THE TECHNOLOGICAL EVOLUTION OF THREE OFFICE BUILDINGS OVER TIME

by

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A Thesis

Submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Master of Science

in

Civil Engineering

May 2013

APPROVED:

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Abstract

From the 1920s until present day, the technological evolution of the office building, or more specifically, the office building skyscraper has been eminent. From past to present, the functions of this building have changed dramatically and with this change, a component cost shift has occurred. An investigation of different technologies that have transformed over the years has been performed on three notable skyscrapers: the Empire State Building (1931 completion), the World Trade Center (1971 completion), and One World Trade Center (late 2013 projected completion). All buildings are located in New York City, New York and were constructed at relatively equal intervals throughout time, from each other. A building can be broken down into different elements and for this analysis; five specific components were investigated. They were the podium, also known as the foundation and floors, the load-bearing members of the structure, or frame, the veneer or curtain wall system, the interior finishes of the building and any machinery involved with the buildings functional usage. All three buildings incorporate all five of these components in their design, but there are distinctions as to how the percentages of importance of each changed as the evolution and knowledge of technology progressed throughout time. This study has addressed the different methods each building used to achieve a technological cutting edge of their respective periods of time of construction, within the scope of the five main building components.

Acknowledgements

I would first and foremost like to thank God for the opportunity that allowed this thesis to become a reality. I would also like to thank my family and friends for their relentless support throughout this process.

This research would not have been possible if not for the encouragement by my advisor, Professor Roberto Pietroforte. His continuous support and interest made this thesis achievable. I would also like to thank any of the other faculty members in the Civil Engineering Department at Worcester Polytechnic Institute who supported me in this endeavor.

I have made every attempt to ensure that all intellectual property of others was properly credited to quoted sources, and I would like to thank all those that contributed no matter how small or large the contribution.

Table of Contents

Table of Figures

Introduction

The investigation of the economic analysis of skyscrapers; more specifically office buildings, has led to the realization of both a cost and technology evolution. Dating back to the 1920s, when skyscrapers were the newest innovation for economical real estate usage in heavily populated areas, skyscrapers have evolved over the decades in several ways. From past to present, a buildings functions have changed dramatically and with this cost change has come a technological shift. The investigation completed contains research performed on three notable skyscrapers. They were chosen in periods of time that are evenly dispersed over the course of the past century, from the late 1920s to present day, to given an impartial comparison.

The first building used for the evaluation, from the late 1920s, was the Empire State Building. Secondly, the World Trade Center, from the 1970s, was used. Finally, One World Trade Center was used for the present day analysis. Intentionally, all three buildings were at one time or another, located in New York City, New York. At the time of their construction, all of these buildings were the tallest in the country, with the former three (Empire State Building and Towers One and Two of the World Trade Center Buildings) being the tallest in the world.

As time has progressed, throughout history, the requirements and demands of an office building have certainly changed. Building components have remained relatively constant, but what has changed has been the percent shift of where the money was spent on these components and the shift of design and construction intents with these shifts in technology. Reasons for these changes included, but were not limited to, technological advances being discovered, more cost-effective systems being invented and component environmental friendliness, among others.

An interest was gained in this thesis topic through the reading and analysis of Gregory R. Turner's book, *Construction Economics and Building Design: A Historical Approach*, from 1986. He outlined the component technologies of buildings and gave a historical evolution of how the building component costs have developed over time, specifically the last century to present day, which in his book was up until 1984. The main components that absorbed the vast majority of a building's costs were broken down in his book into five main elements. They were as follows:

- The *podium*, or the foundation, floors and conveying systems;
- The *frame*, or load-bearing superstructure;
- The *envelope*, or exterior closure and roofing;
- The *machinery, or mechanical and electrical equipment*, and
- The *infill,* or interior construction of the building.

In Figure 1, Turner's cost analysis is shown. Although the pie charts are representative of the costs of buildings from ancient times to the modern day, the shift is evident of where costs have been spent in a building, which in turn meant the amount of certain components have technologically advanced and the purpose of an office building has become more than primarily a frame.

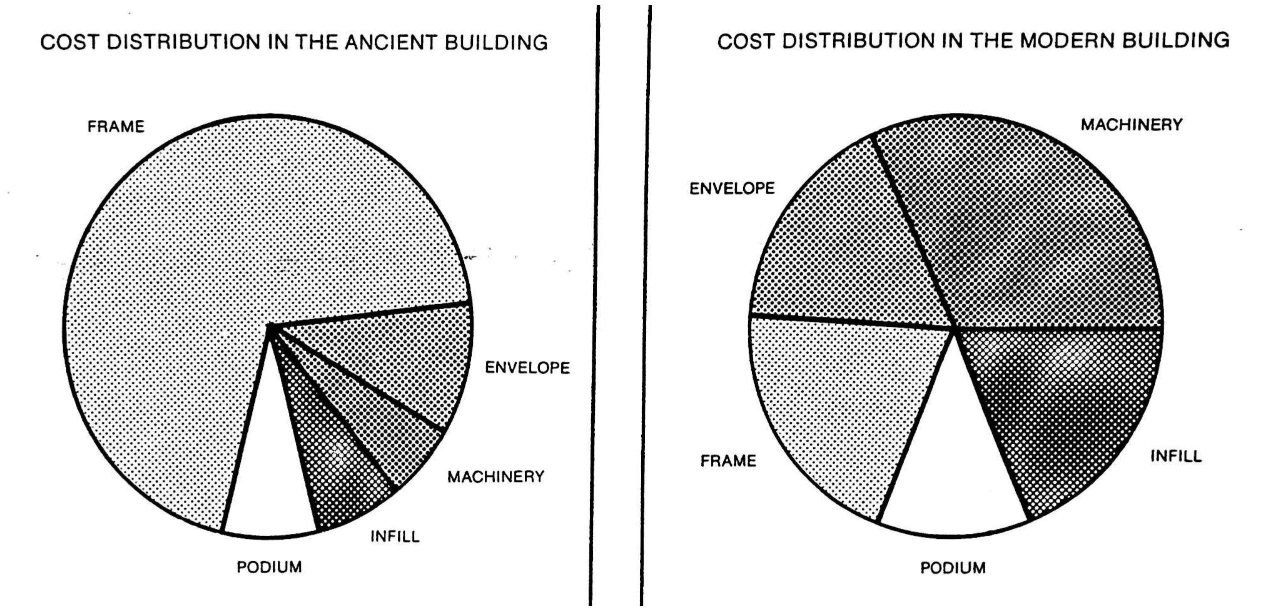


Figure 1: Turner Cost Distribution Comparison (Turner, 1986)

In Figure 2, Turner depicts the building component breakdown from 1800 to 1984. In relation to the pie charts, the correlation is apparent where certain parts of the building are being emphasized more than in the past. In Figure 3, the projected building costs and technology focus is shown, which is useful when One World Trade Center is analyzed, where technology continues to evolve. Costs continue to shift towards the Machinery, most notably, making the office building more and more of a working machine, compared to the traditional "brick and mortar" building.

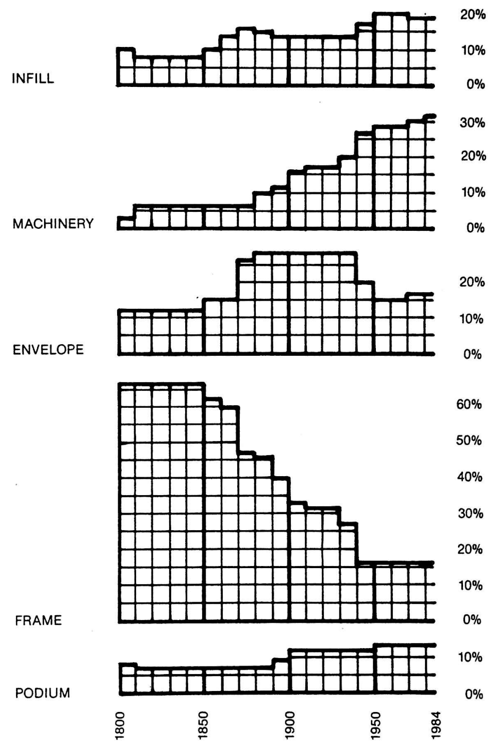


Figure 2: Building Cost Component Breakdown From 1800 to 1984 (Turner, 1986)

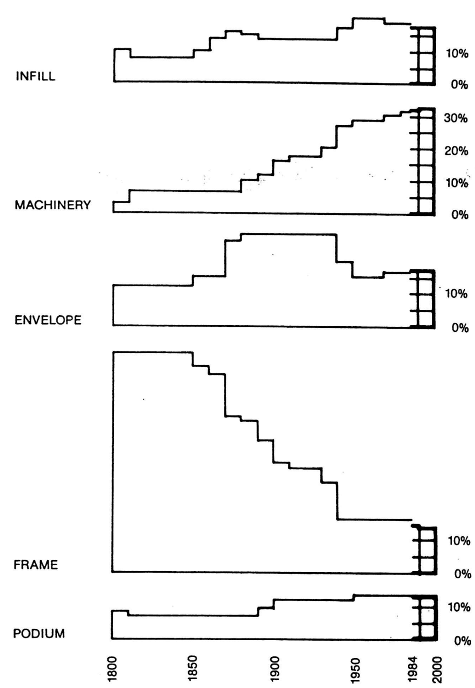


Figure 3: Building Cost Component Breakdown Projections (Turner, 1986)

All three buildings incorporated all five of these components in their design, but there are distinctions as to how the amount of design, time and effort spent on each part of the building evolves as time progressed.

