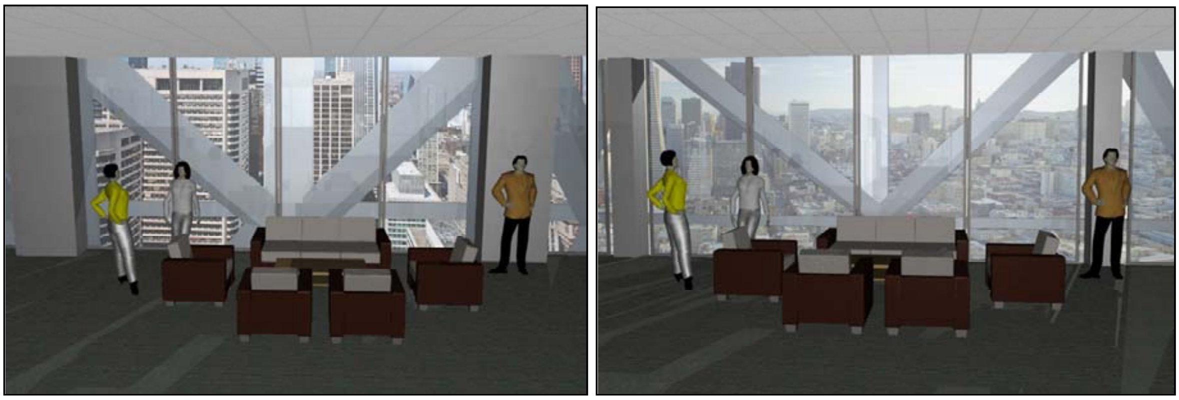


Figure 6.27 (a) A view at a lower floor of a multi-storey double-layer space structure using an exposed structure façade; (b) A view at an upper floor of the building using the same façade

A multi-storey double-layer space structure building using the horizontal folded façade has different open view areas. At the floor that is extended to the external layer, open views are very limited because the glazing leans upward as shown in Figure 6.28. In addition, it is difficult to stand close to the façade to look outside because of a certain distance from the façade. At the floor limited to the internal layer, people can easily stand close to the façade and look outside because the glazing faces downward (Figure 6.29).

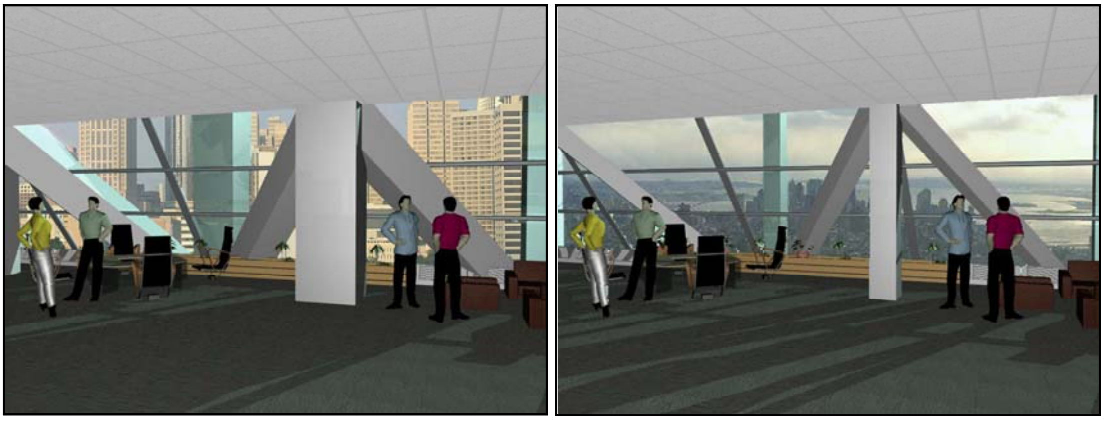


Figure 6.28 (a) A view at a lower floor of the horizontal folded façade building; (b) A view at an upper floor

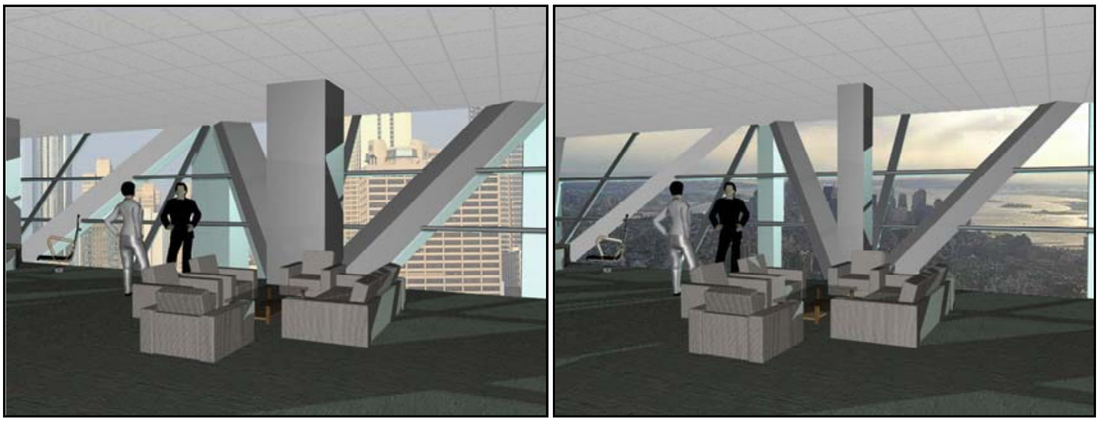


Figure 6.29 (a) A view at another lower floor of the horizontal folded façade building; (b) A view at another upper floor

The building with the vertical folded façade has relatively larger open view areas. This is because the façade area is larger and the obstruction is mainly caused by diagonal and vertical members. Figure 6.30 shows how people can have views from two different sides of the façade in one structural module.

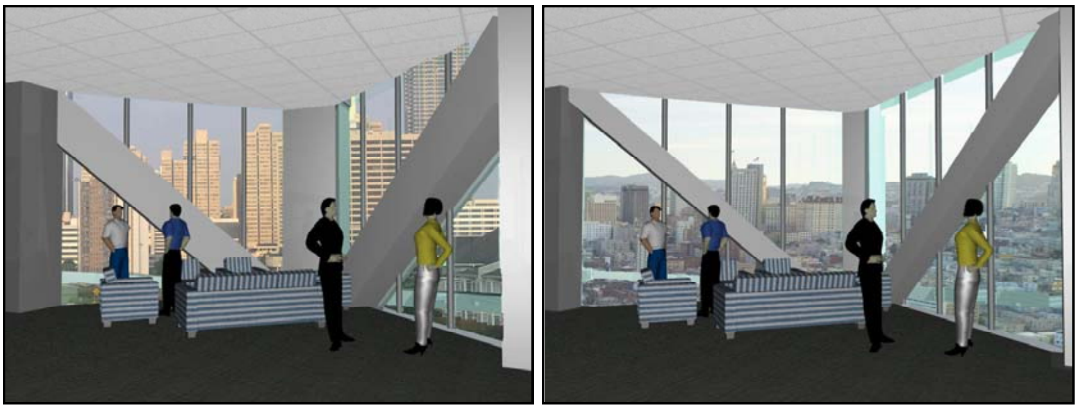


Figure 6.30 (a) A view at a lower floor of the vertical folded façade building; (b) A view at an upper floor of the vertical folded façade building

These examples also show that the open views at the upper floors are much larger than at the lower floors. This is because of the significant differences in structural member sizes at different levels, especially the vertical and diagonal components.

6.5. Building Geometry

This section discusses the potential of vertical double-layer space structures to be used for various building geometries. The variation in building forms of several existing tall buildings is also reviewed briefly.

6.5.1. Integration of Structures with Building Forms

Structural systems play a large contribution to the forms of tall buildings. Rectangular prisms or tapered forms are most common in order to achieve an efficient structural system resulting in considerable cost savings (Ali, Armstrong, & CTBUH, 1995). For example, the Empire State Building, New York, built in 1931, has a rectangular plan and the building form tapers vertically (Figure 6.31 (a)). A similar concept is applied in Willis Tower, Chicago. Built in 1973, it has a bundled-box form. The number of boxes decreases with building height from nine boxes on the ground floor to two boxes on the top floor (Figure 6.31 (b)). Tapered rectangular building forms have dominated tall building designs for many decades.

Figure 6.31 (a) Tapered rectangular form of the Empire State Building, New York (Source: Wikimedia.org); (b) Rectangular form of the Willis Tower, Chicago (Source: Wikimedia.org)

More recently, tall buildings have non-regular floors and generally irregular forms. Complex geometries such as leaning and twisting forms can be seen in several current super-tall projects. Structural and elevator systems are two major issues for leaning towers. Inclined elevators are available on the market but are much more expensive than their fully vertical alternatives. In terms of structural issues, the gravity forces of irregular forms may generate additional overturning moments. A highly redundant structure such as diagrid is desirable as an economic structural system for those building geometries (Scott, Farnsworth, Jackson, & Clark, 2007).

A leaning tower is being constructed in Abu Dhabi. The Capital Gate, 35 storeys and 160 metres high, leans 18 degrees ("Capital Gate," 2010). The main structure is a combination of a concrete core and perimeter and internal steel diagrids. The concrete core for the elevator system is extended up in the overlapping areas of the ground floor and the top floor (Figure 6.32 (a) and (b)). Figure 6.32 (b) also shows that the internal diagrid supports several floors in order to provide an atrium. Figure 6.32 (c) shows a rendered computer image of the building.

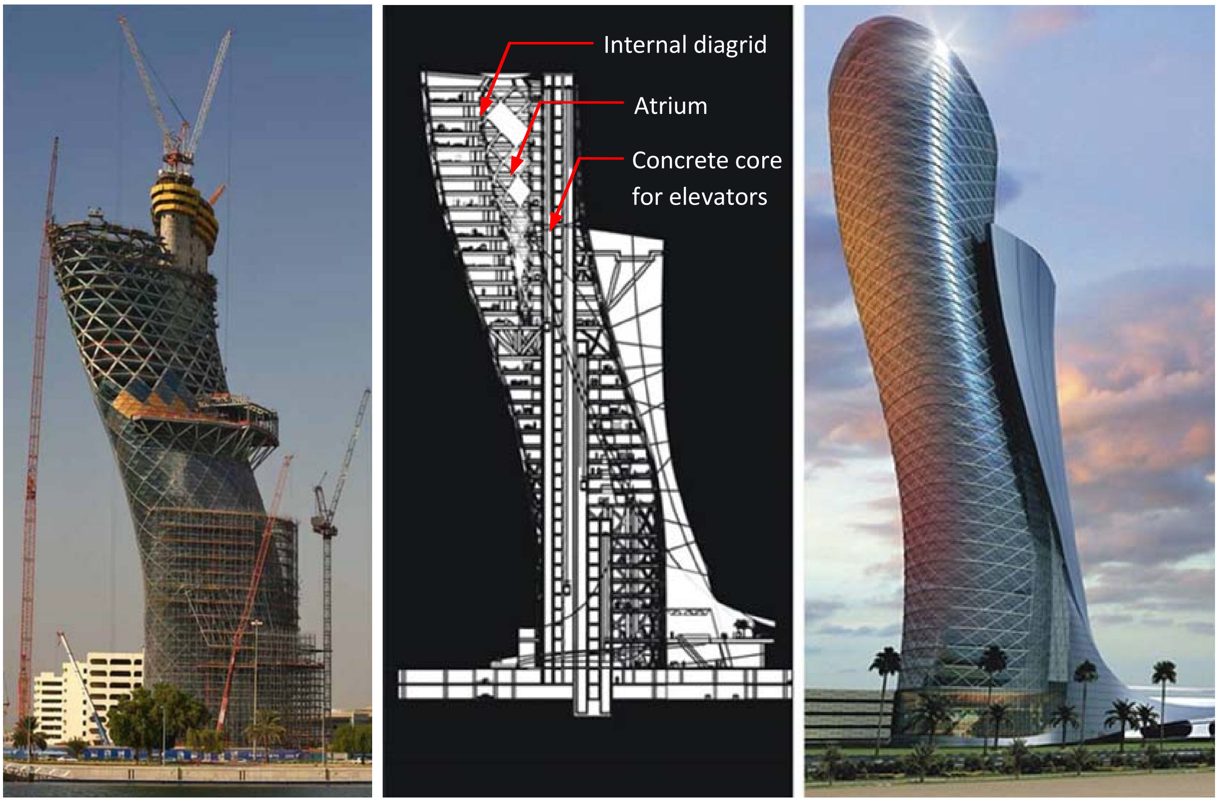


Figure 6.32 (a) The Capital Gate, Abu Dhabi, under construction (Source: Indonetsk.com.ua); (b) A section view (Source: Aedesign.wordpress.com); (c) The computer model (Source: Aedesign.wordpress.com)

Twisting shapes can be seen in the Turning Torso, Malmo. Figure 6.33 (a) shows the 190 metres high building designed by Santiago Calatrava, built in 2006. Another of Calatrava's projects is the Chicago Spire, Chicago, shown in Figure 6.33 (b). It will have a twisting form, 150 storeys and 610 metres high. In twisting towers, services cores and structural systems are two main design issues. Services cores should not be twisted for practical reasons. For example, it is likely impossible to provide a twisted elevator core. Columns can either follow the twisting form or stand vertically without following the building form. Structural systems using external bracing is suitable for twisting towers (Scott, et al., 2007).

Figure 6.33 (a) Turning Torso, Malmo (Source: Wikimedia.org); (b) The Chicago Spire, Chicago (Source: Thebiggestnews.com)

The current tallest twisting tower is being constructed in Dubai. The Infinity Tower, 73 storeys and 300 metres high, is twisted 90 degrees. The structure consists of a combination of a concrete central core and concrete leaning framed tube systems. Figure 6.34 (a) shows that only the perimeter structure twists following the building geometry, but the internal core stands vertical. Figure 6.34 (b) shows a rendered computer image of the building.

Figure 6.34 (a) The Infinity Tower, Dubai, under construction (Source: Imresolt.blogspot.com); (b) A three-dimensional view ("Infinity Tower," 2010)

The CCTV headquarters, Beijing, 2009 expresses the concept of a continuous loop without a traditional bottom or top, beginning or end (Amelar, 2004). Designed by Rem Koolhas, it has two footprints as shown in Figure 6.35. The main structure of this building consists of leaning columns, horizontal edge beams, and triangulated bracing integrated with the building skin (Carrol et al., 2005).

Figure 6.35 The CCTV Headquarters, Beijing (photo by Andrew W Charleson)

Another unique building form can be seen in the Dubai Tower project. Shown in Figure 6.36 (a), it consists of four towers representing candle flames. The tallest tower will be 88 storeys and 550 metres high. The main structure comprises an exterior braced tube connected by outriggers to a core shear wall (Elnimeiri, 2008). The exterior braced tube consists of a sloped paired mega-column system (Figure 6.36 (b)).

Figure 6.36 (a) Dubai Tower 29, Dubai (Elnimeiri, 2008, p. 460); (b) The main structure (Elnimeiri, 2008, p. 463)

These examples show how various irregular building forms are popular and possible with tall buildings. Current and likely future trends of tall building forms indicate that their designs are not based solely on structural form and simplicity. The design trends challenge structural engineers to provide structural systems that are not only cost efficient, but also able to accommodate unique and irregular building forms.

6.5.2. Complex Geometry using Vertical Double-layer Space Structures

The previous sections show how vertical double-layer space structures can be used for simple rectangular vertical forms. In this section, vertical double-layer space structures support various less regular forms in order to give an appreciation of what is possible.

Figure 6.37 A tower using a curved double-layer space structure

Figure 6.37 shows the design of a geometrically complex building using a vertical double-layer space structure. The building is inspired by the project Fiera Milano, Milan, by Daniel Libeskind (2010). The vertical double-layer space structure follows the curved building forms. The form is achieved by changing the slopes and lengths of the vertical and diagonal members at every floor. Integration of the structure and building form is shown clearly in this building. However, the vertical core for elevators should not follow the curved geometry for practical reasons.