In comparison to the previous building breakdown suggested by Turner, the ASTM Uniformat II is a construction project management system of classifying building costs by certain components. Table 1 shows how this cost estimating table is broken down:

A Substructure	A10 Foundations
	A20 Basement Construction
B Shell	B10 Superstructure
	B20 Exterior Enclosure
	B30 Roofing
C Interiors	C10 Interior Construction
	C20 Stairs
	C30 Roofing
D Services	D10 Conveying Systems
	D20 Plumbing
	D30 Heating, Ventilation, and Air Conditioning (HVAC)
	D40 Fire Protecting Systems
	D50 Electrical Systems
E Equipment and Furnishings	E10 Equipment
	E20 Furnishings
F Special Construction & Demolition	F10 Special Construction
	F20 Selective Demolition
G Building Sitework	G10 Site Preparation
	G20 Site Improvements
	G30 Site Civil/Mechanical Utilities
	G40 Site Electrical Utilities
	G90 Other Site Construction
Z General	Z10 General Requirements
	Z20 Bidding Requirements, Contract Forms
	Z90 Project Cost Estimate

Table 1: ASTM Uniformat II (2013)

This table compares how the two different systems have similarities and differences within them. Breakdowns A, B, C, and D are essentially the same that Turner uses, however, B is representative of the Shell, which includes both the Frame and the Envelope of the building. Between Turner's breakdown of the five building components and the ASTM Uniformat II breakdown, it is straightforward to compare certain parts of each building and how technology evolved in each. Turner's breakdown scheme was followed in this thesis analysis, as different components of the building could best be broken down with his classifications.

One variation in his categorization was made with involving the conveying systems within the Machinery of a building. The Podium consisted mainly of steel and concrete elements that are stationary, whereas the Machinery was comprised of moving mechanical and electrical parts. The other two minor differences in this book, from Turner, will be noted as his Machinery being called Services and the Infill referenced as the Interior. In the following section, the component breakdowns will be described in further detail, followed by the methodology being analyzed with the technological evolution.

Organization Breakdown

The organizational breakdown of this report consisted of splitting each of the three aforementioned buildings into the mentioned five major components. Within these five major divisions, several components of each of them were discussed as to the technology they included at the time of construction, how they compared with the industry, and the technological evolution. Technology is always improving so it was interesting to observe how the cutting edge technology, at one point in history, became obsolete. The five major categories that were mentioned as being the major breakdowns of this paper are as follows: Substructure, Frame, Envelope, Interior and Services. Images from Turner's book are used to represent and visualize the different parts of each, the only difference being the elevating systems represented in the Podium are classified as Machinery in this analysis.

Substructure

In terms of the Substructure, or as Turner called it, the Podium, as shown in Figure 4, any beginning work done prior to the frame of the building is included. It incorporated discussion of technologies used and created for the heavy-duty substructures of the buildings, typically made with concrete and steel reinforcement. Different quantities were expected to be

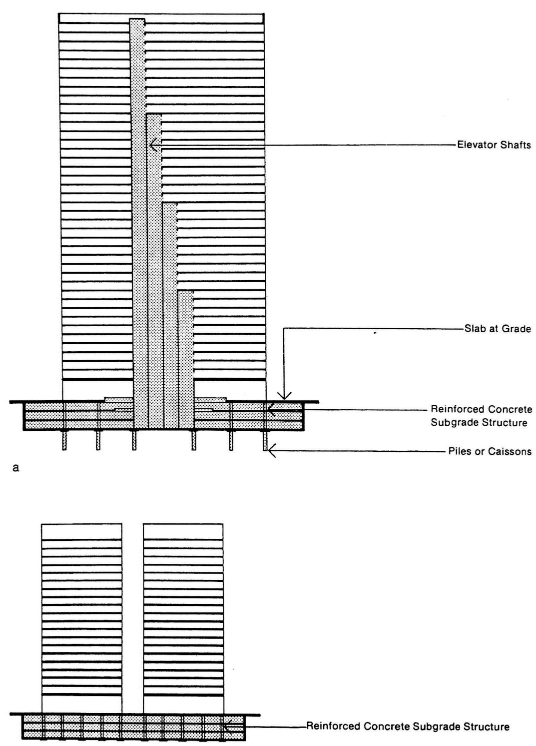


Figure 4: Modern Podium (Turner, 1986)

examined for the three different office buildings as well as types of materials used. Also, for the office buildings, there were unique conditions based on their geographical locations. The buildings being in New York City, close to the Hudson River and extremely close to other large buildings presented a scenario where special provisions needed to be made for creating extraordinarily strong substructures.

Frame

Moving the attention to the frames of the office buildings, they were very unique and different from one another. This portion was very interesting to see exactly how the technology evolved over time and dictated what the frame of the buildings would be like. As seen in Figure 5, on the right, the frame is the structural skeleton of the building, which represents a cage-like structure in Turner's depiction. For example, the Empire State Building and the original World Trade Center had entirely different framing systems. The World Trade Center had a brand new design that was not even considered prior to its design, which was a very good example of how the technology evolved from the 1920s, when the Empire State Building was being designed, to the World Trade Center of the late 1960s, and even how the frame systems had advanced and changed since then, with present-day One World Trade Center.

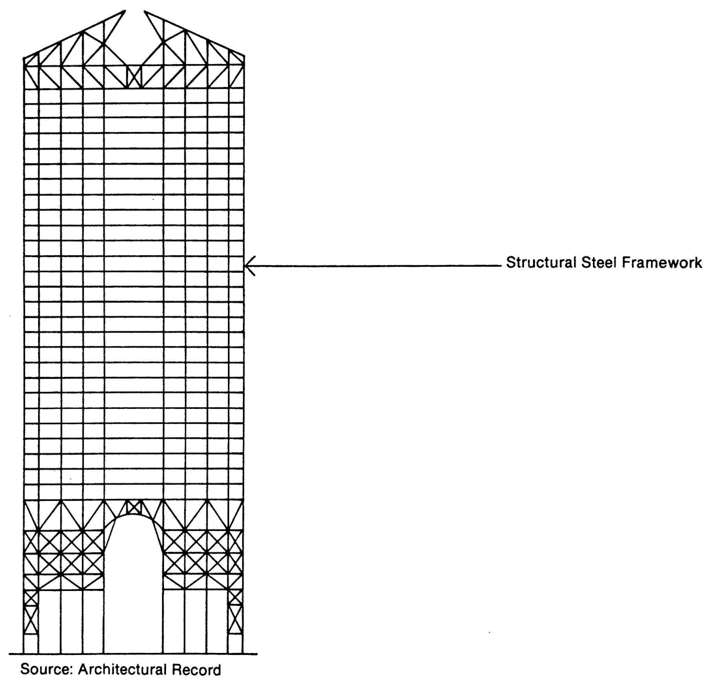


Figure 5: Modern Frame (Turner, 1986)

Envelope

The Envelope, also known as the façade or the skin of the office building, or what is visible to the public were the included items in this component. Different materials and technologies were also discussed for each of the buildings, in this regard. In different time eras of the office building, different types of materials were popular for use, ranging anywhere from masonry to glass. This range of materials can be seen in Figure 6, where the Envelope of the building wraps around the frame, exactly like a skin. In this paper, these materials, in the appropriate time eras was analyzed, as well as certain technological aspects of why certain materials were used. A substantial amount of Envelope materials for the office buildings were reliant upon the structural frame system used underneath, previously introduced.

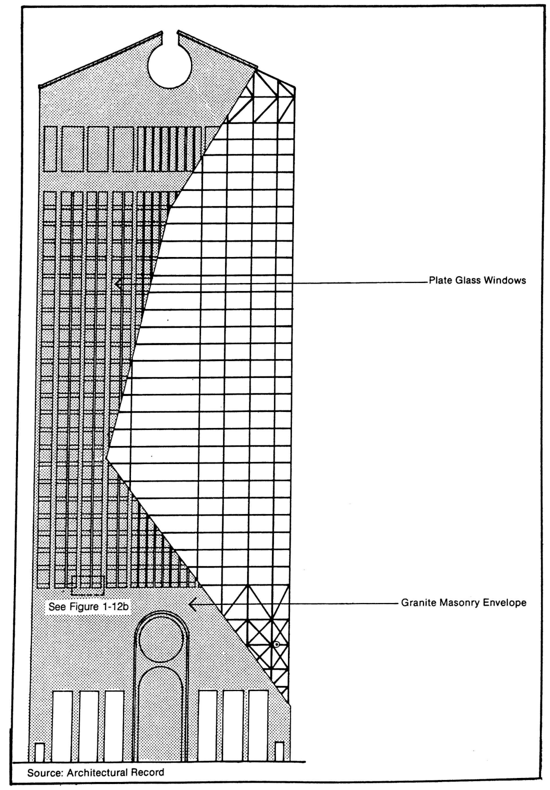


Figure 6: Modern Envelope (Turner, 1986)

Interior

The interiors of the office buildings were also unique, based on the functionality of them and what the expectations of tenants were going to be. This included any interior finishes, how the lobbies were oriented, and what the different flooring, wall and ceiling materials were like. Along with these interior items, it was also discussed how the offices were allocated with certain spaces, or the layouts of the interiors. Some maintenance items were discussed in this section as well, and how the technology of keeping up with the interiors of the buildings has evolved, as they are all heavily trafficked locations. In Figure 7, shown below, the different components of the inside of a typical office building are shown, regarding the different interior finishes.

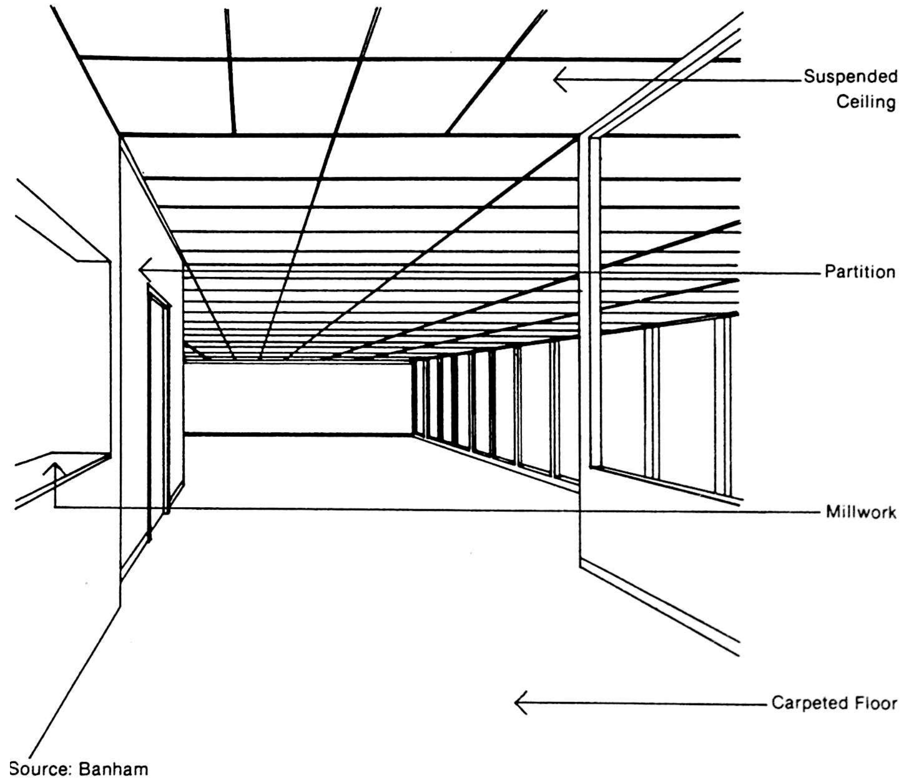
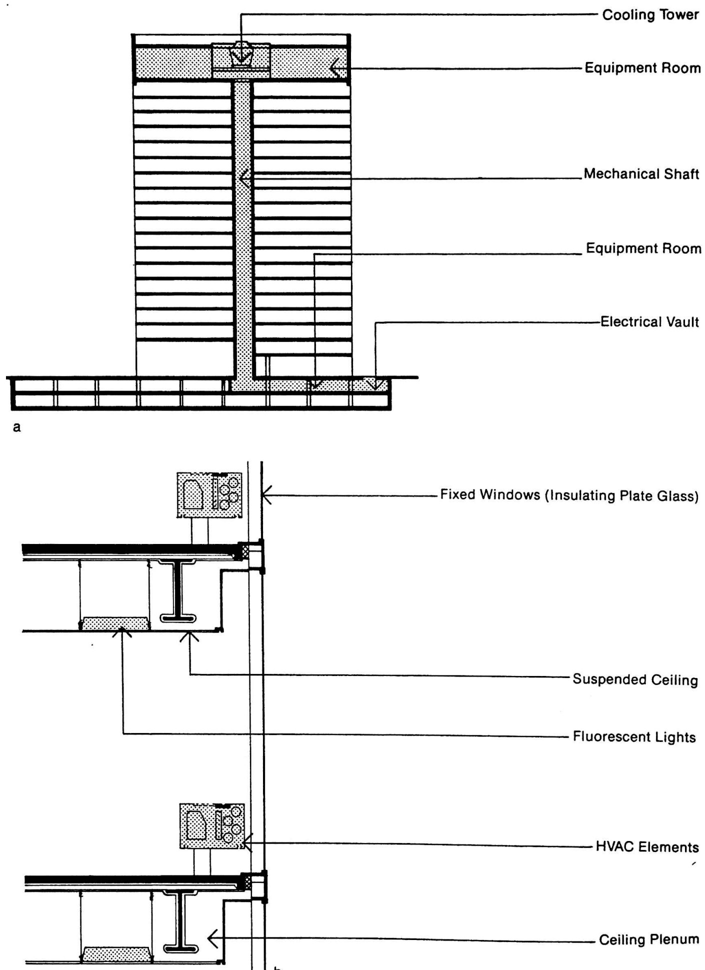


Figure 7: Modern Interior (Turner, 1986)

Services

Lastly, the Services were discussed in detail. Out of all of the different elements of the office building, the Services technologically advanced the greatest. This section included any items ranging from the window cleaning systems, to fireproofing systems, vertical transportation systems (elevators, stairs and escalators), and heating, ventilation and air conditioning (HVAC), among other elements. In Figure 8, several parts of the Machinery that Gregory Turner depicted can be seen. Items involved in the Machinery were generally placed within the core section of the building and brought to the exterior either through the ceilings or the floors. In some cases, as will be described later, there were specified floors in the office buildings designated for Machinery purposes, especially as they became a larger, more integral part of the building system, where more areas for services became required.



Source: Architecture + Urbanism

Figure 8: Modern Machinery (Turner, 1986)

Now that the organizational breakdown is complete, a brief history and background will be provided about each of the three buildings analyzed, to familiarize with the time era in which they were designed and constructed. This section reveals how the approaches in design and constructability were reached and leads into the investigation of how each component of each building changed and how the importance of technology shifted over the course of time.

Technology Evolution

As delineated earlier, there has not only been a cost evolution over time, but more importantly, a technology evolution in office buildings. The former is much harder to quantify over the course of time, between inflation, labor rates, material availability and other variables that can drastically change component costs of a large office building. In such case, only the technology evolutions that have happened were reviewed and analyzed in further detail to follow.

There has been a vast amount of knowledge of technological evolution from the 1920s until present day. For instance, there have been heat transfer and thermal properties in buildings that have been around and studied since the 1920s. The most important element has been the quantity of heat flowing through building components. A building with a constant thickness and thermal properties is uniform or homogeneous, such as a brick or concrete wall. From the 1920s until now, the thermal resistance of a building's envelope is something that has been mastered and this analysis will reveal how the facades have dramatically changed over time. Similar to these thermal requirements, air temperature and movement regulations have been studied as well, for the purpose of air quality. The purpose of ventilation is to ensure the purity of the indoor air without causing coldness or draughtness. Artificial or mechanical ventilation is necessary for buildings with air conditioning and windows that do not open. Over the course of time, the research and development of air conditioning systems has been extensive. The unit, fans, ductwork, coils and filters that make up the system have been both created and tweaked to work at their optimal efficiency, as well as how the supply is even brought to the office building location, in the congested New York City.

Along with these regulations and standards that have been around for decades, today, there are even regulations for acoustic or sound requirements. These regulations provide freedom of annoyance from intrusive noises, speech privacy between rooms or spaces and requirements such as having a certain level of quality within rooms or spaces. Many of these regulations rely on insulation of a building. Older buildings, many times, provided natural sound insulation due to the heavy walls and floors, but as technology of these components has changed, other methods of sound insulation needed to be made.

As technology has changed, a major reason for the shift has been the need to conserve resources. For example, there has been a push to conserve materials such as steel and concrete. Originally, only naturally found products were used for a building; materials such as stone, clay, timber and other parts of plants. However, as the technology of materials has evolved, new composite materials such as special concretes, wood, glass and alloys have become materials that are used by standard in the industry. Specifically, in construction, important products that have been applied are ones like the polymers and polymer composites, such as rubber, cellulose nitrate and polyurethane. Other products more popular in roofing have gone from wood shingles, stone slabs, or even thatch to materials such as asphalt, membranes, and elasto-plastic systems (EPDM).