Figure 6.38 shows an example of a vertical double-layer space structure in a twisting tower. To provide the twisting form, alternative strategies for the structural design are as follows:

- Internal columns are extended up vertically to the roof level.
- External columns lean, following the twisting geometry of the building.
- Diagonal members irregularly connect the internal and external columns.

This example shows how the twisting form can be realised by the external layer of structural components. Since, the internal structural members do not follow the twisting form, regular floor plans can be provided and the interior spaces can be flexibly designed without interruption by the twist. The disadvantage of this system is that the design and construction process of the vertical double-layer space structure will be complicated because of the large number of irregular structural components and joints.

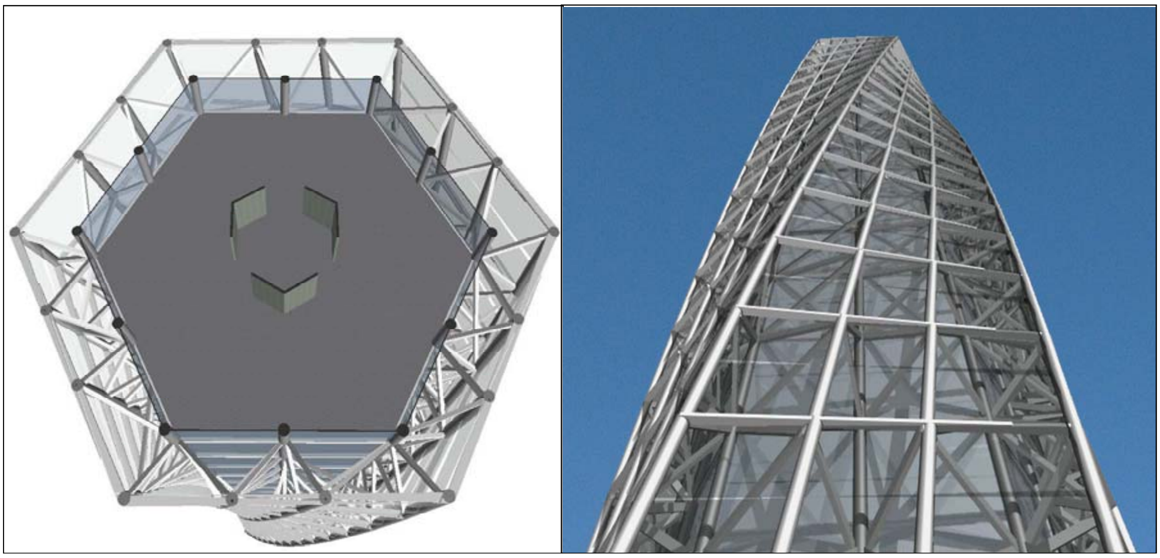


Figure 6.38 A twisted tower using a vertical double-layer space structure

As previously discussed, exterior braced structures like diagrid and braced-tube systems are appropriate for buildings with complex geometries because the loads can travel the most efficient way to the ground through the structure (Scott, et al., 2007). The concept of these structural systems also applies to vertical double-layer space structures, which comprise perimeter self-braced structures. Compared to other conventional structural systems excluding exterior braced structures, vertical double-layer space structures have three advantages in adopting complex geometries:

- The diagonal braces of these structures transfer gravity and lateral loads from the inclined columns in tension and compression. This condition avoids moment and torsion in every structural member caused by the leaning and twisting geometries.
- The dual-layer structural components provide stability as redundant structures especially for resisting overturning moments and torsion caused by the complex geometries.
- The space between the two structural layers can be varied vertically and horizontally in order to provide the desired building form.

These examples show that vertical double-layer space structures, like other exterior braced structures, are suited not only to rectangular buildings, but also for buildings with complex geometries.

However, double-layer space structures in geometrically complex tall buildings have an issue with services components. Elevators and stairs cannot be placed within the two structural layers as in regular buildings with typical floors. Services components normally will have to be placed in a vertical core for practical reasons.

6.6. Summary

This study has discussed structural-architectural integration of vertical double-layer space structures with building façades, entrances, lobbies, interior space, and building geometries by exploring several design strategies and alternative applications. These strategies are summarised as follows:

- Optimising the uniqueness of structural expression, which has a combination of vertical, horizontal, and diagonal components, as well as the dual layers system, to visually and physically integrate with building façades and balconies.
- Several structural members on the ground floors should be modified in order to provide a larger area for entrances and lobbies.
- Interrupted circulation of the internal space can be avoided if the façade is positioned at the same plane either vertically or horizontally with the structural members as shown in the examples in Section 6.3.2.
- Complex geometries are possible in double-layer space structures. The strategy applies by modifying the slopes and lengths of the vertical and diagonal members at every floor in order to follow the building geometry. However, services systems including elevators and stairs cannot be positioned at the perimeter of complex geometry buildings as proposed in Chapter 5.

These strategies have the advantages and disadvantages that are discussed below.

The advantages of structural-architectural integration of vertical double-layer space structures in super-tall buildings come from the uniqueness of these structures, which not only have vertical and horizontal components but also diagonal and a double-layer of structural components. The structural system has the potential to provide many integrated design alternatives. The visual presence of the structure itself is a powerful architectural feature. Various combinations of physical, visual, and performance integration are achieved by expressing the structure as a part of the building façade, placing balconies in the space within the structure, and positioning an entrance between ground level structural members.

The disadvantage of this structural system is the open view obstruction caused by the structural components on the building perimeter. This problem also occurs in other perimeter structural systems. However, the view obstruction is minimised on the upper floors, where the open views are more valuable. Another disadvantage is view obstructions by services components that are located at several areas of the building perimeter as discussed in Chapter 5. Views are blocked by observatory elevators, stair walls, pipes, and ducts.

This study has discussed structural-architectural integration of multi-storey double-layer space structure by showing several strategies for the systems integration including their advantages and disadvantages. Many other alternatives could be explored for this structural system. However, this study offers initial guidance and a starting point for further architectural exploration of vertical double-layer space structures to be used in general high-rise applications.

Chapter 7: Construction

This chapter discusses the constructability of double-layer space structures as a multi-storey structural system. The discussion covers structural materials, profiles and joints, erection methodologies and construction equipment in order to answer the research sub-questions in Chapter 3. An analysis on the construction aspect of multi-storey double-layer space structures is very important as a part of systems integration. For example, by determining the most suitable structural materials, profiles and joints, the integration of structural system with services and architectural systems can be explored. The aim of this chapter is not only limited to analysing suitable structural materials, profiles and joints, but also to consider how to construct this structural system and investigate any construction challenges for general high-rise applications. The study also explores the installation of services components and building façades. Several factors that potentially affect construction costs are also briefly discussed.

As explained in Section 3.4, the study is conducted using the following steps. The construction of several recent tall structures is reviewed, especially those that are relevant to the construction of multi-storey double-layer space structures. The building models designed in Chapter 4 are used as a case study. Based on the literature review on existing high-rise construction, this study explores several construction alternatives, including structural profiles, joints, and construction methodologies, that might be suitable for the models. The advantages and disadvantages of these alternatives are analysed, leading to conclusions for the construction of double-layer space structures in general high-rise applications.

7.1. Structural Materials and Section Profiles

This section discusses the structural profiles and joints that are suitable for these structures from a construction point of view. Chapter 4 has indicated the structural profiles used for a 100-storey double-layer space structure for the purpose of structural efficiency. In this section, structural profiles used in horizontal double-layer space structures and several super-tall buildings are reviewed from a construction perspective. This review leads to a discussion about structural materials and profiles that can be used in double-layer space structures for high-rise applications as discussed in the following sections.

7.1.1. Conventional Horizontal Double-layer Space Structures

The most common structural material for space structures is steel. However, other materials such as reinforced concrete, timber, aluminium, stainless steel, and reinforced plastic can be used as well (Chilton, 2000). For multi-storey double-layer space structures, steel is suitable because of its high-strength and relative light weight nature.

Various structural sections used in horizontal double-layer space structures relate to the joint system. Tubular profiles are commonly used in these structures because they provide efficient compressive resistance, good aesthetic appearance, and allow for connections by various joint systems. The Mero KK system, which connects circular tube members with ball joints was the first commercially available and is the most elegant system (Figure 7.1 (a)).

Other structural sections used in space structures are box and channel sections, and their combinations. They can also be combined with tube members. The Unistrut system comprises of box or channel sections as the members, and steel plates as the joints using strut, bolt, and nut (Borrego, 1968). The Harley system connects continuous chords, which can be box or channel sections without special node components for the joints (Figure 7.1 (b)). This system can reduce structural cost (Chilton, 2000).

Figure 7.1 (a) Mero KK system (Photo by: Hendry Y Sutjiadi); (b) Harley system (Photo by: Hendry Y Sutjiadi)

The characteristics of vertical double-layer space structures differ compared to horizontal double-layer space structures in terms of force distribution. Conventional horizontal double-layer structures mainly resist gravity loads. The structures act as a slab distributing gravity loads horizontally to the supports as shown in Figure 7.2 (a). Vertical double-layer structures resist combination of lateral and gravity loads. However, as buildings rise taller, lateral loads impact the buildings much more than vertical loads (Taranath, 1988). Like other vertical structures, vertical double-layer space structures act as vertical beams cantilevering from the earth (Taranath, 1998) as shown in Figure 7.2 (b). The differences between horizontal and vertical double-layer space structures are summarised below:

- Horizontal double-layer space structures

  The top and bottom chords normally have the same or similar sizes because they resist moment in compression and tension. The diagonal chords have smaller sizes resisting shear in compression and tension.

- Vertical double-layer space structures

  As shown in Table 4.2 and Table 4.4 in Chapter 4, the vertical structural components are the largest because they resist a combination of lateral and gravity loads. The diagonal members, which resist shear forces from lateral load, have smaller sizes. All member sizes increase from the top to the bottom floors as gravity and lateral loads accumulate.

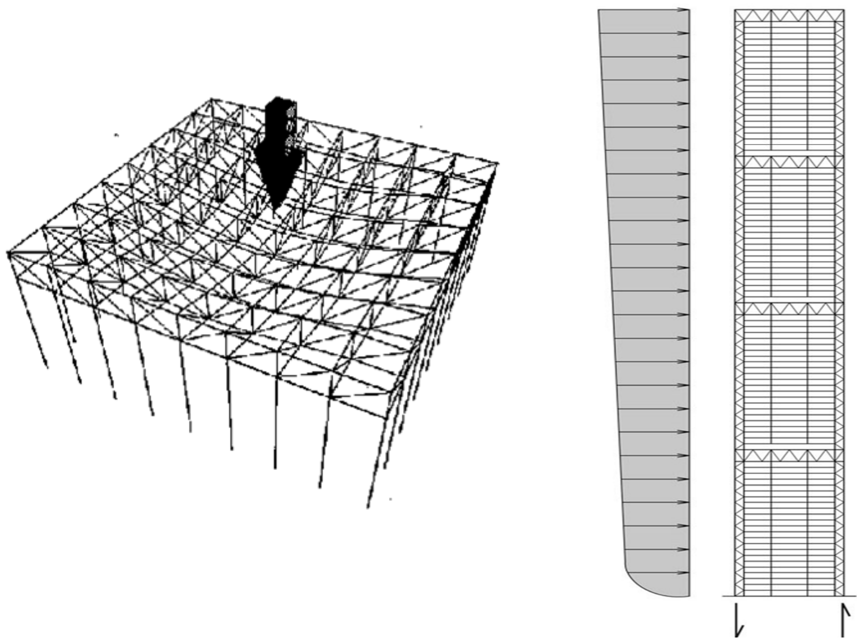


Figure 7.2 (a) Conventional horizontal double-layer space structure (Chilton, 2000, p. 13); (b) Vertical double-layer space structure

This condition makes vertical double-layer space structures quite different from conventional horizontal double-layer space structures in terms of structural sections and joints. Section 7.1.3 discusses the structural profiles and joints that can be used.

7.1.2. Structural Members and Joints in Super-tall Buildings

Structural connections are mainly classified into pinned connections which allow rotation of the beam, and moment connections which resist moment (Davison & Owens, 2003). Multi-story framed steel structures mainly have column-to-column and beam-to-column rigid connections.

In super-tall buildings, column profiles have developed beyond conventional I-steel shapes to mega columns that commonly comprise of concrete-steel composite columns or concrete filled tubular steel columns.

Willis tower for example, built 442 metres high in 1974, comprises I-steel profiles (Figure 7.3). The structure, using a bundled-tube system, has the maximum dimensions 0.99 m deep and 0.61 m wide for columns and 1.07 m deep and 0.41 m wide for beams. The maximum flange thicknesses are 102 mm for columns, and 70 mm for beams (Iyengar, 1972).

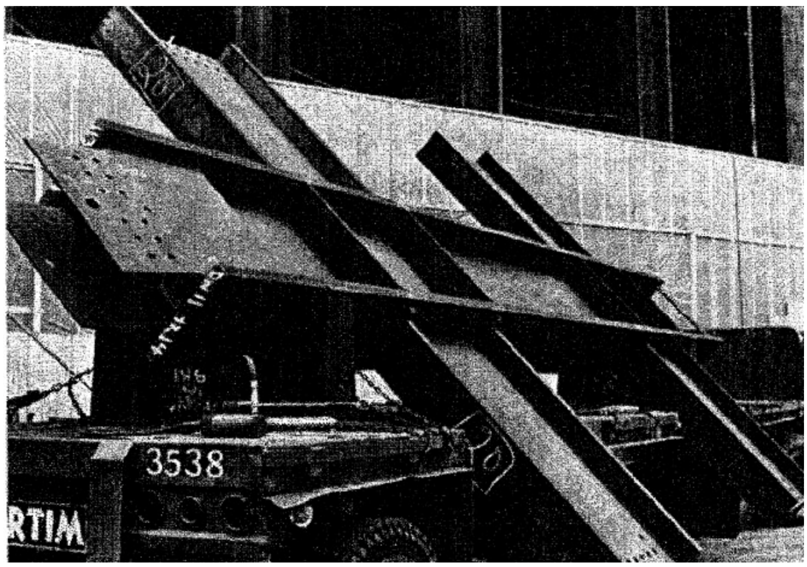


Figure 7.3 A beam-column assembly for the Willis Tower (Iyengar, 1972, p. 73)

In 1998, the Jin Mao tower in Shanghai was constructed using a reinforced concrete core linked to perimeter composite mega-columns by outrigger trusses. The composite columns vary from 1.5m x 4.8m at ground level to 0.9m x 3.3m at level 87 (Korsita, Sarkisian, & Abdelrazaq, 1996).

In Taipei 101, the concrete-filled-steel-tube columns have the maximum size of 2.4m x 3.0m using 60 ksi yield strength steel plates of 80 mm thickness. Columns at the top floor are 1.8m x 2.2m. Figure 7.4 shows two vertical stiffener plates provided at each side of the column to reduce the plate's width to thickness ratio, increase strength, and enhance confinement to the concrete (Shieh, Chang, & Jong, 2003). The mega columns are connected to each other by welding on site (Inoue, 2003).