Since 1945, the construction of even taller, larger towers has been possible, due to new, technologically advanced materials, such as steel and high-strength concrete. There have also been new design concepts, the introduction of lightweight curtain wall partitions (substantially reducing weight), and new structure components, such as HVAC and elevators. Certain other considerations in the architectural and structural design of towers needed to be taken into account, such as: gravitational and lateral forces affecting the tall buildings, stiffness to prevent drift, oscillations caused by fluctuating wind loads, creep, shrinkage, temperature, fire protection, foundation being strong enough for the loadings and earthquake resistance. Earthquake and wind are the substantial difference of design of tall structures as a pose to other buildings, because of their height and overall massiveness. To counteract many of these load and force restraints, most building have the "tube-in-tube" design or the hull-core structure. They consist of the outer-framed tube, the hull, and an internal core. Another design was the braced-tube structure, where the framed tube was increased in efficiency by diagonal bracing. The buildings discussed in this paper will be analyzed as to what frame structure they used (Sebestyen, 1998).

In this paper, the methods of utilizing these technologies in the given time periods for the buildings being analyzed will be discussed as to how these requirements were fulfilled. The future of construction lies more in the maintenance and renovation of existing buildings as the popularity of new construction is diminishing.

The Empire State Building

Background

The Empire State Building was designed, engineered, erected and ready for tenants in a twenty-month period of time. This schedule was extremely ambitious, but worked because of the team-design approach that was used involving the collaboration of the architects, owners, builders and engineers in the planning, problem-solving and organizational genius of the general contractors. The contract documents were signed with the architects in September of 1929, and the office building opened on May 1,1931.

John M. Carrere and Thomas Hastings owned the firm that designed the Empire State Building. They both had worked for McKim, Mead & White together and when this company reached its peak they decided to branch off and start their own practice. When Carrere was killed in 1911 by a trolley hitting his cab, Hastings lost his momentum and retired in 1920. While they were in business, they had two very good associates, Shreve and Lamb, making it a four-man operating team. Shreve and Lamb continued the business when the original two designers were removed from the practice, and renamed the company after their own last names. The name eventually evolved into Shreve, Lamb and Harmon, when they picked up another important associate.

The men who were responsible for the eventual funding and owning of the Empire State Building were John J. Raskob and Alfred Emanuel Smith. John J. Raskob was the moneyman behind the Empire State Building's construction. He was heavily into stocks and investments, one of which was GM, which at the time was flourishing. Smith was New York's governor, yet not nearly as valuable.

The actual erection process of the building was done in 11 months. One of the main drivers for the speed of construction was of course, economics. May 1st was a typical start date in the year for new leases, so the designers and builders wanted to make sure they reached completion before this deadline. The building rose to a total of 1,454 feet; its height being unsurpassed until the 1970s, when the World Trade Center buildings rose higher. Zoning laws in New York City, at the time, limited commercial buildings. After a certain height, the building had to step back as it rose with a diagonal drawn from the center of the street, which many times dictated the overall size of the buildings (Willis, 16).

Figure 9: Waldorf – Astoria Building (New York Architecture Images)

The Starret Brothers and Eken ended up winning the project. They promised to complete the entire project in 18 months. This project was a flat fee project. Before they could begin construction on the Empire State Building, the Waldorf-Astoria building had to be demolished first, which is seen in Figure 9. At the time, this building was the largest, most luxurious hotel in the world. It opened in 1893 and saw a short life, before being demolished in 1929 (Willis, 1995).

It had been observed that cities grew in fits known as real estate cycles. In the mid-1920s, the buildings were about 30-40 stories. However, by the end of the decade, they were mostly ranging from 40-50 stories. From 1929-1931, many new buildings surged greater than 50 stories. This was because of the increased land costs, so more stories had to be built on one site. The height and the beauty of the Empire State Building rose strictly out of practical considerations. At the time, unlike Chicago, New York City did not put a cap to how tall a building could be. There were, however, setback requirements. "Buildings had to be set back from the street based on some given multiple of the street width" (Barr 2010). Limitations in Chicago made it so both rising cities had completely different looking skylines. Chicago's was that of a lower, more block-shaped building profile, while New York City had narrower, rising structures.

The most economical height for the elevators was one of the biggest determining factors, for deciding how many office space floors to have. At around 85 stories, this economical limit would be reached, which is why the building consists of 85 stories of commercial and office space (2,158,000 sq ft), an 86th floor observatory and 16 additional floors above this, in the Art Décor tower. The reason elevators were such a major reason were because of their considerable cost, in comparison to other aspects of the project. The total building cost of the skyscraper, at the time, was $40,948,000, including land. The building itself, was constructed at a cost of just over $24,000,000 (*The History of the Empire State Building*, 2011).

Substructure

The Empire State Building contained more than 62,000 cubic yards of concrete. According to the Uniformat II organization, in the Substructure heading, the majority of concrete was in the Foundation and basement construction of the Empire State Building. Unlike newer buildings, the Empire State Building was fortified by a sturdy steel truss, braced with diagonal beams, in the area around the central elevator shafts, to limit building sway for wind resistance. The more recent adoption to preventing sway is by using concrete cores, built in the center of the building, which at the time, the technology was not available. It is much more popular today, mainly due to the fact that much stronger concrete is capable of being made. However, as will be noted later, the structural steel columns were encased in concrete, for fireproofing.

To construct the substructure, an astonishing 28,529 truckloads of earth, rock, steel and debris had to be removed from the site. The steel that was included was some remaining from the demolition of the Waldorf Astoria Hotel, which occupied the land beforehand. The foundation was laid on the Midtown Manhattan surface, which was an igneous rock called Manhattan schist. This layer was reached about thirty-eight feet deep, so digging continued to the forty-foot mark. (Tauranac, 1995).

The foundation, at forty feet down, began with pier holes that were dug, where steel supports could rest. This is where the 210 columns that made up the building's vertical frame began. Twelve of these 210 ran uninterruptedly from the foundation to the top of the building, 1050 feet high, to join the columns for the eventual mooring mast (Tauranac, 1995).

Frame

As far as the Shell, or superstructure, was concerned, there were approximately 57,000 tons of steel that were used for columns, beams and other members in the Empire State Building. As far as technological methods used, the contractor tried to save on time, money and manpower. The steel was all manufactured in Pittsburg, PA and transported by train, barge and truck to New York City. Materials were delivered to their appropriate locations on the job site so they could be hoisted almost immediately after being on site. It was said "workers could swing the girders into place and have them riveted as quickly as 80 hours after coming out of the furnace and off the roller" (Historic Construction Projects, 2012). As one can see from Figure 10, the structural frame of the Empire State Building can be seen being constructed. As stated previously, the materials were delivered appropriately to their site location and it was evident that the site was kept very neat, with the field offices showing from this angle. The steel columned frame can be seen, throughout the structure, which when the next office building of the World Trade Center is discussed will be a totally different system. The materials were manufactured to sizes within 2mm of tolerance and prepared so they could either be bolted or riveted. The rivet connection was a technology first used in building ships. The steel rivet end

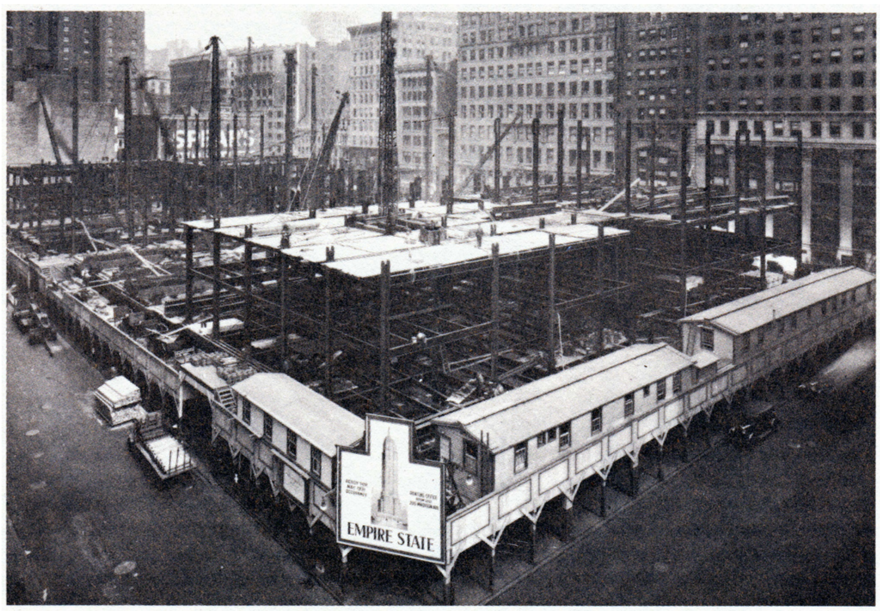


Figure 10: Empire State Building Frame System (American Monuments, 2012)

would be heated up until the end was hot, passed through the two sections it was connecting and then shaped with a special rivet gun, rounding the end to be permanently fixed in its position (Ryan, 2009).