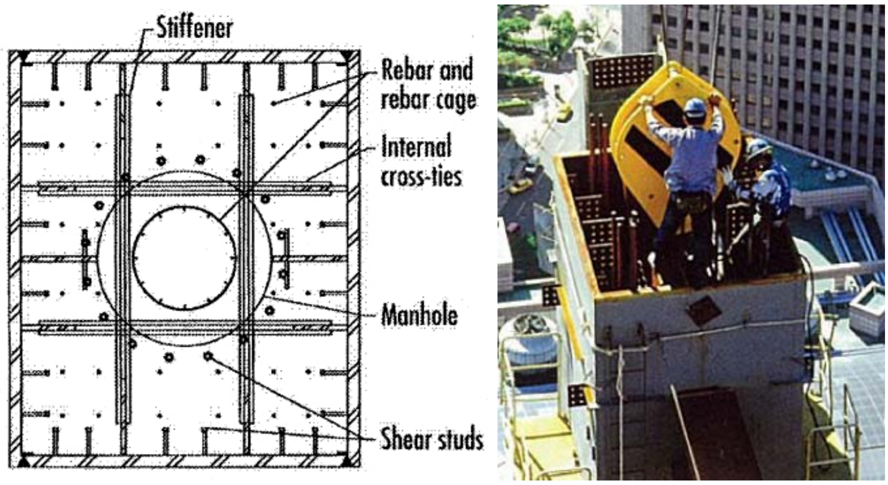


Figure 7.4 (a) Column section in Taipei 101 (Shieh, Chang, & Jong, 2003, p. 33); (b) Column erection (Binder, 2008, p. 68)

These super-tall buildings, which were built in different decades, use different structural systems and materials, but they all have large structural components. This condition shows how current super-tall buildings used large size structural members especially for columns.

7.1.3. Structural Member and Joints in Vertical Double-layer Space Structures

Considering the structural profiles and joints of conventional horizontal double-layer space structures and multi-story steel structures discussed above, several structural profiles and connection systems are suggested for the vertical double-layer space structure. Welding is used here almost exclusively. Bolts are also used to connect horizontal and vertical members since the horizontal members are relatively small.

Alternatives of structural section shapes for the vertical double-layer space structure are discussed as follows. The discussion develops the structural profiles shown in Table 4.2 and

Table 4.4 in Chapter 4. As mentioned in Section 4.1.4, various structural member profiles can be used as long as they have the same profile areas and moment of inertia with the structural profiles in those tables. This section discusses alternative structural profiles for practical construction considerations. Tubular sections, either circular or rectangular, can be used for all members. They provide reasonable moments of inertia, good appearance, and relatively simple connections. Like columns of other super-tall structures, they are large, so they must be prefabricated. The horizontal members are relatively small, so they can be purchased pre-formed. Box, wide flange or channel profiles are suitable for these horizontal chords.

Several alternatives of structural member profiles and connections are explained as follows. The first alternative profile shown in Figure 7.5 (a) has the same perimeter sizes and profile areas as those of Box 950x950x95 shown in Table 4.2 for lower floors external vertical members. Assembling several plates 50 mm thick is easier for fabrication and minimizes cracking during fabrication and erection rather than using 95 mm thick plates (Miller, 2010). This profile, although having less buckling resistance and inertia compared to the profile in Table 4.2, does not significantly affect the structural capacity because the design is driven more by lateral deflection limit than strength limit as mentioned in Chapter 4, so area is more important than moment of inertia. The internal plates work as stiffeners to avoid localised buckling of the external plates. The second alternative is shown in Figure 7.5 (b). These two alternative profiles have different yet suitable structural connections that are discussed below.

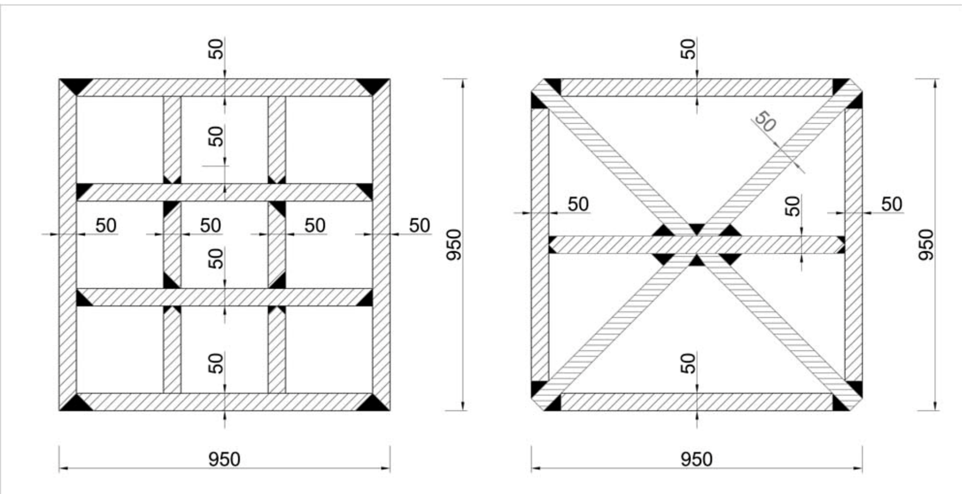


Figure 7.5 (a) Rectangular hollow section using internal steel plates; (b) Another alternative rectangular hollow section

Figure 7.6 shows the technique and detail suggested to connect two large vertical members shown in Figure 7.5 (a). These members are connected by welding, and finally two steel plates are welded to cover the joint. The vertical members shown in Figure 7.5 (b) can also be connected using the same technique as shown in Figure 7.7.

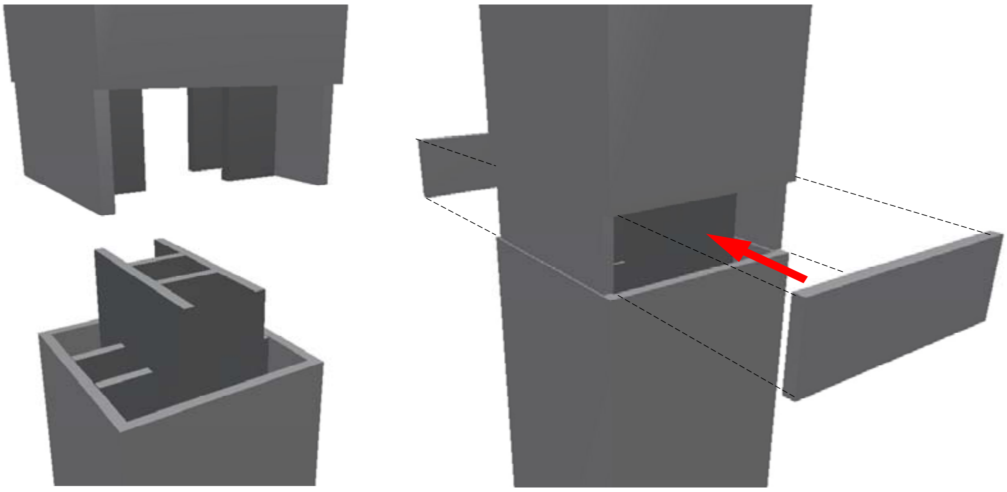


Figure 7.6 Two steps of connecting the vertical members

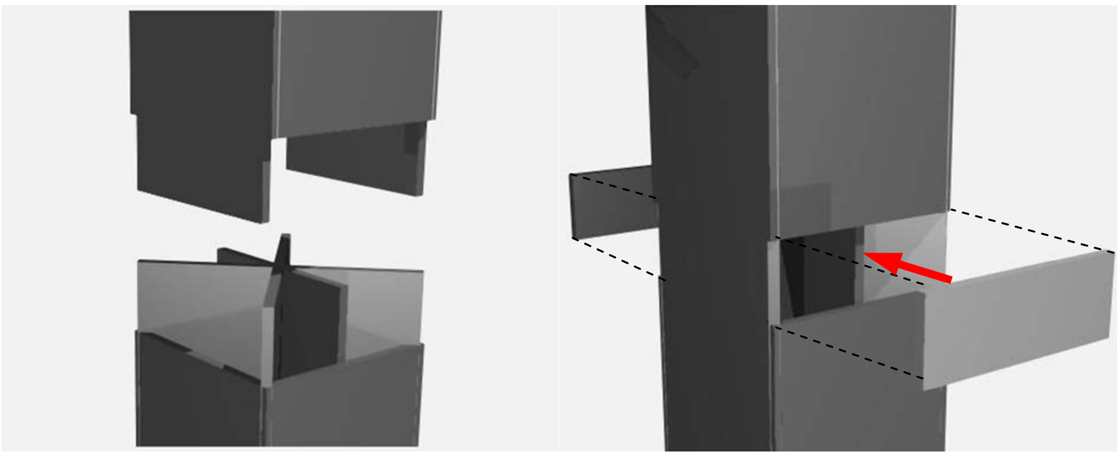


Figure 7.7 The same steps for connecting the other type vertical members

Figure 7.8 (a) shows another alternative for vertical members using a concrete filled rectangular steel tube. The concrete is assumed to have 70 MPa compression strength and steel bars can be used to minimize creep and cracking. The conversion from steel Box 950x950x95 to the concrete filled rectangular steel tube using the same perimeter sizes is based on their capacity resisting axial compression force only. The structural weight of the composite column is about 25% higher than the steel column. Figure 7.8 (b) shows another alternative concrete filled rectangular steel tube. The outer dimensions are smaller but the plate thickness is higher than those in the first alternative. The column gross area reduces about 30% but the structural weight increases about 13% compared to that of the steel tubular rectangular column. The second alternative concrete filled rectangular steel tube has smaller profile and less weight, but thicker steel plates compared to the first alternative. This discussion shows that composite materials can be used as an alternative for the members of vertical double-layer space structures.

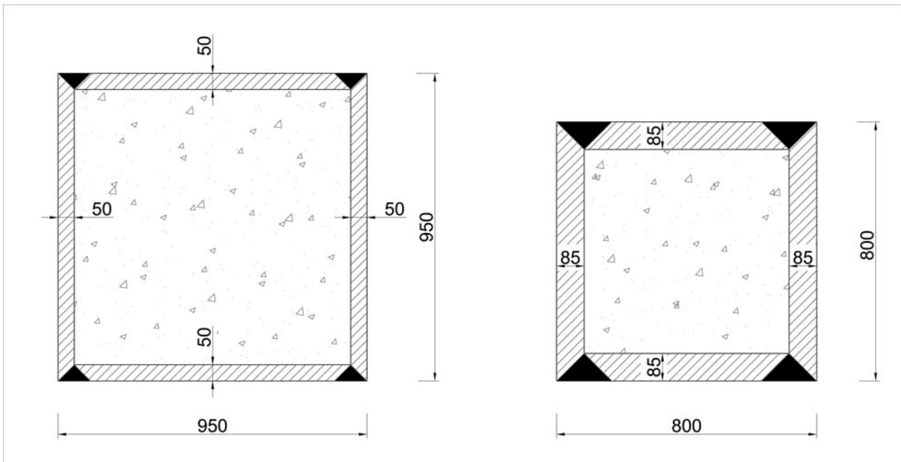


Figure 7.8 (a) Concrete filled rectangular steel tube; (b) Smaller size concrete filled rectangular steel tube

In terms of structural joints, Section 7.1.1 has explained that structural connections of horizontal double-layer space structures cannot be used in vertical double-layer space structures because of different force distribution. Therefore, a structural joint using gusset plates can be an alternative to connect the diagonal to the vertical members. The gusset plates are welded to the corners of the vertical members. This joint can be used for both circular and rectangular hollow sections as shown in Figure 7.9. This type of joint is suitable for the vertical members shown in Figure 7.5 (b) and does not induce torsion and moment since forces act at the centre line of each member. These joints are relatively simple compared to the Mero KK and Orona systems of conventional horizontal double-layer space structures.

A special joint using three-dimensional welded gusset plates connects the diagonal members to vertical members (Figure 7.10). This joint can be used for the vertical members shown in Figure 7.5 (a). Since the diagonal members do not meet at the centre line of column an eccentricity occurs. These eccentric axial forces from the diagonal members vary depending on the vertical member sizes. The moment caused from the eccentricity is resisted by the internal stiffener plates. This type of joints is not suitable for upper floor structural members because the vertical members are relatively small.

A simple pinned joint with plates and bolts can be used to connect the horizontal and vertical members (Figure 7.10). This type of joint is suitable for practical construction because the horizontal members are relatively small compared to the other members.

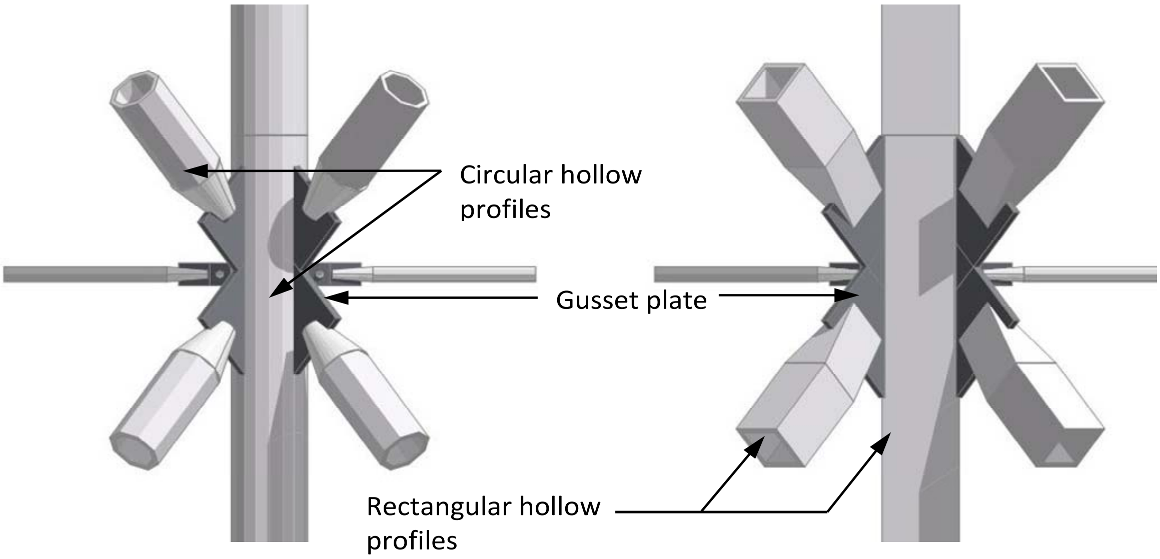


Figure 7.9 Structural joints for circular and rectangular hollow profiles

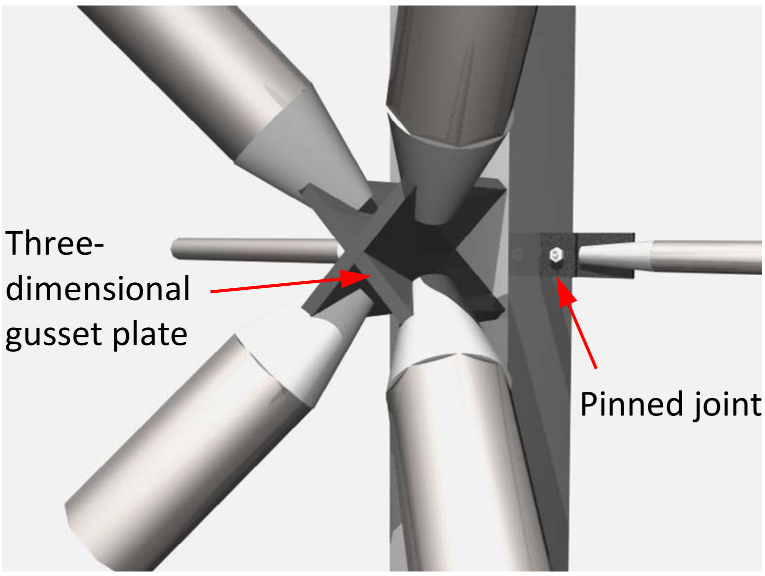


Figure 7.9 The three-dimensional gusset plate for the diagonal members and the pinned joint for the horizontal members

This study has discussed the constructability of vertical double-layer space structures by showing examples of structural member profiles and joints that are suitable for general high-rise applications. Since the discussion does not cover their strength, more sophisticated study using a finite element analysis and physical tests in a laboratory can be used to investigate the strength of these connection systems. Based on literature review on horizontal double-layer space structures and tall steel structures, structural member profiles and joints that are suitable for high-rise double-layer space structures are illustrated using computer modelling as examples. These examples are presented from an exploration of various physical models using a different material and a smaller scale in order to visually analyse their constructability. They also have discussed in what situation each structural member profile and connection might be more applicable. By presenting examples based on the literature study, this section concludes the constructability of multi-storey double-layer space structures using plausible structural member profiles and connections.