Figure 11: Construction Workers Connecting Columns (Vintage Photos, 2012)

It can be seen in Figure 11, where two to three construction workers were forming a connection between two columns on the Empire State Building. This process was done thousands of times, all on site for the construction of the office building. It can also be noted, from this image that no fall protection, hard hats or safety glasses were used for the workers in this time era. It is amazing to think that workers worked over one-thousand feet in the air, balancing on beams and other parts of the structure without anything below to catch their fall. Another technological advance that can be taken from this photo is safety and how important and inclusive within construction it has become. There were 2.1 million square feet of rentable space in the Empire State Building, so the building consisted of about 54.3 lb/sq.ft. of steel, only including rentable space. If you take the entire square footage of the building (2,768,591 sq. ft.), the load is a lighter 41.18 lb/sq.ft. The contractor, Starret Bros. & Eken, had various firms do the work for them, unless there was some task that they could perform for less money than anyone else was asking. Post & McCord was chosen to perform the steel erection. They were fellow tenants in the Architects Building, and also the firm who had supplied the twenty-one thousand tons of steel for the Chrysler Building. Since there was such a tight schedule, Post & McCord actually decided to split the steel-fabricating contract between the American Bridge Company and the McClintock-Marshall Company.

The columns were columns that were to be designed unlike anything ever before. "The simplest and smallest rolled-steel I-beam column that was used was capable of carrying loads up to 4.5 million pounds. The next largest, a reinforced I-beam column, could support loads up to 5.7 million pounds" (Tauranac, 1995). Then there were the largest columns, which were "fabricated as the 'master' link in the steel framework, were box columns with a core section of the heaviest rolled column, two plate webs, four angles, and cover plates as wide as forty-two inches. These columns, 693 square inches of steel in cross section, weighed a ton a foot, and were designed to support a weight of five thousand tons, or more than 10 million pounds" (Touranac, 1995). As stated earlier, these columns ran from the substructure to the very top of the building, where the mooring mast was. In Figure 12, the mooring mast can be seen. It was very intricate in design, but apparent how the members of the steel frame have significantly gotten more slender from the base members.

Figure 12: Mooring Mast (Flickr, 2010)

Envelope

The exterior enclosure of the Empire State Building was made out of Bedford Indiana limestone. Approximately 200,000 cubic feet of this Indiana limestone were used on the Empire State Building. According to Gregory R. Turner's building breakdown as delineated earlier, this is considered the "Envelope." According to the Uniformat II organization, however, this building feature is still considered a part of the Shell, but for this paper Turner's breakdown is used as it helps to better break down the building components. The limestone was gray, yet hardly monochromatic looking.

To begin, this material was used because it was easy to turn limestone to ashlar at the quarry at a low cost. It was also able to be finished locally and was durable enough to last five hundred years, if it was protected from moisture build-up between the rest of the building frame (Tauranac, 1995). Prior to the Empire State Building, many buildings had massive frames assuming the role of an enclosure. However, as sheet metal, insulation and exterior stone veneer technologies, such as limestone, were developed, they became common alternatives. The exterior façade can be seen, on the following page, in Figure 13, as the majority of the façade was made of limestone and the detailing around the windows consisted of the steel and brick system, described in further detail later in this section. The limestone also worked as a heat storage mechanism, because of its inertial properties. The main reason that the envelope was no longer used as a structural frame, such as masonry walls, was that the dead load became tremendously heavier the higher a building rose. This created structural members on the lower floors to be much larger, to support the weight of the rising floors. As these members grew larger, the rentable floor space grew smaller, thus making the design financially deficient. Amongst the

Figure 13: Empire State Building ("New York City: New York")

limestone panels, there were 6,500 windows over the course of the 102 floors of the Empire State Building (*The History of the Empire State Building*). Limestone was used because at the time it was one of the lighter, more thermally resistant enclosures. This was a very innovative feature of the building, consisting of vertical bands of brick back-up masonry faced with limestone. This design alternated with vertical bands of steel framed windows and cast aluminum spandrel panels. There was continuous vertical stainless steel mullions anchored to the steel spandrel beams. These mullions were located between pairs of windows and at the edges of the limestone-clad columns. There was a brick back-up masonry system, which fully embedded the building's steel columns and backed up the immediate stainless steel mullions. Over ten million bricks were used in the creation of the Empire State Building. A single wythe of brick masonry in-fill backed up the cast aluminum spandrel panels. The bands of limestone, steel frame windows, and combination or steel and aluminum are flexible enough to deform during horizontal sway, from the wind, without cracking (Nacheman, 2006). The rest of the exterior enclosure system is best described in the following article, from the January 2006 edition of *STRUCTURE Magazine*:

> The structural steel frame incorporates two spandrel beams at each floor level; an inboard beam to support the concrete floor and live loads, and an outboard beam to support the exterior wall masonry. Each story of the masonry "piers" typically has four courses of limestone cladding in front of the common brick backup masonry. Typically, three out of the four limestone courses at each story are four-inch-thick stones backed up by eight inches of brick masonry. The back-up brick masonry behind those stones is supported on the outer spandrel beams. One stone course at each story is eight inches thick with only one wythe of brick masonry back-up. This "key" stone is supported on one of the wythes of brick back-up masonry below it, which in turn is supported by the outer steel spandrel beam. The brick back-up masonry is anchored to the structural steel columns with bent d-inch diameter steel rod anchors, and the limestone is anchored to the brick masonry with flat section bent iron bars that are hooked into the brick masonry and into cut out slots or 'kerfs' in the top, bottom and side edges of the limestone unit (Nacheman, 2006).

The exterior envelope of the building was important to the structural integrity of the building. In order to "knock over the Empire State Building," it was calculated that a wind blowing at 4,500,000 pounds pressure was required. This force was extremely large and because of it, the tolerance of the building was designed to remain vertical to within five-eighths of an inch. The envelope of this structure, being a heavy limestone, steel and brick material, helped to strengthen the building, which over time, the purpose of the envelope would greatly change.

Interior

Within the Empire State Building, which includes interior construction, stairs and roofing, there are many features, which change from this time period to the construction of the 1970s and even to present day. From the bottom of the building to the 102^{nd} floor, there are 1860 steps.

Figure 14: The Empire State Building Lobby (O'Keefe, 2010)

The interior construction of the Empire State Building was architecturally classified as having an Art Deco style. It consisted of two sections: "the main entrance lobby off Fifth Avenue and the long corridors and elevator banks which, with the inner store windows and entrances, create the effect of a grand concourse" (U.S. Dept. of the Interior, 1985). In the lobby, the ceilings were very high and the halls were very long and narrow. There were numerous symbolic pictures and plaques, all of which relate to the building or it's history in some way.

There was also an information desk, built with a black marble base, a lighter marble body and an aluminum top, which can be seen in Figure 14. The walls of the main lobby were lined with storefront windows and doors, many of which have been altered slightly from the original design. It can be derived that within the lobby there was a lot of marble work. This gave away the Art Deco style, which was mentioned earlier. The following describes the lobby and interior finishes in further detail:

> The lower portion of the walls closest to the street contains storefronts, some of which have been altered. Where the original elements survive, the doors and windows are enframed by modernistic metal strips and are set off from each other by vertical panels of rounded marble. Along the inner walls are five openings leading to the elevator banks. Above the central opening at the mezzanine level on either corridor is a striking, modernistically designed aluminum bridge, giving access to the mezzanine offices from the second floor elevators. The original modernistically patterned ceilings are intact but have been obscured by the present suspended ceilings. The one-story entrance halls leading in from West 33rd and 34th Streets continue the marble walls and storefronts; each has a zigzag ribbed ceiling, and, where the ceiling meets the walls, there is a long horizontal lighting fixture with modernistic metal training. Along the walls are a series of modernistically designed medallions symbolizing various crafts and industries involved in the creation of the building (U.S. Dept. of the Interior, 1985).

In George H. Douglas' book, *Skyscrapers: A Social History Of The Very Tall Building In America*, he says:

If the exterior of the building could be called straightforward and 'clean,' the public interior was clearly in the lavish art deco tradition. There was a four-story lobby made of imported marble giving the effect of crushed strawberries smeared into a gray surface. On the long ceiling were gold and silver suns and circles, as well as various other geometric patterns and shapes. There were streamlined bridges crossing the lobby, later encased in glass; the elevator doors were black with somber silver lines suggesting the entrances to Egyptian tombs. The interior was altogether far less expensive than the details of the Chrysler Building, but every bit as impressive (Douglas, 2004).

The arrangement of the elevators, stairs, toilets, shafts and corridors were arranged as compactly as possible in the center of the building. The office spaces surrounding the "core" and the corridors were twenty-eight feet in depth. "In essence there is a pyramid of non-rentable space, surrounded by a greater pyramid of rentable space" (U.S. Dept. of the Interior, 1985). The famous architect at the time, Philip N. Youtz, said the building was said to be "a milestone marking the beginning of modernism, [with] no attempt at novelty, no tendency to welcome the bizarre" (Tauranac, 1995).

The design of the interior for the majority of the floors had twenty-eight feet between the windows and the corridor wall. There were about twenty feet between the center points of the columns, along the exterior walls, making the average office unit approximately nineteen feet wide. "With partitions down the middle, the interior could be comfortably divided to form two nine-foot-wide offices, each with its own window, and an anteroom" (Tauranac, 1995). One of the three main designers, Harmon said “nine-foot-wide offices were considered the most desirable by the greatest number of tenants – there was room for a desk and a passage, as well as a few chairs and cabinets – so the resulting offices would be ideal. Whatever the configuration, the space would be bright, since each unit would have two windows” (Tauranac, 1995). As mentioned in the envelope section of this paper, the thin aluminum spandrels of the windowsills allowed the radiators to be hidden in the interior design. This allowed for a neater looking office as well as improving rentable area.

At the base of the interior, there were some thirty-six stores with entrances from the sidewalks and either the lobby or the corridors on the main floor that wrapped around the building. To hide the base columns, all of the windows were flanked with narrow aluminum mullions that had some sort of ornamental spiral design to them.

Services

The services were certainly one of the most technologically influenced parts of the office building as time has evolved. They involve items such as the conveying systems (elevators), plumbing, heating, ventilation, and air conditioning (HVAC), fire protection systems and electrical systems, among others. The Empire State Building consisted of sixty-four elevators. There were over seven miles of shafts within the elevator. Inside of these seven miles of shafts were over 27 miles of main and counterweight rails for the elevator tracks. The following quote best describes how the office building is laid out with all of the machinery items:

> A certain amount of space in the center, arranged as compactly as possible, contains the vertical circulation, mail chutes, toilets, shafts, and corridors. Surrounding this is a

perimeter of office space 28 feet deep. The sizes of the floors diminish as the elevators decrease in number. In essence there is a pyramid of non-rentable space surrounded by a greater pyramid of rentable space, a principle modified of course by practical consideration of construction and elevator operation (Tauranac, 1995).

The equipment was centered in the building and tapered upward as a cone shape, instead of being distributed throughout the wings of the building. One of the main purposes of this design was to optimize the natural light in the offices. By putting all of the services in the center of the building, offices could surround the entire perimeter of the core.

The elevator system was one of the main keys when determining how high a building could rise, both at the time the Empire State Building was constructed, as well as today. The Otis Elevator Company was chosen for the $2.9 million contract to design, manufacture and install the elevators for the Empire State Building. At the time, the designer for the elevating system in the Empire State Building, Otis, had a plan for running both express and local cars in the same shaft, but the designers

Figure 15: Empire State Building Elevator Banks (DiDomenica)

rejected this idea. They also rejected the "skylobby" or plaza floor, which would be later used for buildings, such as the World Trade Center (1973). A third idea they rejected still was the double-decked elevators, such as in the Citicorp Building (1979). The designers decided to use the elevator banks that were placed parallel to the main axis of the building, with four groups of high-rise elevators. The elevators in the Empire State Building were capable of a speed of 700 feet per minute, which was the maximum speed permitted by code, at the time. In Figure 15, notice how the elevators were set up in the Empire State Building, as well as some of the interior finishes that are around the elevator banks, on the ceilings, floors and walls.

When it came to economics, involving elevator services, the rentals were affected as well. Floors that had the nonstop services were demanding premium figures, since they had the fastest service and were transfer floors as well. The following is a breakdown of how the Empire State Building broke down their elevators, among the floors:

- Bank A, four cars, third to seventh floors
- Bank B, ten cars, seventh to eighteenth floors
- Bank C, eight cars, eighteenth to twenty-fifth floors
- Bank D, ten cars, twenty-fifth to forty-first floors
- Bank E, eight cars, forty-first to fifty-fifth floors
- Bank F, eight cars, fifty-fifth to sixty-seventh floors
- Bank G, ten cars, sixty-seventh to eightieth floors

Above the eightieth floor, there would be two more transfer elevators, with access to the eighty-sixth floor (Tauranac, 1995).

Another important service feature of an office building, back when the Empire State Building was constructed, as well as today, were the telephone lines. In this building there were approximately 17 million feet of telephone wire installed to service the building (Rosenberg, 2013). This was the New York Telephone Company's single largest installment ever. They installed approximately six thousand pairs of house cables, four thousand sets of wires to the central office and more than five thousand station telephones. These all linked in to more than three thousand trunk-line switchboards.

For the fire protection system, the original system consisted of call boxes on each floor that made a sound when manually activated. The sound would sync with the floor in which the fire was on, with a certain number of "bongs" for each floor. Along with this system, the structural steel was protected by iron oxide and linseed oil paint, to prevent corrosion. All of the steel members were also enclosed within concrete, for additional fireproofing. The building's water delivery system was first-class for the time period of installation. It consisted of water tanks being inside the building, as a pose to on the roof, which provided seventy miles of piping to delivering water to the entire building. Each floor was self-contained and compartmentalized, with each floor using their own cooling and heating ducts and utility shafts, which makes it extremely difficult for fire to spread between floors. Finally, dealing with fire protection safety, the stairwells were fireproof, which was a requirement for high-rises, beginning in 1930.

Originally, the Empire State Building was created with no air conditioning system. Windows were used both for ventilating the offices as well as providing a lot of light in the building. "Maximizing daylight in the room meant that the interior lighting systems could operate at significantly reduced level, while still producing illumination required by code" (Bose, 2010). Since air conditioning was installed in 1961, the windows were originally created as operable, and even today can be opened, for the times when occupants still just want to open a window for fresh air. This was how work was conducted within the Empire State Building for the first thirty years of its existence. A man named Willis Haviland Carrier was known as "The Father of Cool," because of his invention of the air conditioning system. In 1921, the centrifugal refrigeration machine was patented by Carrier, and the 'centrifugal chiller' was the first method of cooling large spaces. "Cooling for human comfort, rather than industrial need, began in 1924, noted by the three Carrier centrifugal chillers installed in the J.L. Hudson Department Store in Detroit, Michigan" (Bellis, 2013). The technology to provide air conditioning for an entire skyscraper was not yet efficient enough to work for the Empire State Building and "the Great Depression and then WW2 slowed the non-industrial use of air conditioning. After the war, consumer sales started to grow again. The rest is history, cool and comfortable history" (Bellis, 2013).

Even though the building did not originally contain air conditioning, in the future this feature and more services were added to the building, to help modernize it. For example, nowadays, the illumination levels of the offices adjust automatically. There is a control system, which regulates the time of day and occupancy usage of a space. The sensors work even so integrally with the furniture, such as desks. This allows for energy usage monitoring, by the energy managing system, all purposed reducing overall energy usage.

World Trade Center

Background

This project was initiated in the early 1960s through the influence of David and Nelson Rockefeller, and the creation of the Rockefeller Center. The vision was to revive the future of trade and finance on the island. Originally, Skidmore Owings and Merrill tried to design the site for the World Trade Center, but the Port Authority of New York accepted none of their designs. The Port of New York Authority was formed in 1921, and recommended policy and carried out improvements in the development of the port district. By 1959, they had developed into a wealthy entrepreneurial organization and were a good candidate to run the WTC, because they could issue revenue bonds and could condemn private property through the governmental power of "eminent domain." There was an organization created, called the Downtown-Lower Manhattan Association, who produced the basic scheme and concept for the World Trade Center Plaza and the question of who was going to build it was raised.

The advisory board for the development of architectural ideas was composed of three of the most famous names in American architecture of the time: Gordon Bunshaft, of Skidmore Owings and Merrill, Wallace Harrison, of Harrison and Abramovitz and Edward Durell Stone. The original design called for a plaza, with the space for ten million square feet of office space. This number remained consistent throughout the design of the project, but originally, a 72-story skyscraper was going to be one of the main pieces of the plaza. The top eleven floors of this 72-story skyscraper were to be reserved for a hotel for world-traders. The 350 rooms were going to be "one of the most magnificent views in the Port of New York" (Robins, 1987).

In March of 1961, a proposal for the WTC in the Port of New York was made to the mayor and governors of New York and New Jersey. It was going to cost about $350 million. The governor of New Jersey declined to lend his support because he saw little advantage to New Jersey citizens, no matter how beneficial it was to lower Manhattan or the Rockefellers, which caused the project to fall dormant. Eventually, Harrison, Bunshaft and Stone fell out of the running for what was to be the biggest architectural commission of the day and the Port Authority had to find a new architect for the project. The reason this happened was because they asked for too high of a fee, believing they deserved something substantial because of the long period of time that they had already been with the organization. The Port Authority denied their request and began searching for a new candidate.

The Port Authority had a team of their own engineers and architects who carried out detailed evaluations of the architects' recent work, so they had a lot on file in order to carry on the process of finding an appropriate architect for the largest project that New York has ever seen. The final recommendations were based on interviews, submissions and evaluations. When looking to find a firm, the Port Authority narrowed their search to seven potential candidates. Four of them were deemed as being too uncreative, one was apparently unqualified and one was too old and leaning towards design collaboration. In the end, they were left with Minoru Yamasaki, a Japanese architect. He ended up being exactly what they were looking for. In late August they decided that Yamasaki was going to be the man for the job.