7.2. Erection Methodologies

This section discusses several alternative construction methodologies for multi-storey double-layer space structures. Erection methodologies commonly used in steel high-rise buildings are reviewed. The review shows that double-layer space structures have a different structural member configuration than that normally used in multi-storey steel structures by the existence of the diagonal members and double-layer structural members. This condition leads to a need for further developing construction methodologies and erection techniques used in conventional high-rise structures.

7.2.1. Erection of Multi-storey Steel Structures

Factors that should be considered in multi-story steel construction are material assemblies and erection methodologies (Lin, 2001). To select erection methodologies that are applicable for the multi-storey double-layer space structure, firstly three examples of steel construction systems commonly used in tall and super-tall buildings are discussed. A unique construction method is also reviewed because the structure has a similar characteristic with multi-storey double-layer space structures. These examples are discussed as a starting point for exploring strategies for constructing vertical double-layer space structures.

Material assemblies and erection methodologies of recent super-tall structural systems are varied and more complicated than construction of conventional rigid frames. Beams, columns or other structural members are normally fabricated before being erected to their final position, like the assemblies of structural elements and connections in the trussed tube of the John Hancock Center, Chicago. The diagonal members, columns, and beams were all made of built-up steel H-sections, and the major joints were fabricated in the workshop (Khan, 2004). The thick steel plate joints were prefabricated by welding and then connected to other steel members using bolts as shown in Figure 7.10 (a). This concept has also been applied in the construction of the Shanghai World Financial Center, Shanghai. Diagonal members, which are welded steel boxes, are connected to composite columns of structural steel in-filled with reinforced concrete (Katz, Robertson, & See, 2008) as shown in Figure 7.10 (b).

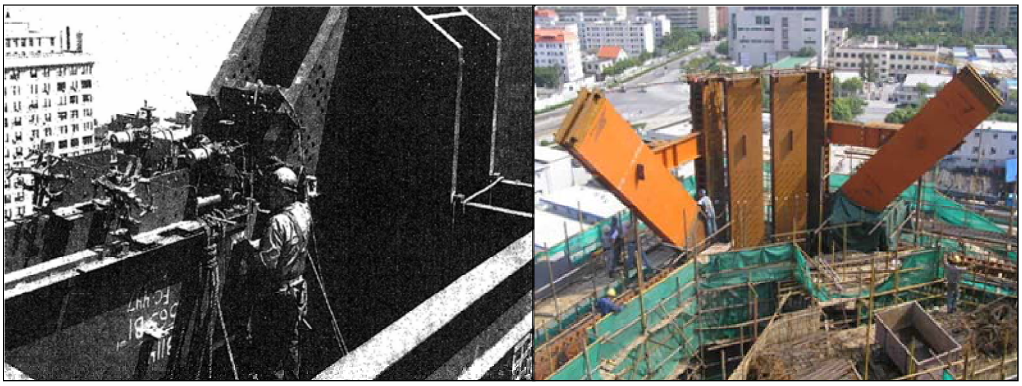


Figure 7.10 (a) Joints in the John Hancock Center (Khan, 2004, p. 19); (b) Joints in Shanghai World Financial Center (Katz, Robertson, & See, 2008, p. 72)

Another example of pre-assembly of structural materials can be seen at the Commerzbank Tower, Frankfurt. Figure 7.12 (a) shows that the columns, beams, and diagonal members were assembled as one piece to ease the erection process (Davies & Lambot, 1997). This concept

Figure 7.11 (a) Construction of Commerzbank Tower, Frankfurt (Davies & Lambot, 1997, p. 115); (b) Panels in World Trade Center, New York (Source: 911review.org)

was also applied in the World Trade Center, New York, as shown in Figure 7.12 (b). The panels, which consisted of box beams and columns, were connected to each other around the building perimeter to make a framed-tube system.

An example of a unique construction methodology of a suspended structure can be seen in HSBC Headquarters, Hong Kong (Figure 7.12). In this building, a temporary support was placed to hold the centre tension hanger above. Another temporary support on the lower zone had been removed from its position because the truss system had been installed; therefore the centre hanger could hang from it. This means that the construction started with the erection of vertical members followed by gravity beams and the centre hangers. This step continued on each level until the main truss level was reached. After the main trusses were installed, the centre hanger could then take all gravity loads from the floors below in tension (Lambot, 1986).

The system of a suspended structure applied in HSBC Headquarters, Hong Kong, can also be used in the multi-storey double-layer space structure. Temporary supports are also used to transfer the gravity loads from the internal gravity columns to the foundation during construction. The construction of lateral and gravity systems of vertical double-layer space structures are discussed in the following section.

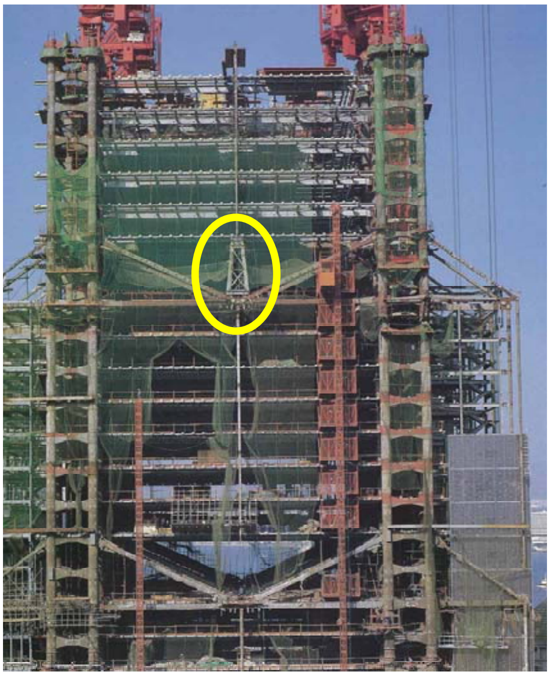


Figure 7.12 A temporary support on the construction of HSBC Headquarter, Hong Kong (Lambot, 1986, p. 32)

7.2.2. Construction of Vertical Double-layer Space Structures

From the discussion about construction of multi-story steel structures above, several construction alternatives are suggested for the vertical double-layer space structure.

The first alternative erection: a conventional method

Vertical double-layer space structures are naturally self-bracing free-standing structures. At least two external vertical members and one internal vertical member should be erected first and connected to each other with diagonal and horizontal members as shown in Figure 7.14 (a). At this stage, the assembly of the members form a stable structure. After the first module is built the rest of that side is completed. This process continues until all sides of the building at the ground level are completed as shown in Figure 7.14(b).

The higher the floor levels, the lighter the structural members. For the higher floors, the vertical, horizontal, and diagonal members can be assembled together and then craned up to their final position, minimising erection time.

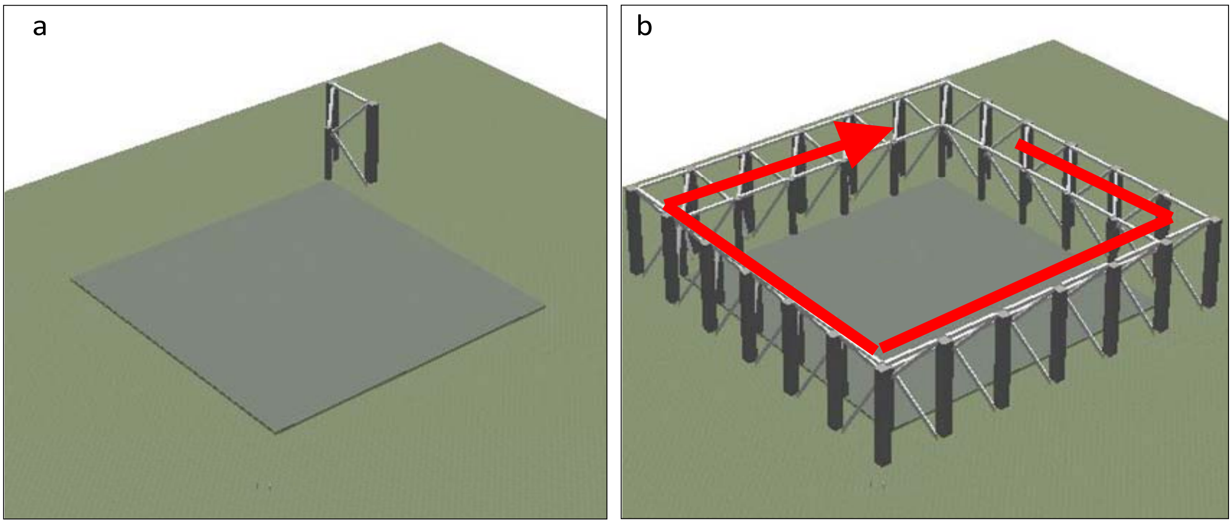


Figure 7.13 (a) The first step construction: forming the first module; (b) Completion of the ground floor structure

A conventional method used in typical high-rise buildings can be used for the erection of the gravity system. Gravity columns are erected and then gravity beams connected to them. When suspended columns are used, temporary supports like those used in the construction of HSBC Headquarters, Hong Kong, can also be used. The process carries on from the ground to the top floor. Corrugated steel-decking is then placed after the primary structural members have been erected, and followed by concrete topping.

The second alternative erection: a new method

Another erection technique is proposed using the following steps:

1. The vertical perimeter double-layer space structure is erected on three sides from the ground floor to the level of the horizontal space structure as shown in Figure 7.14 (a). The structure on the fourth side is not erected in order to provide enough space to deliver materials to the ground floor area of the building.
2. The horizontal double-layer space structure is installed at ground floor and then hoisted to its final position. At this stage, the structure is more stable than at the first stage because three vertical structures have been connected with a horizontal structure forming a diaphragm shown in Figure 7.14 (b).
3. This procedure is repeated for the vertical and horizontal structures of the upper zones. At the same time, the gravity system of the bottom zone can be erected using the following steps.
4. Three hoists on rails are installed below the bottom chords of the horizontal double-layer space structure to enable the hoists to move horizontally. At the same time the gravity columns on the ground floor are erected. If suspended "tension" columns are used, temporary "compression" columns should be placed to support the gravity structure. Assemblies of the gravity beams and corrugated steel-decking (or hollow core concrete slabs) are placed at their final position by the hoists. The sequence of placing these assemblies from the ground floor to the upper floor is shown in Figure 7.14 (c). This process continues horizontally from the side where there is perimeter structure to the side where the perimeter structure has not yet been installed, as shown in Figure 7.14 (d). Alternatively, joists that move in two directions can be used.
5. The assemblies of gravity beams and corrugated steel-decking (or hollow core concrete slabs) in the last grid to be completed must be hoisted at the same time as the supporting internal vertical layer of the perimeter structure as shown in Figure 7.14 (e). Rails for the hoists can be lengthened to cantilever from the horizontal double-layer space structures so the hoists have enough space to crane the assemblies. This process is followed by concrete topping either using concrete pumps or a bucket craned by the hoists.
6. The final step is erecting the vertical double-layer space structure on the last side (to its final position) by tower cranes as shown in Figure 7.14 (f).

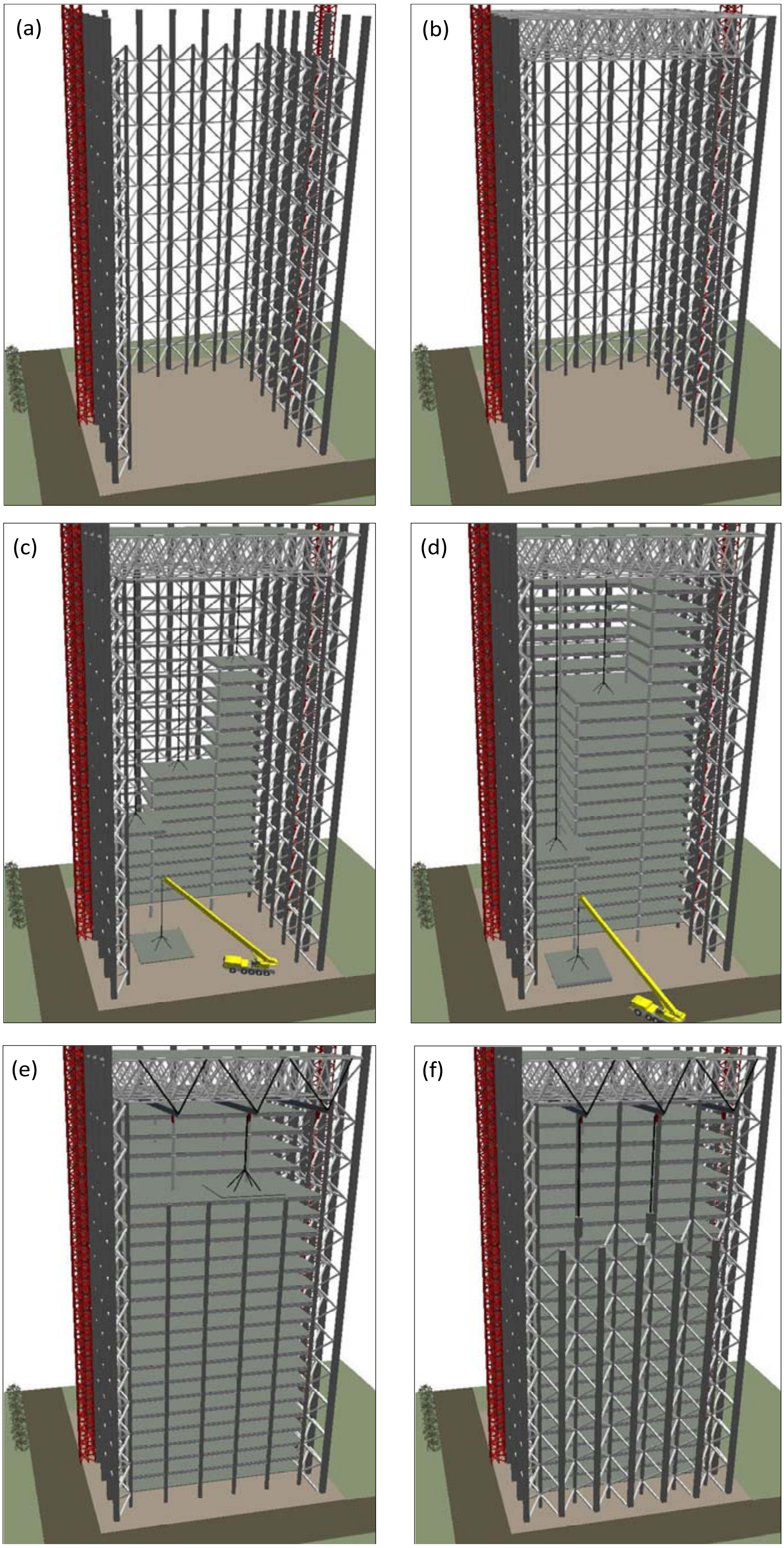


Figure 7.14 Construction sequence

7. This procedure is repeated for the gravity structures of the upper zones. Tower cranes are used to deliver materials to the base floor of the zone, and then installed in their final positions using the hoisting procedure explained above.

Construction considerations

Factors to be considered in the construction technique explained above are as follows:

1. Structural stability under wind loads during construction.

   The most critical step of the erection is when the three sides of the vertical perimeter structure are erected but unconnected to the horizontal double-layer space structure. Structural analysis using ETABS (*ETABS version 9*, 2005) has been conducted to analyze the structural stability under wind load for this condition. The analysis covers four different construction heights, 100, 200, 300, and 400 metres. Figure 7.16 shows that the demand/capacity ratios of the structural members are under 0.5s representing adequate structural stability.

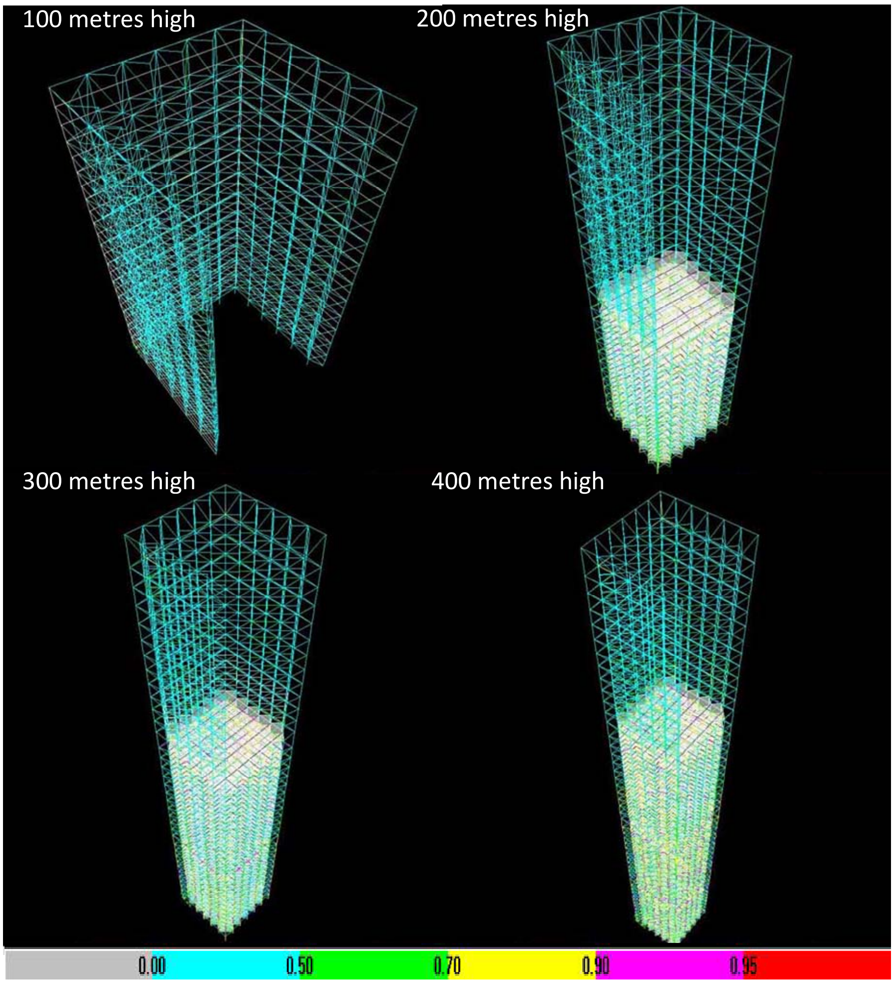


Figure 7.15 Demand/capacity ratio of the vertical double-layer space structure during construction in 100, 200, 300 and 400 metres high.

2. Connecting gravity beams to the vertical members.

   Gravity beams should be connected to the vertical members by pinned joints for two reasons. Firstly, to prevent the gravity structures resisting lateral loads; the second, to ease the construction process. Temporary support brackets can be used for easier placing and attaching beams to columns. As the final step, the beam web should be permanently connected to the columns, either by bolts or welding (Figure 7.16).

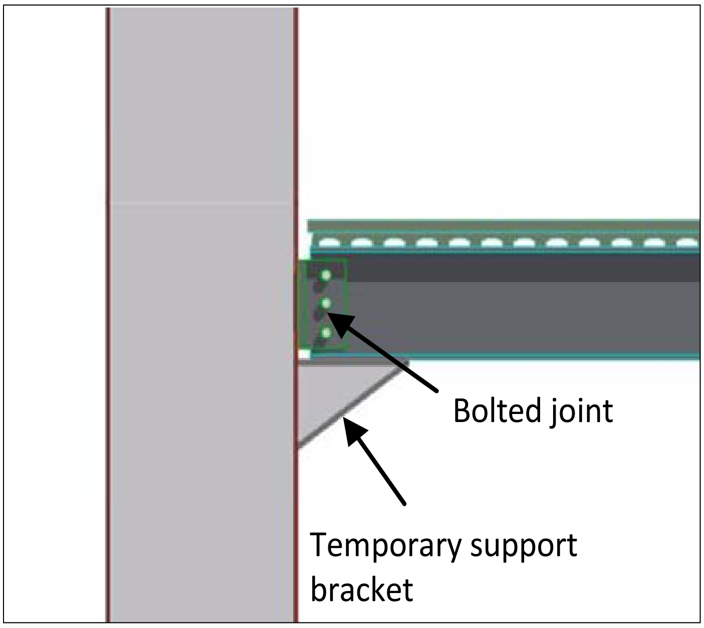


Figure 7.16 Temporary support brackets to ease placing gravity beams at the vertical members

7.3. Installation of Services Components and Building Façades

Chapters 5 and 6 have discussed the integration of double-layer space structures with services and architectural components. Since the composition of this structural system is different from those of other high-rise structures, the connection details of services components to the structure and the construction of the building façades are explored in this section, presented as an alternative installation that can be applied generally.

7.3.1. Connection Details of the Services Components to the Structure

In conventional tall buildings, services components like pipes, ducts, elevators, and stairs are mainly located in the core. In the double-layer space structure building, it is proposed that several services components are placed within the perimeter structure. Since this application is not common, their installation details should be analysed. The details of these services components including the observatory elevators and the fire stairs connected to the double-layer space structure are discussed.

Connection of the Observatory Elevators to the Structure

The elevator components can be connected to the structure using various strategies. A strategy is described as an alternative as follows:

- The elevator rails are attached to the beams of the internal layer of the perimeter structure.
- The position of the counter-weights is near the external columns. The counter-weight rails can be attached to the diagonal members.

Figure 7.18 shows how the elevator components are connected to the structural members.

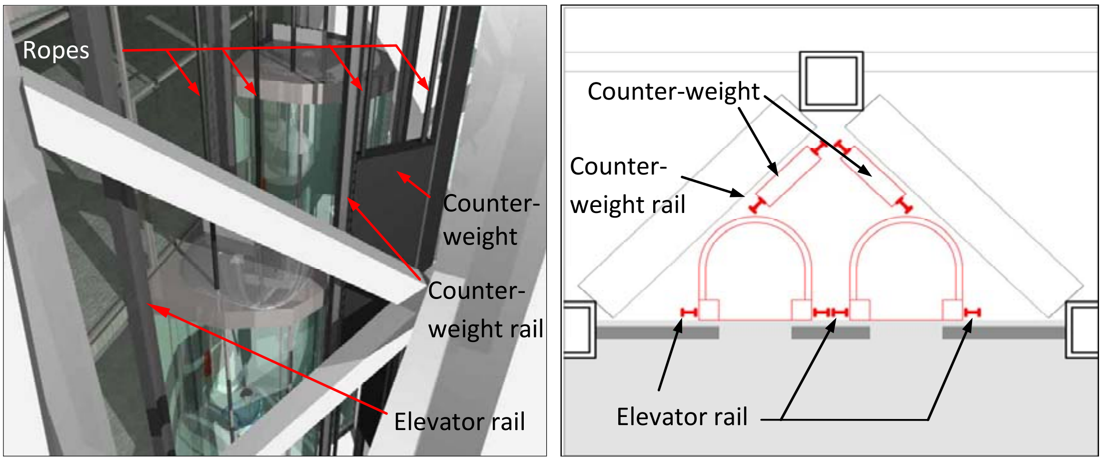


Figure 7.17 (a) The elevator components; (b) Elevator details in plan

Connection of the Fire Stairwells to the Structure

Fire stairwells have to have their own route to the ground, so evacuees don't have to enter the building area. In a multi-storey double-layer space structure building, the fire stairwells can be located within the perimeter structure at two different locations distant from each other. Enough space for stair landings is provided to minimise the fatigue of people on their way downstairs to the ground floor, and to meet health and safety requirements. Landings also allow enough space to open the doors without interrupting evacuation using the stairs. Either single- or double-layer fire-rated walls can be used to protect the stairwells from fire. Figure 7.19 shows the detail of the fire stairwell integrated within the double-layer space structure.

These two examples show that the space between the two structural layers can be used for elevators and stairs. Pipes and ducts can also be placed within the perimeter structure as in a core. The above installation details present a strategy to integrate elevators and stairs with the structure. However, this strategy cannot be applied for super-tall buildings with complex geometries because they do not have vertical linear shafts. These types of buildings need different strategies for structural-services integration.

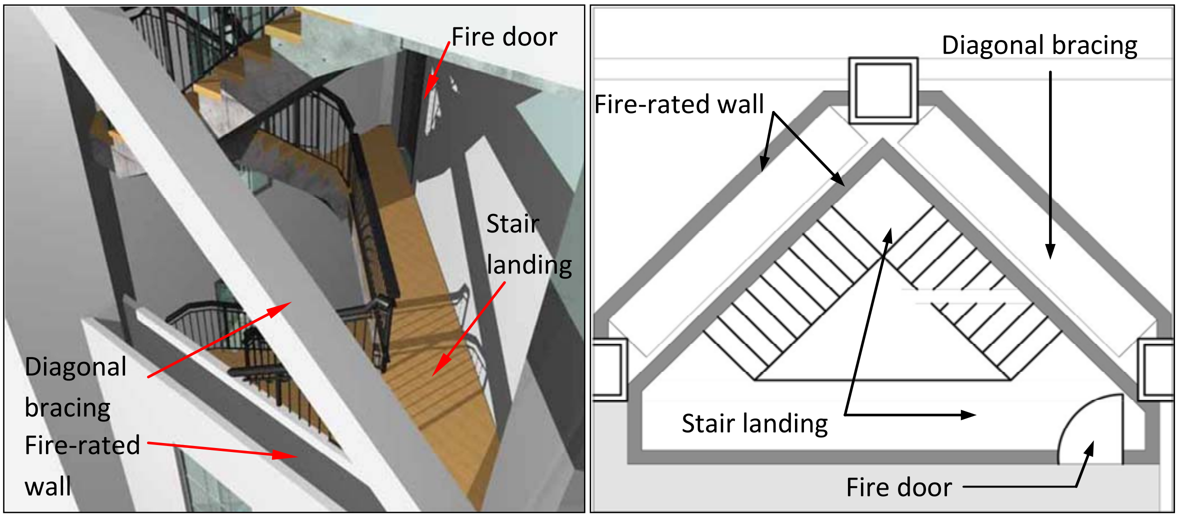


Figure 7.19 (a) The fire stairwell within the structure; (b) The fire stairwell in plan

7.3.2. Construction of the Building Façades

Façade systems in tall buildings normally comprise prefabricated double-glazed panels. Panel systems minimise the construction difficulties of façade installation, especially at very high levels. Figure 7.20 shows façade installation in the Business Tower, Nuremberg. The façade panels were attached to brackets mounted on the concrete structure of the building. An irregular-form façade can be seen in the Capital Gate, Abu Dhabi. A façade panel consisting of several pieces of glass is attached to two triangulated structural modules (Figure 7.18). Since the building has a complex leaning geometry, the façade panel sizes are different from each other.

Figure 7.20 The façade panels installed in the Business Tower, Nuremberg (Oesterle, 2001, p. 136)

Chapter 6 discussed various façade systems that can be used in double-layer space structures. The construction of these façade systems is more complex compared to conventional high-rise façade construction because of the double structural layers and the diagonal members. The construction of four façade systems - the exposed structure, the double-skin façade, the vertical folded façade, and the horizontal folded façade - is discussed in the following sections.

Figure 7.18 The façade panels in the Capital Gate, Abu Dhabi (Source: dubaiconstructionupdate.blogspot.com)

Exposed Structure

In the exposed structure of double-layer space structure buildings, the façade is placed at the internal structural layer. Installation using panels cannot be applied in this façade system because the diagonal members and external structural layer make the installation very difficult. The façade can be assembled on site by installing the glass and its frame from inside the building as shown in Figure 7.22. The mullions and glass frames can be attached to the top and bottom concrete slabs.

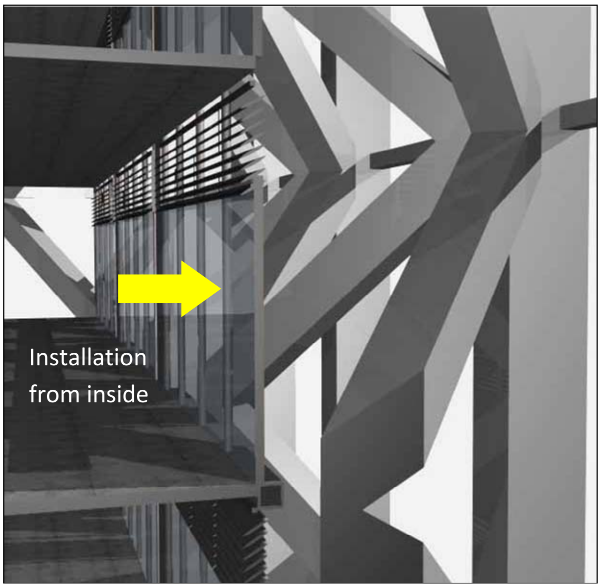


Figure 7.19 The façade installation of the exposed structure building

Double-skin Façade

In a double-skin façade building, each layer can be installed simultaneously or separately using two different techniques. The façade of the internal layer can be assembled from inside as in the exposed structure building. The façade of the external layer should consist of pre-assembled panels for the purpose of practical construction. A panel can be sized to fit the net area between the vertical and horizontal members. This technique is common in the façade installation of high-rise buildings. However, the panel installation in the double-layer space structure building is more complex than for conventional high-rise buildings because there is a gap there is nowhere for the construction workers to stand. In the double-layer space structure building, workers cannot install the panel from the concrete slab as they do in conventional high-rise buildings as shown in Figure 7.20. To solve this problem, a steel beam or truss is attached to the top of the panel. The beam and the panel are be craned together, while workers can install the panel by standing on the beam. Figure 7.20 shows the installation of the panels in a similar way to how steel workers install steel beams in conventional high-rise buildings.