Minoru Yamasaki was from Troy, Michigan and chosen to be the lead designer. Emery Roth & Sons were the associate architects for the assemblage of the buildings. The architect, Yamasaki, was well known in the 1960s and generally concentrated on the needs of urban renewal and mixed-use mega development. He had a conservative style of architecture and favored materials such as woods, smooth and painted concrete, stainless steels and anodized aluminum plate. His style was never accepted as modernistic. Yamasaki was a man who dedicated his life to architecture, yet his work rarely ever showed any extensive creativity. The towers in New York City set themselves apart from adjacent buildings and other physical properties of the city. The critics were those who speculated from the outside, while corporate leaders, such as IBM and Alcoa, loved the bold and politely modernistic style. Yamasaki's firm was very small in size and at first thought the $280 million estimate was a mistake to the tenth power. He tried over 100 schemes in the process of trying to find a way to create 10 million square feet of office space. Somewhere between the twentieth and fortieth attempt, he had the idea of a pair of towers (Robins, 1987).

Besides Yamasaki, Leslie Robertson had the most influence on the form of the buildings, being in the lead position of the structural engineer for the towers. The structural engineer, or third collaborator, was Worthington, Skilling, Helle, and Jackson. Robertson was in charge of innovating ideas for how to fulfill the space requirements for the client. He also needed to innovate ideas for the lateral movement of the towers, lightness of the floor slabs and the rigidity of the tower (Fernandez, 2002).

The electrical engineer for the project was Joseph R. Loring & Associates. The mechanical engineering firm was Jaros, Baum & Bolles. All of these parties worked close together, because of the extreme complexity of the project.

When the towers were built, they were the tallest in the world. They only held this position for a very brief period of time, however, as the Willis Tower (formerly known as the Sears Tower) surpassed it in 1973. The World Trade Center Towers One and Two measured at 1,353 feet in height. The cost of building them was an estimated $1.5 billion, putting each at approximately $750 million. Each of the two towers had approximately 3,800,000 square feet of office space for rent. Each floor had 40,000 square feet, as the footprint of each floor was approximately an acre in size. There were 110 stories, eight of which were set aside for technical services, or considered mechanical floors, in four two-floor areas that were evenly spaced up the building (7/8, 41/42, 75/76, and 108/109) (Fernandez, 2002). The North Tower of the World Trade Center was completed in 1970 and the South Tower, in 1972.

Before beginning on the breakdown of the World Trade Center towers, the following excerpt from Angus K. Gillespie's book, *Twin Towers, The Life of New York City's World Trade Center*, paints a nice outline to the construction of the World Trade Center, and how it was constructed with the unique technological advances that it used, leading into the component analysis:

> First, there was the construction of the core or rectangular elevator-service area where all the interior columns are clustered together. From the core, the floor system reaches in a clear and unobstructed clean sweep to the exterior wall. Although few tenants subsequently took full advantage of the dramatic interior layout potential, the fact remains that the architecture offers great possibilities. It was at the core that the giant kangaroo cranes, to be discussed in more detail later, lifted the steel from the outside.
>
> Second, there was the construction of the exterior wall. Naturally, the placement of the load-bearing outer columns proceeded at the same pace as the erection of the core columns. The wall was put up in prefabricated panels with the vertical columns already welded to the horizontal beams called spandrels. Each unit weighed about twenty-two tons and was three modules wide, or about ten feet. The units came in two sizes; they were either two or three stories high. The finished wall presents a series of columns at intervals of three feet, four inches, a fairly narrow spacing designed to accommodate even narrower windows of twenty-two inches that make the occupants, even acrophobes, feel secure. Even if you stand right at the windows, you do not feel as if you might fall out.

Third, there was the installation of the floor. As the columns and walls rose, the floor was installed in preassembled sections that spanned from the elevator core to the exterior walls. The floor sections were thirty-two-inch-deep trusses, or triangular metal frameworks, made by the Laclede Steel Company of St. Louis. The floor trusses had a corrugated metal lid on top designed to accept the poured concrete floor slab. The end result was a solid, smooth, and safe floor. To simplify later work, the ductwork for the telephone and electrical distribution lines made by Granite Steel Company of Granite City, Illinois, was built into the corrugated deck. Below the truss decking, sheet-metal workers, or "tin knockers," placed the air-conditioning ducts, which were to be covered by the ceiling underneath. The work of the floor framing kept pace with the erection of the exterior wall.

The fourth and final step for the Twin Towers was the installation of the curtain wall cover. Metalworkers put up a skin of aluminum with stainless steel trim that enclosed the structural steel. The contract for fabricating the aluminum had gone to the Aluminum Company of America (Alcoa). The practical purpose of the curtain wall is to keep water out and to keep either cooled or headed air inside. But the curtain wall is also the face that the building presents to the world, so it is supposed to be handsome as well. Other workers sprayed a slushy gray fire-proofing mixture containing asbestos on each steel column before placing the outside curtain walls. Of course, the curtain wall is also supposed to let in some light. The twenty-two-inch spaces between the columns are for windows, which are recessed ten inches in order to shade them from all but direct sunlight. The architect specified a bronze-tinted, heat-reflective glass for the 43,600 windows (Gillespie, 1999).

Substructure

Before even being able to build the substructure, a significant amount of demolition needed to be done at the site of the future World Trade Center buildings. Demolition began on March 21, 1966, when the Ajax Wrecking and Lumber Corporation began demolishing the first of twenty-six structures on the proposed site. One of the major obstacles that the demolition process ran into was the hundreds of pipes, utilities, and water lines that ran under the site. These all needed to be carefully excavated and relocated, to keep their functionality. To build the substructure of the World Trade Center, approximately 1.2 million cubic yards of dirt and rock had to be excavated for the 60-70' deep foundations. The area, known as the "bathtub" was a box of 800 feet by 400 feet that needed to be excavated. The material was actually used to create 23.5 new acres of land for Manhattan on the shores of the Hudson River, which is currently the site of Battery Park City. The basement completion of the World Trade Center was an extremely difficult endeavor because of the magnitude of the project, which up unto this point, was a first. Five surrounding streets were closed to allow access to the construction site. There were two subway lines on the site, which were kept running through construction. The foundations and basements had to be built around these pre-existing structures.

In building the substructure, the use of slurry walls was used for the first time in the United States. Before this decision was made, other methods were thoroughly considered:

All conventional methods for building the basement wall had substantial drawbacks. The old pneumatic caisson method was too slow. The open cut method was too expensive. They went down the list, considering more than ten different textbook possibilities. It looked as if nothing would work. Then John M. Kyle, Jr., the chief engineer of the Port Authority, came up with a solution: the slurry trench method. Although it had been used in Europe and in Canada for subway construction, the method was practically brand new in the United States. True, it had been used in Allegheny, Pennsylvania, for the installation of a cutoff wall under a dam to stop the infiltration of water, but never in foundation work. It was a big gamble because no one knew if it would really work. There were no American firms available for the work, so it had to be done by an Italian company (Gillespie, 1999).

This technology consisted of digging a trench in the eventual location of the perimeter retaining walls. The excavating machines used their clamshell buckets to dig out a three-foot-wide trench, which would be the same width as the basement wall planned for that space. This excavation was done in twenty-two-foot segments. As seen in Figure 16, material, such as bentonite slurry, was pumped into the trench, as it was being excavated, and used to keep the trench open against the surrounding earth. This material came from Wyoming, mined, bagged and shipped to New York, and it was a type of fluffy, expansive gray clay. The material was strong enough to hold back the groundwater and maintain the sides of the trench without any additional bracing in the trench. Once the trench was completed, reinforcing bar was lowered into the trench, as seen in Figure 17. This reinforced mesh was a preassembled, seven-story-high steel cage of reinforced rods. This provided the framework for the eventual concrete that was

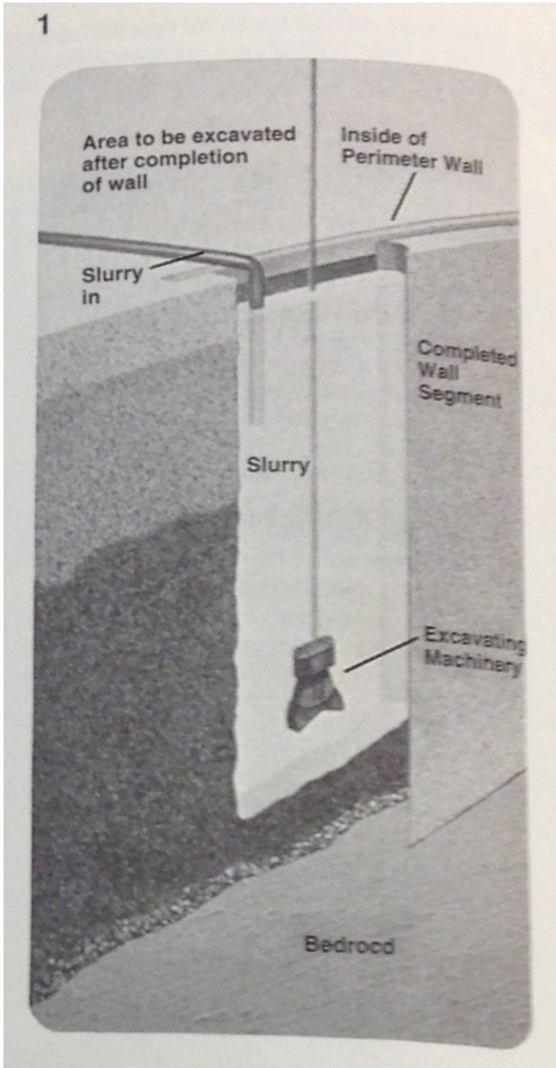


Figure 16: Excavation for Slurry (Gillespie, 1999)