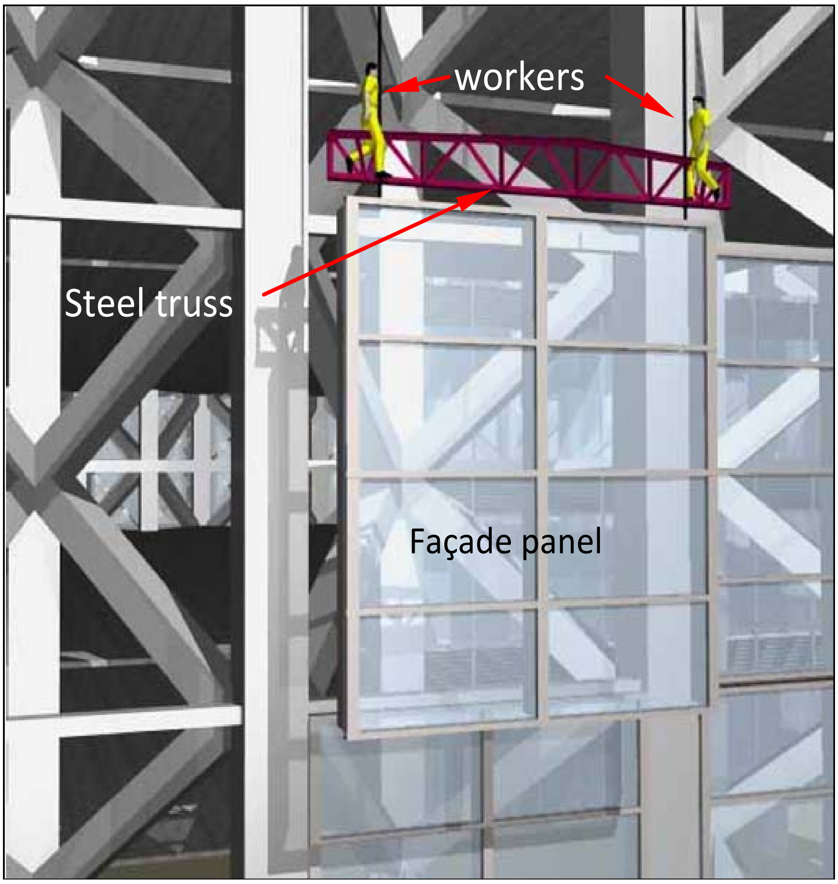


Figure 7.20 Installation of the external façade

Vertical folded façade

In the vertical folded façade installation, the façade can be pre-assembled in panels. The panels are installed to the external and internal columns forming a zigzag façade in plan. The top and bottom panel frames are attached to the top and bottom concrete slabs. This installation is more complex than façade installation for the double-skin façade. The panels cannot be craned close to the concrete slab because of the horizontal structural members. The installation requires co-operation between two teams. The first team of workers stand on the steel truss craned up together with the panel. The second team on the concrete slabs wait for the panels. They lead the first team by drawing the panel close to the concrete slab using simple equipment like a rope or a steel wire (Figure 7.24).

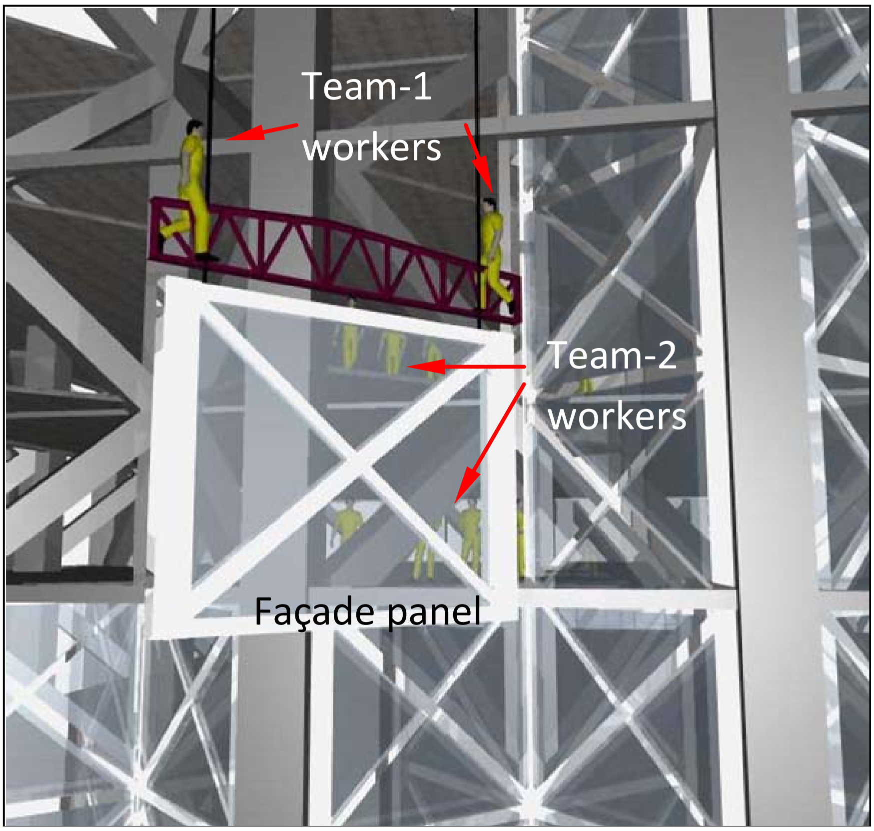


Figure 7.21 Workers in two teams install the vertical folded façade panels

Horizontal folded façade

The horizontal folded façade can be installed using the same technique as for the vertical folded façade. The only difference is in the shape of its panels. Triangulated panels are used in the horizontal folded façade, while rectangular panels are more suitable for the vertical folded façade. The triangulated panels are attached to the diagonal and horizontal structural members. Figure 7.22 shows the triangulated panels of the horizontal folded façade.

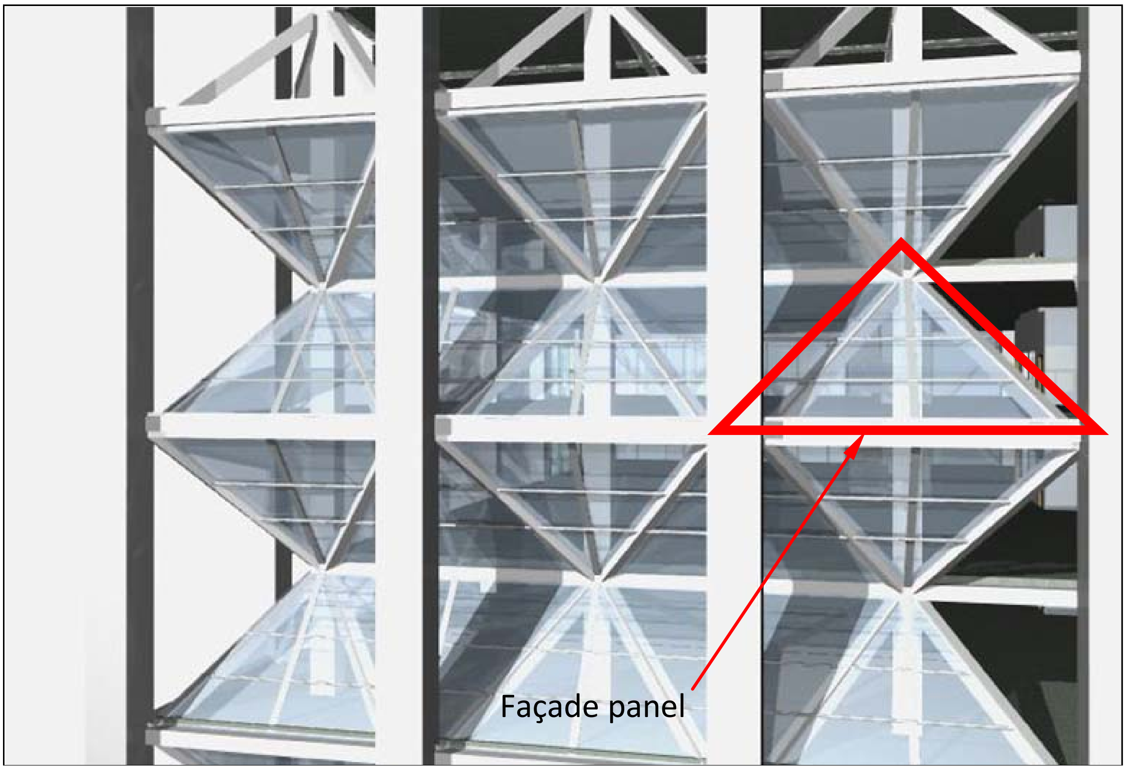


Figure 7.22 The panels of the horizontal folded façade

The installation of the alternative façade systems in double-layer space structure buildings has been presented above as an alternative strategy. These installation techniques are more relatively complex than those of conventional high-rise buildings. Further research is recommended to explore more practical techniques of installing double-layer space structure façades.

7.4. Construction Equipment

This section discusses the equipment required for the construction of multi-storey double-layer space structures. This discussion is presented as an alternative that can be used for general applications. In real life, different construction methodologies might require different construction equipment.

Construction equipment normally used for conventional high-rise buildings can be used for the first alternative erection procedure discussed in Section 7.2.2. For example, tower cranes should be used and placed in strategic positions to optimise their handling capacity.

Also, fixed-base tower cranes located outside the building footprint can be used to ease assembly operations, and delivery and lifting of materials and equipment (Gray & Little, 1985).

Construction of the bottom floors involves larger and heavier structural members than those of the upper floors. High-capacity tower cranes are can be used for erecting the heavy vertical members on the lower floors. For example, an 8-metre long 950mm x 950mm vertical member weighs about 20 tons. Tower cranes that normally have a main jib between 30 and 60 metres long, and maximum lifting capacity of 6 and 12 tons (Peurifoy & Schexnayder, 2002) are unsuitable for this situation. Two high-capacity tower cranes, which can each carry 26 tons at the radius of 85 metres (Manitowoc, 2010a) shown in Figure 7.26, can be used for the construction of the 48m x 48m building. To determine the required number of the tower cranes, an important factor that should be considered is the relationship between construction time and tower crane capacities (Gray & Little, 1985).

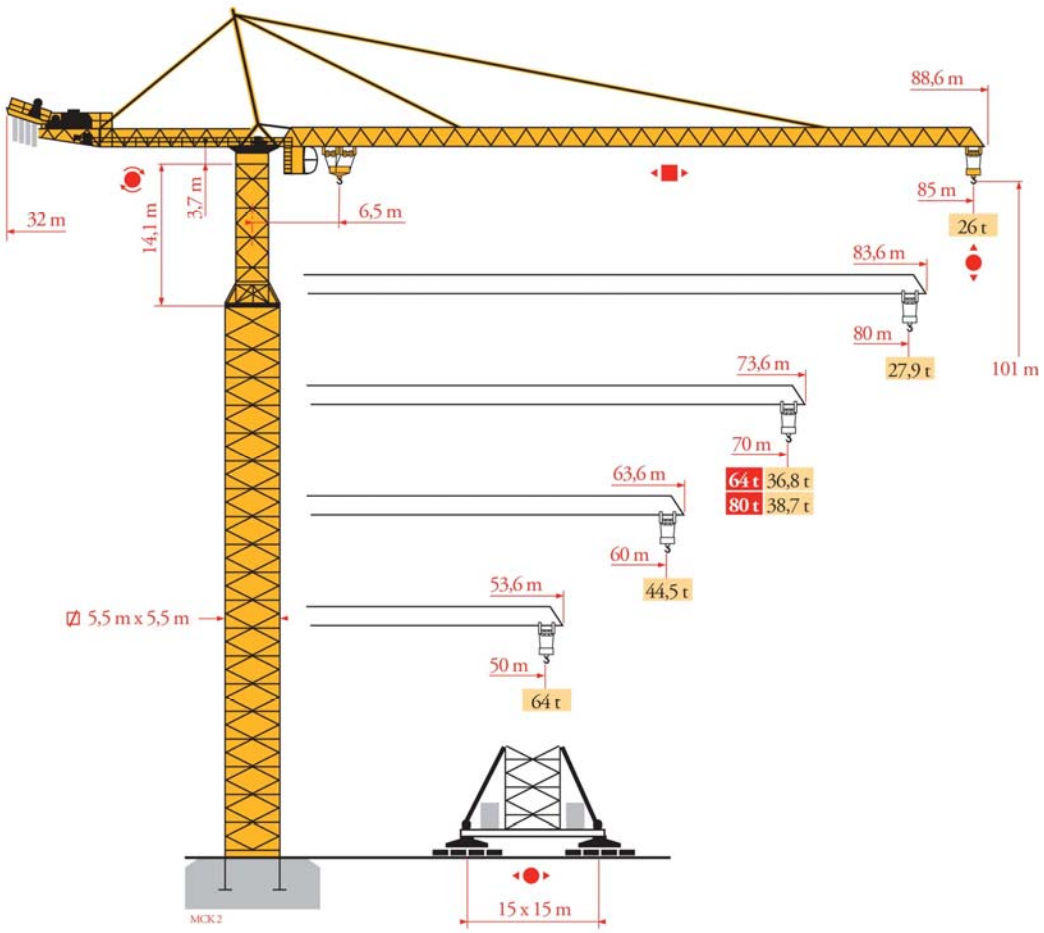


Figure 7.23 Details of a high-capacity tower crane (Manitowoc, 2010a)

An alternative is to use high-capacity mobile cranes with long booms combined with medium size tower cranes to reduce equipment cost. For example, mobile cranes with 450 ton capacities and 60 metre booms, which can lift 25 tons 40 metres high (Manitowoc, 2010b), can be used for heavy structural member installation from the ground to the eighth floor, and medium size tower cranes can lift lighter materials to upper floors.

The second erection technique discussed in Section 7.2.2 proposes movable hoists to lift the gravity structure. The hoists and rails can be attached to the horizontal double-layer space structure and can be removed after the construction is complete.

The equipment above has been discussed as alternatives. However, contractors might have different techniques because projects always have different conditions.

7.5. Construction Costs

This section discusses several factors that affect the construction costs of multi-storey double-layer space structures. Detailed cost estimations or cost comparisons with other structural systems are not provided because the costs of construction in different locations and conditions vary.

Tall buildings tend to be more expensive than low-rise buildings since construction costs rise with height (Seeley, 1995). Construction cost per unit floor area has been commonly used as a parameter to compare costs of buildings with different heights (Bathurst & Butler, 1980). The increased costs of tall buildings mainly arise from more expensive structures and elevators because of their higher performance requirements (Warszawski, 2003).

Structural costs are primarily determined by material and labour costs. The relative contribution of each varies for different structural materials. Concrete structures might have lower material costs but higher labour costs where compared to steel structures. Material and labour costs of concrete and steel structures differ for different countries and at different times. For example, steel construction in the United States comprised about 40% material costs and 50% fabrication and erection labour costs in 1983. This composition had changed to 25% material costs and 60% fabrication and erection labour costs by 1998 (Carter, Murray, & Thornton, 2002).

Factors that affect construction costs of multi-storey double-layer space structures, such as structural materials, structural member sizes and connections, building façades, as well as cost composition, are discussed in the following sections.

Structural Materials

Structural material quantities have a significant effect on overall structural costs. Chapter 4 shows that multi-storey double-layer space structures are relatively material-efficient when compared to other high-rise structural systems. This means that their material costs are relatively low. Expenses for the foundations can also be minimised where a lighter structure is used.

Structural Member Sizes and Connections

Multi-storey double-layer space structures use various member sizes. The size differences between the lower and upper floors are significant. Like in other tall structures, the number of structural member sizes specified is commonly reduced for practical purposes. This increases the material costs but labour costs decrease because of simplified tasks due to repetition and uniformity (Carter, Murray, & Thornton, 2002).

Chapter 4 shows that multi-storey double-layer space structures have a large number of structural members, in comparison to other structural systems, requiring a large number of structural connections. The fabrication cost of the structural joints is relatively high because of the labour and processes like welding and bolting.

However, the structural member sizes of double-layer space structures are relatively small when compared to the other super-tall structural systems in Table 4.5. In addition, simple structural connections using gusset plates can be used for double-layer space structures as discussed at the beginning of this chapter. As a result, material costs of the structural members and connection can be minimised.

These conditions show that material costs of double-layer space structures are reasonably comparable to those of other tall structures that have fewer structural members and joints, but large member sizes and connections. This topic can be studied further for future research.

Building Façades

Various façades can be applied to double-layer space structure buildings as discussed in Chapter 6. The façade installation in these structures was shown to be relatively more complex than that in other tall structures. These façades, depending on their type, may have larger areas where compared to more conventional ones. Greater complexity and size makes the construction costs for façades of double-layer space structures to increase.

Composition of Construction Costs

The above sections indicates that multi-storey double-layer space structures might require less structural material and labour costs, but higher costs of façade installation. Other components such as HVAC equipment, elevators, pipes, and ducts do not significantly change construction costs between different structural systems.

It is likely that the cost savings from less structural materials and labour will outweigh the additional costs for façade installation. This is because structural costs represent the largest proportion of overall costs. A cost comparison on tall residential buildings of different heights in Israel by Warszawski (2003) shows that structural costs are more dominant in taller buildings. Another construction cost study of tall buildings in London also shows that sub- and super-structures comprise the largest proportion of the construction expenses (Watts, Kalita, & Maclean, 2007). Since the cost saving of these structures occurs to the largest proportion, the overall construction costs could be minimised as well.

The discussion about construction costs of vertical double-layer space structures is based on logical thinking that links the findings from the design and analysis of the structures with the common situation about construction costs. This cost study has not been proven by any calculation, so it is presented as an indication only. It is recommended to conduct further research on construction costs of vertical double-layer space structures using case study.

7.6. Summary and Conclusion

This chapter has discussed the constructability of multi-storey double-layer space structures including structural materials, erection methodologies, services and façade installation, construction equipment, and indicated construction costs. Several advantages of multi-storey double-layer space structures are summarised as follows:

- Gusset plate structural connections of these structures are relatively simple by using compared to the joints of conventional horizontal space structures that normally require three-dimensional joints.
- In multi-storey double-layer space structures, large vertical members are required only for several levels above the ground, while large columns in other super-tall buildings normally extend to the roof to provide adequate building stiffness.
- Unlike typical steel moment frames, assemblies of vertical, horizontal, and diagonal members form a free-standing structure even before concrete slabs and gravity columns are installed, and gravity beams are connected to the main structure. This enables the gravity structure be erected and connected to the horizontal double-layer space structure while construction of upper zones continues independently. While the perimeter structure of the upper zones is being constructed, the gravity structure on the bottom zone can be installed simultaneously, saving considerable time.
- Horizontal double-layer space structures can accommodate hoists to lift the gravity structures speeding up erection of the gravity structure.
- Unlike for other tall structural systems, structural components of multi-storey double-layer space structures on higher levels are much lighter than those for lower levels. High-capacity tower cranes are not required at those levels. However, if they are used for all levels, installation of multiple components is possible and will save construction time.
- Construction costs of these structures indicate to be competitive to those of other structural systems.

Besides these advantages, disadvantages of double-layer space structures and suggestions of how to minimise them are:

- The second erection technique proposed for these structures, explained in section 7.2.2, needs more equipment than for conventional tall structures. Hoists and rails hung from each horizontal double-layer space structure are required. Nevertheless, the additional cost for the equipment can be off-set by the value of saved construction time.

- Façade installation costs of these structures are higher than those of other tall structures. However, as mentioned before the overall cost could be lower because the structural costs comprise the largest proportion of the overall construction costs.

In conclusion, it is feasible to construct double-layer space structures for multi-storey buildings in terms of simple structural members and connection, and construction method. Although contractors might have different construction techniques, the findings of this study that are presented by several examples including the discussion about their advantages and disadvantages can be useful information for exploring construction strategies of multi-storey double-layer space structures.

Chapter 8: Discussion, Conclusions and Recommendations

This last chapter concludes the study of double-layer space structures in super-tall buildings, beginning with a discussion about the importance of systems integration that was discovered during the design process. The results of this study are then summarised and conclusions provided to address the research question:

"Are double-layer space structures suitable for super-tall buildings?"

Several limitations of this research are then discussed, and these lead to several recommendations for further research.

8.1. Discussion about the Impact of Systems Integration in the Design Process

This section discusses the importance of integrating building systems into the structural design process. Since this research is about a new application of an existing structural system, double-layer space structures, the study began from a structural point of view. A 100-storey double-layer space structure building was modelled. At the first stage of the design, the geometry including building sizes, structural modules, and the space between the two structural layers was determined for the purpose of structural considerations. Other elements like services and architectural components were designed in the second and third stages. In the 48m x 48m building for example, the 4-metre distance between the centre lines of the two structural layers was assumed to be enough to accommodate stairs and observatory elevators. The 8-metre deep horizontal double-layer space structures located at four different levels were assumed to provide sufficient spaces for plant rooms. The design steps are briefly explained below.

In the first stage, the structure was designed and analysed using ETABS. The iterative design and analysis process optimised structural member sizes.

The second stage was the design of services systems including HVAC, stairs, and elevators, ensuring enough space for all the services components could be provided. The design study showed that the space between the two layers of the horizontal space structures was adequate for plant rooms. Observatory elevators could also be placed within the two layers of the vertical space structure. However, there was not enough room for a fire stairwell. Egress stairs require adequate stair landings and a direct route to the ground without entering the building. To solve this problem, the design was modified by moving the horizontal members, to which the stairs are attached inside the building, so the centre lines of the horizontal and vertical members are offset, as explained in Section 5.2. This provided larger and sufficient areas for the stairwells.

The third stage involved the design of architectural components; namely building façades, entrances, interior spaces, and building geometries. Many alternative designs were explored to integrate the architectural components with the structure. A problem arose in the design of the entrances. A functionally satisfactory entrance could not be placed in the building because of diagonal structural members on the building perimeter. Therefore, the structure was modified by changing the ground floor diagonal members from spanning one to two storeys. As a result, a larger area is provided, not only for an entrance, but also for the interior space at the perimeter of that ground floor. A further modification to the position of several ground floor structural members provided for an even better entrance. This modification is discussed in Chapter 6.

The next stages were to analyse fire safety and construction. In these steps, there were not significant issues regarding systems integration and a double-layer space structure so no further structural changes were required.

The need for some structural design iteration between the design stages showed the importance of systems integration being given greater emphasis at the beginning of the design process. In this study, structural efficiency was considered only at the first stage. As a result, the overall integrated design was not optimised. In the second and third stages, the structure had to be modified to accommodate vertical circulation and architectural requirements such as entrances. This experience leads to an important lesson: all major building systems, including structure, building services, architecture, construction, and their integration should be considered at the first stage of the design. Detailed structural design should not be undertaken until all other systems have been reasonably resolved.

8.2. Discussion about Systems Integration achieved in the Case Study

This study has explored various design possibilities of double-layer space structures in super-tall buildings to achieve physical, visual, and performance integration. Physical integration is where building systems share space; visual integration occurs when the expression of building systems becomes a visual design element; and performance integration involves building systems sharing functions. Systems integration occurs to some extent in every building, but in different levels and conditions. For example, façades are normally a part of interior, but not all structural systems can visually integrate with building façades.

This section discusses systems integration in double-layer space structure buildings. Discussion does not focus on what levels of integration have been achieved by each individual building component. Rather, it focuses on how double-layer space structures integrate with other building systems in ways that do not normally occur in tall buildings using other structural systems.

In the design process, a real effort has been made to achieve high level physical integration by placing services components (ducts, pipes, stairs, and elevators) within a vertical double-layer space structure. From five levels of physical integration (the lowest to the highest levels: remote, touching, connected, meshed and unified), the meshed level is achieved because services and structural systems occupy the same space. This same level of integration also occurs within the horizontal double-layer space structures designed to accommodate plant rooms and façade maintenance units.

Double-layer space structures were also designed to visually integrate with architectural components. As a part of building façades, the components of double-layer space structures are either exposed or visually integrated with various configurations of glazing façades. The uniqueness of the structural geometry, consisting of vertical, horizontal, and diagonal components, as well as the dual-layer system, provides various aesthetic integrated design alternatives. Visual integration at level two, where different systems are visible but no modification is needed, is achieved because the structural system can be aesthetically exposed without necessarily changing its shape or position.

Several aspects of performance integration in double-layer space structure buildings are also achieved. Satisfactory spatial performance is realised because diagonal components of the structure do not interrupt the interior space by placing them within the exterior walls/glazing. Thermal performance and indoor air quality can be maximised by natural ventilation using double-skin façades integrated with the structure. Double-skin façades can also be designed to improve acoustic performance.

This study investigates the potential of the integration of these structures with other building systems. A multidisciplinary approach that considers the impact of integration of structural and services systems, architecture, and construction has been used to provide many alternative solutions.

8.3. Summaries and Conclusions

The results of this study are summarised to answer the research sub-questions presented in the first chapter.

Structural System

- *What are the structural features of a double-layer space structure as a vertical structure?*
    - Double-layer space structures of super-tall buildings resist gravity and lateral loads by tension and compression in their members.
    - As for other tall structures, the design of a 100-storey building using this structural system is driven by the lateral deflection limit.
    - The lateral deflection shapes of these structures are curved, showing that they respond more in bending than in shear.

- *How efficient are these structures as compared to other current structural systems?*
    - Double-layer space structures are relatively efficient compared to other tall building structural systems. The study shows that 100-storey double-layer space structures

using two different typical floor areas are the second lightest compared to three other structural systems. In terms of structural efficiency, the braced-tube is the most efficient, followed by the double-layer space structure. The bundled-tube and diagrid structure have similar weight. All structural systems use the same building geometries and gravity systems.

- Double-layer space structures require a large number of structural members, but they use considerably smaller member sizes at the upper floors like several other structures do.

Services Systems

- *To what extent can services systems integrate with double-layer space structures?*
  - A vertical double-layer space structure on the building perimeter can integrate with services components. Some of the space between the two structural layers can effectively accommodate ducts, pipes, elevators, and stairs, located at two building corners. Physical integration at the meshed level is achieved since structural and services components occupy the same volume.
  - The space within the horizontal double-layer space structures located at four different levels of the building can be used for plant rooms to accommodate HVAC components such as AHUs, chillers, boilers, water pumps, and cooling towers; elevator components including motor rooms and pits; refuge floors as a part of an egress system, and the cranes of façade maintenance devices. Again, physical integration at the meshed level is achieved.

- *To what degree can these structures integrate with fire safety and egress systems?*
  - A vertical double-layer space structure can accommodate standpipes and egress by elevators and stairs within its depth.
  - The horizontal double-layer space structures, located at four different levels of the building provide space for water tanks and refuge floors.
  - Standpipes and egress can be located within the perimeter structure at two building corners. This allows one to still work even if the other one is disrupted.

- *How stable are these structures during fire and in the event of localised failure?*
  - Like all steel structures, multi-storey double-layer space structures have to be fire-protected.
  - Double-layer space structures are three-dimensional structures that can stand alone without being braced by the floor system. As highly redundant structures, they can transfer loads to other structural members and then to the ground even if several structural members collapse. This minimises the possibility of progressive collapse.

- *To what degree is this structural system compatible with energy efficient design concept to be found in the current literature?*
  - These structures can accommodate sun shading devices to minimise cooling load, double-skin façades to allow natural ventilation, wind turbines, and photovoltaic panels to generate energy for the building.

- *What are advantages and disadvantages of this integration?*
  - The structural-services integration using the above approaches has an impact on usable floor area. Compared to other typical tall buildings that normally house services in their central cores, a double-layer space structure building that locates the majority of its services components at the building perimeter provides a larger usable floor area.
  - The disadvantage of this approach is that a larger site area is required. However, the required additional site area is outweighed by the additional available usable floor given the large number of floors. Normally, super-tall buildings require a larger site area than the tower area for a podium, garden, and car park area.
  - Another disadvantage of integrating services with the structure is that the building maintenance for the façade is more complex than for other typical tall buildings. However, the technologies of façade maintenance have developed significantly and they can cope with buildings with complex geometries.

Architectural Aspects

- *What strategies can be used to integrate the structure with architectural components including building façades, entrances, interior spaces, and building geometry?*

- Structure-façade integration can benefit from the unique structural form that provides opportunities for several different façade systems, such as double-skin façades, exposed structure, vertical and horizontal folded façades, and many possible combinations. Balconies of various configurations can also be integrated within the perimeter structure.
- Entrances can be integrated with the structure using several approaches such as: enlarging the slope of ground floor diagonal members to minimise unusable space around them, attaching a podium to the tower, and re-orientating the position of several ground floor structural components to provide a larger entrance space.
- Usable interior space without disruption caused by diagonal members of a multi-storey double-layer space structure is enabled by placing the façade in the same plane as the diagonal members, either vertically or horizontally.

- *What are the advantages and disadvantages of this type of and degree of integration?*
    - Double-layer space structures in high-rise applications can adopt complex geometries like leaning and twisting towers. This is because each structural member works in tension and compression, and avoids the moments and torsion usually caused by complex geometries. However, in these instances the integration of circulation and elevators within irregular double-layer space structures may not be possible.
    - Another potential advantage lies in the uniqueness of the diagonal and double-layer structural components, which can provide many integrated design alternatives compared to other structural systems. Visual integration can be achieved by exposing the structure. This may be considered a significant architectural feature.
    - The disadvantage of this integration is the reduction in open views because the majority of structural members are at the building perimeter. Different façade systems discussed in Section 6.1 provide different extents of open views, depending on how the glazing is positioned with aspect to the structural members. Open views are also obstructed by the elevators and stairs at the building corners.

Construction

- *What construction methods, including primarily structural members' profiles and connections, erection methodologies, and construction equipment are suitable for this application?*
  - Rectangular or circular hollow sections are suitable for the structural members of these structures. Structural connections using gusset plates are relatively simple.
  - A conventional erection methodology normally used in multi-storey steel structures can be used for a vertical double-layer space structure. However, an alternative erection methodology, presented and discussed in Chapter 7, reduces construction time.
  - Construction equipment normally used in high-rise buildings like mobile and tower cranes can also be used for the erection of these structures. Hoists and rails are required for the second alternative erection method.

- *What are the impacts of vertical double-layer space structures on construction costs?*
  - Compared to some other systems, a vertical double-layer space structure might have less expense in terms of structural materials, but higher costs in façade installation.
  - The cost saving in the structural materials might outweigh the additional costs for façade installation because structural costs comprise the largest proportion of the overall costs.

The results of this research are also summarised in a very compact form in Table 8.1.

Table 8.1 The advantages and disadvantages of multi-storey double-layer space structures

Advantages	**Disadvantages**
Structural Analysis	
- Reasonably light weight and material efficient - Small components at the upper floors - Reasonable structural module size	- Guidance in building codes regarding ductility under seismic conditions is required
Building Services Analysis	
- The cavity of horizontal double-layer space structures can be used for plant rooms - The cavity of the vertical double-layer space structure can be used for pipes, ducts, stairwells and panoramic elevators - Redundancy of fire safety and egress systems by locating the systems within the structure far apart - Redundant structure, minimising the possibility of a progressive collapse - A larger usable floor area	- Potentially complex façade maintenance - Requires a larger ground floor area, although this is compensated by the additional usable floor area at each storey
Architectural Integration	
- Aesthetically pleasing integration of structures with glazing façades and balconies - Minimal interior space obstructions - Potential for complex geometry buildings	- Modifications are needed to provide acceptable size entrances - Open view obstructions from structure, services, elevators and stairs
Construction Analysis	
- Simple structural connections, resisting compression and tension only - Bracing and temporary supports unnecessary for erection - Saving on a construction time for an alternative erection approach that allows parallel construction of gravity and lateral load resisting structures	- Large number of members and joints - More construction equipment required for an alternative erection method

The table presented above shows the advantages and disadvantages of double-layer space structures when applied in super-tall buildings. The disadvantages of these structures mainly arise due to the majority of structural members being at the building perimeter and services components outside the floor area, obscuring views and requiring a larger ground floor area. In addition, both the dual layer of structural members, and their diagonal members, lead to other issues such as complex façade maintenance, limited areas between structural members to provide entrances, and a large number of exposed structural components that have to be fire protected.

The advantages of these structures result from the use of the space between their two layers for services components, and the visual integration of their structure with architectural concerns. Their main advantage is in their relatively high structural efficiency as measured by their weight per unit area that leads to lower construction costs for superstructure and foundations. Since the majority of vertical structural members and integrated services components are outside floor areas, several other advantages occur such as maximising usable floor areas and redundancy of fire safety and egress systems. In addition, multi-storey double-layer space structures are free-standing structures that do not require bracing during construction. This condition can save construction time. Finally, as highly redundant structures, double-layer space structures can be used for buildings with complex geometries and to minimise the possibility of a progressive collapse.

Bearing in mind these advantages and disadvantages, it is impossible to provide an absolute answer as to whether double-layer space structures are suitable or not for super-tall buildings. Suitability does not depend on how many advantages there might be, but on how significant the advantages and disadvantages are and to whom. They can be perceived differently by architects, engineers, contractors, occupants, and developers. For example, structural efficiency, which leads to relatively low construction costs and the optimisation of usable floor areas yield significant benefits for developers. Further, contractors demand simple structural joints and fast construction. Architects highly value building aesthetics. Enhanced fire safety and stable structures will make occupants feel comfortable. On the other hand, less open views are a significant problem for both architects and occupants. The opinions of interested parties about this designed case study are outside the scope of this research.

In order to answer the research question, the two main aspects in this research, structural efficiency and systems integration, are considered. As discussed in Section 1.2, the application of double-layer space structures in super-tall buildings raises questions:

- How efficient are they compared to other structural systems?
- To what degree can systems integration be applied, and what are its impacts on architectural aspects, construction, and fire safety?

From the perspective of these aspects, the results of this research can be concluded as follows:

- Double-layer space structures are structurally efficient where compared to other efficient structural systems in super-tall buildings.
- Double-layer space structures integrate well with other building systems. High level physical and performance integration as well as several aspects of performance integration can be achieved. This integration provides a number of significant advantages, but several disadvantages need careful attention.

The findings and conclusions of this study can be relevantly applied to double-layer space structures in general high-rise applications in the scope of the study.

8.4. Recommendations

The results of this research have been summarised and conclusions drawn. However, even though the research has answered the research question, it also raises new questions that require further research.

Opinions from Building Designers, Constructor and Occupants

This research has provided alternative integrated design solutions for an application of double-layer space structures in super-tall buildings. Advantages and disadvantages of this application have been discussed, but this research does not investigate how significant they are. The question of significance is outside the research scope. Opinions from architects, structural and mechanical engineers, contractors, building occupants, and developers about this application would be very useful. This is highly recommended for further research.

More Relevant Method for Wind Analysis

The 100-storey double-layer space structures were designed for wind load using Method-2 ASCE (2005). This method applies an analytical procedure and can be used for the structural design of regular-shape buildings. It was used in this research because the double-layer space structure buildings were designed using regular shapes. They were compared with other structural systems using the same building shape. The other reason for using this method was to simplify the design and analysis process. However, the structure of super-tall buildings, especially with irregular shapes, should be designed according to Method-3 ASCE

(2005) using a wind tunnel procedure. Further research using a wind tunnel is recommended to fully explore the wind effect on the structure. Double-layer space structure buildings with various façade geometries, discussed in Chapter 6, will have different interactions with the wind, and this can only be explored using a wind tunnel. In addition, wind effects on double-layer space structures with higher and more complicated geometries can also be thoroughly investigated.

Structural Ductility

Structural ductility is an important factor in seismic analysis. ASCE (2005) does not provide the R value, or structural ductility, of vertical double-layer space structures. This is probably because these structures have not been used for tall buildings. Further research on the ductility of multi-storey double-layer space structures is recommended. The aim is to provide a safe and more economical design of vertical double-layer space structure buildings located in seismic areas.

Buildings with different heights

This study has analysed 100-storey double-layer space structures that represent buildings with 75 to 125 storeys. However, this analysis would provide more accurate findings by conducting another case study research for buildings with different heights. The aim is to discover the relationship between building heights and structural weight per unit floor area. For buildings over 400 metres high the analysis should use a wind tunnel procedure as recommended in Method-3 ASCE (2005).

Building Maintenance Unit

This research has explored how various building façades can be integrated with vertical double-layer space structures. Double structural layers and diagonal members make façade maintenance complex. As explained in Chapter 5, the main problem for the façade maintenance system of a multi-storey double-layer space structure is the need for horizontal movement of its façade cleaning device. This makes façade maintenance time consuming. Further research is recommended to explore simpler and more practical building maintenance units for multi-storey double-layer space structures.

Structural Erection Techniques and Façade Installation

Chapter 7 discussed how conventional erection methods normally used in high-rise steel structures can also be used for double-layer space structures. A sophisticated erection technique that allows structure at upper zones to be erected in parallel with the erection of the lower zone structure has been explained. The installation of alternative façade systems in double-layer space structure buildings was also presented. However, the erection techniques of the structure and the façade installation techniques discussed in this research might not be the most effective construction solutions. Factors like site conditions, construction equipment, labour skills, and construction costs play an important role in determining a construction method. Further research on various erection techniques of double-layer space structures as well as the installation of various façade systems is recommended.

Construction Cost Analysis

This research does not provide detailed cost estimates of double-layer space structures or cost comparisons with other structural systems. Since construction costs vary for buildings in different locations and conditions, further research on cost analysis of double-layer space structure buildings would be valuable. By varying factors like structural material volumes, labour unit costs, and façade unit costs, the effect of these factors on the overall costs can be explored. Cost comparisons with other structural systems are also necessary.

Energy Efficiency of Double-layer Space Structure Buildings

Several approaches to energy efficiency have been discussed in this research. However, their energy efficiency hasn't been analysed. Future research should be conducted to investigate how energy efficient these approaches. It is also recommended to explore other strategies that might enhance energy efficiency as an approach to more sustainable super-tall buildings.

8.5. Final Word

This study about the suitability of double-layer space structures for super-tall buildings provides a new structural option for the design of super-tall buildings. The contribution of this research to the knowledge of structural systems and technologies in super-tall buildings is a starting point for further exploration of this existing structural system applied in a new way.

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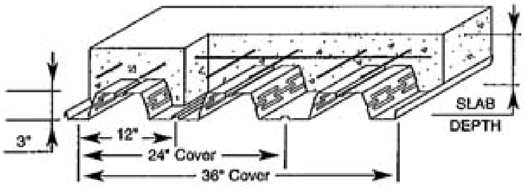
Appendix A: Slab Deck Technical Data

3.0 SB Normal Weight



145 pcf Normal Weight Concrete

Section Properties (per ft. of width)

Gage	t in	Wd psf	Sp In^3	Sn In^3	Ip In^4	In In^4	As In^2	Fy ksi
22	0.0295	2.1	0.428	0.436	0.766	0.749	0.524	50
20	0.0358	2.5	0.551	0.565	0.965	0.945	0.636	50
18	0.0474	3.3	0.820	0.826	1.315	1.311	0.842	40
16	0.0600	4.1	1.051	1.050	1.667	1.667	1.066	40

Total Slab Depth D	Gage	Maximum Unshored Clear Spans			Composite Properties		Superimposed Live Loads - psf: No Studs											
Wt. Conc.		Single	Double	Triple	Iavg	Sc	Span - Feet and Inches											
Area Conc.		Span	Span	Span	In^4/ft	In^3/ft	9'-0"	9'-6"	10'-0"	10'-6"	11'-0"	11'-6"	12'-0"	12'-6"	13'-0"	13'-6"	14'-0"	14'-6"
	22	9'-1"	10'-1"	10'-5"	9.373	1.331	253	224	198	176	157	141	126	113	102	92	83	75
5-1/2"	20	10'-6"	12'-8"	13'-2"	10.014	1.589	310	274	244	217	195	175	158	142	129	117	106	96
48.3 psf	18	11'-7"	13'-10"	14'-3"	11.089	2.042	319	282	251	224	201	180	162	147	133	120	109	99
35.4 in^2	16	13'-3"	15'-6"	15'-7"	12.125	2.502	319	282	251	224	201	180	162	147	133	120	109	99
	22	8'-4"	9'-3"	9'-7"	12.034	1.534	293	259	230	204	182	163	147	132	119	107	97	87
6"	20	10'-0"	12'-2"	12'-7"	12.835	1.832	358	317	282	252	226	203	183	165	150	136	123	112
54.4 psf	18	11'-0"	13'-2"	13'-8"	14.181	2.354	369	327	290	259	233	209	189	170	154	140	127	116
39.5 in^2	16	12'-7"	14'-10"	15'-2"	15.483	2.886	369	327	290	259	233	209	189	170	154	140	127	116
	22	7'-9"	8'-6"	8'-11"	15.164	1.745	335	296	262	234	209	187	168	151	136	123	111	100
6-1/2"	20	9'-7"	11'-8"	11'-11"	16.149	2.084	400	362	322	288	258	232	209	189	171	156	141	129
60.4 psf	18	10'-6"	12'-8"	13'-2"	17.811	2.679	400	373	332	297	266	240	216	195	177	161	146	133
43.8 in^2	16	12'-0"	14'-4"	14'-10"	19.426	3.290	400	373	332	297	266	240	216	195	177	161	146	133
	22	7'-2"	8'-0"	8'-4"	18.801	1.963	378	334	296	264	236	212	190	171	154	140	126	114
7"	20	9'-4"	11'-0"	11'-2"	19.997	2.344	400	400	364	325	292	262	237	214	194	176	160	146
66.5 psf	18	10'-3"	12'-3"	12'-8"	22.021	3.016	400	400	375	336	301	271	245	222	201	182	166	151
48.2 in^2	16	11'-8"	13'-9"	14'-3"	23.995	3.708	400	400	375	336	301	271	245	222	201	182	166	151
	22	6'-9"	7'-6"	7'-9"	22.985	2.185	400	373	331	295	264	237	213	192	173	157	142	128
7-1/2"	20	9'-0"	10'-4"	10'-5"	24.419	2.610	400	400	400	363	326	294	265	240	218	198	180	164
72.5 psf	18	10'-0"	11'-10"	12'-3"	26.850	3.363	400	400	400	376	337	304	274	248	225	205	187	170
52.8 in^2	16	11'-5"	13'-4"	13'-9"	29.231	4.139	400	400	400	376	337	304	274	248	225	205	187	170

							Superimposed Live Loads - psf: Studs @ 1'-0" O.C.											
D, Wc, Ac	Gage	Single	Double	Triple	Stud Factors		Span - Feet and Inches											
		Span	Span	Span	2' o.c.	3' o.c.	9'-0"	9'-6"	10'-0"	10'-6"	11'-0"	11'-6"	12'-0"	12'-6"	13'-0"	13'-6"	14'-0"	14'-6"
	22	9'-1"	10'-1"	10'-5"	0.96	0.88	372	330	294	263	236	213	193	175	159	144	132	120
5-1/2"	20	10'-6"	12'-8"	13'-2"	0.92	0.85	400	396	354	318	286	258	234	213	194	177	160	144
48.3 psf	18	11'-7"	13'-10"	14'-3"	0.91	0.84	400	400	373	335	302	273	247	225	205	187	172	157
35.4 in^2	16	13'-3"	15'-6"	15'-7"	0.87	0.81	400	400	400	400	373	338	307	272	242	216	193	174
	22	8'-3"	9'-3"	9'-8"	0.97	0.88	400	377	336	301	270	244	220	200	181	165	151	138
6"	20	10'-0"	12'-2"	12'-7"	0.92	0.86	400	400	400	364	328	297	269	244	223	204	186	171
54.4 psf	18	11'-0"	13'-2"	13'-8"	0.91	0.84	400	400	400	384	346	313	284	259	236	216	197	181
39.5 in^2	16	12'-7"	14'-10"	15'-2"	0.87	0.82	400	400	400	400	400	391	355	324	296	272	247	222
	22	7'-9"	8'-7"	8'-11"	0.97	0.89	400	400	378	338	304	274	248	225	204	186	170	155
6-1/2"	20	9'-7"	11'-8"	11'-11"	0.93	0.86	400	400	400	400	370	335	303	276	252	230	210	193
60.4 psf	18	10'-6"	12'-8"	13'-2"	0.91	0.84	400	400	400	400	391	354	321	292	267	244	223	205
43.8 in^2	16	12'-0"	14'-4"	14'-10"	0.87	0.82	400	400	400	400	400	400	400	368	336	308	283	261
	22	7'-2"	8'-0"	8'-4"	0.97	0.89	400	400	400	376	338	305	276	250	227	207	189	173
7"	20	9'-4"	11'-0"	11'-2"	0.93	0.87	400	400	400	400	400	373	338	307	280	256	235	215
66.5 psf	18	10'-3"	12'-3"	12'-8"	0.91	0.85	400	400	400	400	400	394	358	326	297	272	249	229
48.2 in^2	16	11'-8"	13'-9"	14'-3"	0.87	0.82	400	400	400	400	400	400	400	400	377	345	317	292
	22	6'-9"	7'-5"	7'-9"	0.97	0.90	400	400	400	400	372	335	303	275	250	228	208	190
7-1/2"	20	9'-0"	10'-4"	10'-5"	0.93	0.87	400	400	400	400	400	400	373	339	309	283	259	238
72.5 psf	18	10'-0"	11'-10"	12'-3"	0.92	0.85	400	400	400	400	400	400	395	360	328	300	275	253
52.8 in^2	16	11'-5"	13'-4"	13'-9"	0.88	0.83	400	400	400	400	400	400	400	400	400	382	351	324

1) Refer to the Design Notes, Note 7, for information on live load limits for fire-rated construction. See Page CD-3.
2) If stud spacing exceeds 1'-0" o.c., reduce live load by applicable stud factor listed above for actual stud spacing.
3) If welded wire fabric is not used, the live loads should be reduced by 10%.

Source: http://www.roofdecking.net/

Appendix B: Passive Chilled Beams Technical Data

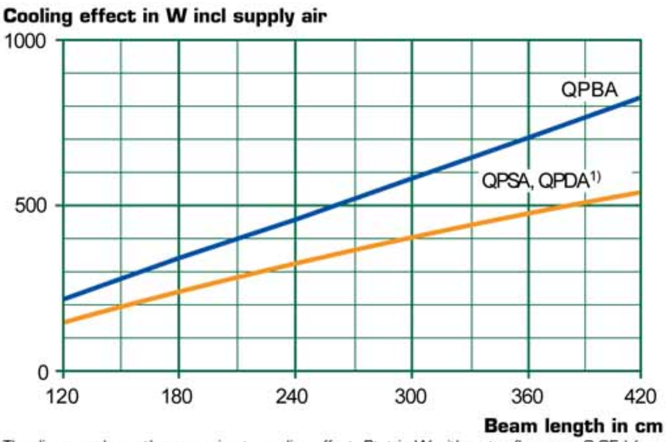
Passive chilled beams QPSA, QPBA, QPDA

Functions

- Controls
- Lighting

The Flexicool® QPSA, QPBA and QPDA passive chilled beams provide for the cooling in a room.
QPSA is a narrow, passive chilled beam (width 290 mm), QPBA is a broad passive chilled beam (width 430 mm), and QPDA is our new passive chilled beam with a designer casing (width 400 mm). The passive chilled beams are either ceiling installed, in which case they lie flush with the suspended ceiling, or free space installed without ceiling. QPDA can only be free space installed. The passive chilled beams are available in lengths 1.2-4.2 m (not QPDA, which is only available in sizes 1.8 and 4.2 m) at 60 cm intervals. In installations with passive chilled beams the air is supplied by means of separate supply air valves.

Quick Selection



The diagram shows the approximate cooling effect, Ptot in W with water flow, qv = 0.05 l/s difference between room air temperature and average water temperature = 8 °C and max sound pressure level LA10 = 30 dB(A). 1) QPDA is available in sizes 1.8 m and 2.4 m.

Product Facts

- Passive chilled beams QPSA and QPBA for ceiling installation or free space installation
- QPDA Passive chilled beam with designer casing for freely suspended installation.
- Coil and casing are easy to clean
- Adapted control and adjustment equipment and lighting (QPDA) available as accessories
- Quick and easy installation with suspension rods.

Product code example

430 mm wide passive chilled beam QPBA manufactured by Fläkt Woods, length 240 cm.
Chilled beam QPBA-240-1 for individual installation.

Source: http://www.flaktwoods.com/