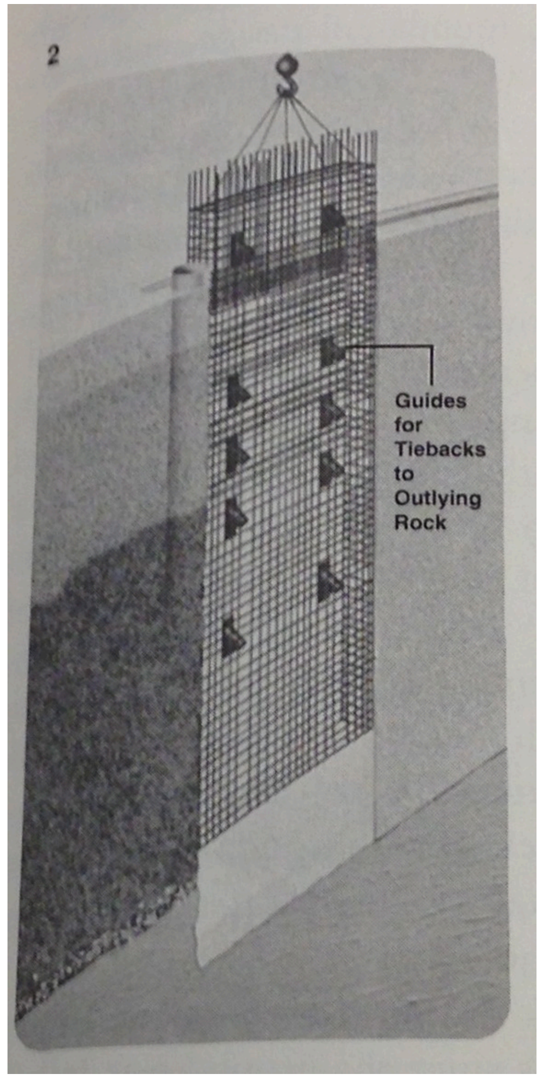


Figure 17: Reinforcing Bar (Gillespie, 1999)

placed to create the reinforced concrete wall around the perimeter of the World Trade Center, which can be seen in Figure 18. As the concrete was pumped into the trench, the lighter slurry was forced out the top, or into other segments of the trench. In total, one hundred and fifty-two of these twenty-two-foot trench segments were created to enclose the area of two blocks wide by four blocks long. Once the wall was cured, the excavation could begin. Tiebacks were used, through the concrete wall, and into the surrounding soil to help provide stability for the excavation, as you can also see from the image. Internal braces could not be used because they would have interfered with the future steel erection. In a lot of cases these tiebacks were

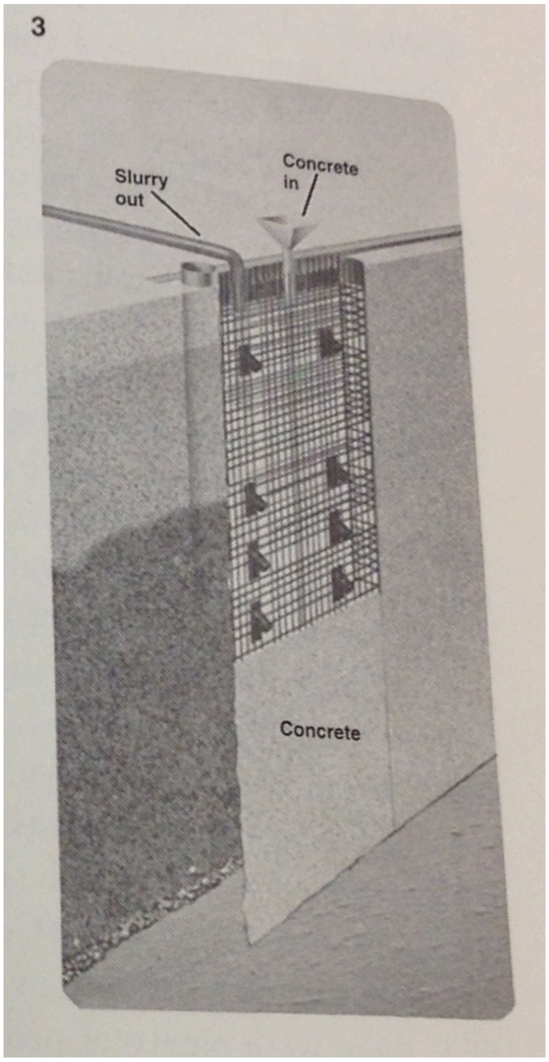


Figure 18: Pouring of Concrete (Gillespie, 1999)

permanent, but in the construction of the World Trade Center, they were temporary and replaced with laterally supportive floor slabs. "Although this sounds simple, it was difficult to route the tie-rods away from sewers and wires. There were also legal complications because many of the tie-rods had to be anchored into rock on property belonging to other people" (Gillespie, 1999).

As stated earlier, the two subway lines were an additional challenge that was in the substructure construction of the World Trade Centers. The Interboro Rapid Transit System 1 and 9 subway lines, which were operated by the MTA, ran from north to south across the middle of the site, next to the east wall of the substructure. The second subway system, Port Authority Trans-Hudson (PATH), which was operated by the Port Authority, ran beneath the western half of the site. It made a 180-degree terminal bend. It had to be temporarily supported across the excavation and incorporated into the final construction (McAllister 4).

The total amount of concrete that was used per each World Trade Center building was approximately 106,000 cubic yards (Roberts, 2003). This number was about twice the amount that was used for the Empire State Building. A large amount of the concrete was used in the bathtub, itself, where workers blasted a series of pits into the rocks, the rock was cut away and eventually these pits were filled with concrete to form "footings" to support the steel for the towers. The concrete was reinforced with steel bars and capped with grillages, thick steel frameworks, on which the core columns rest. An example of how one of the concrete core column bases looked, with the steel framework can be seen in the following section, in Figure 19. The framework was secured straight to the bedrock so the foundation would be unquestionably secure, for such a massive load to eventually be placed on top. Details on the exact sections used in this core column could not be found, but as one can see the base frame of the World Trade Center is extraordinary in mass.

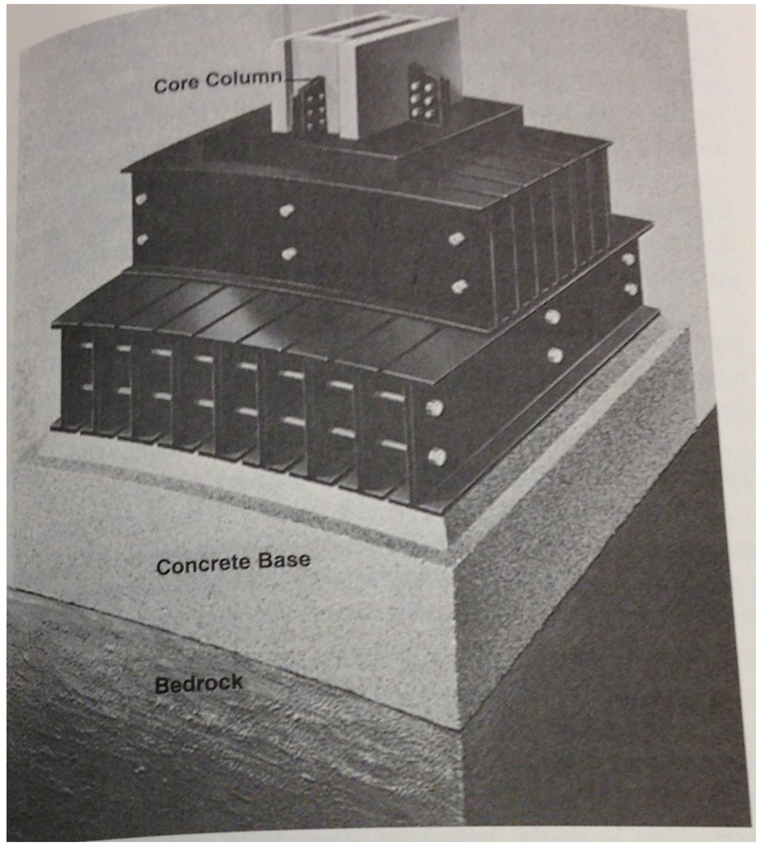


Figure 19: Core Column (Gillespie 101)

Frame

The frame of the World Trade Center was a tube-framed design, consisting of three main parts:

> The center core's solid steel columns took much of the buildings' downward weight. The outer skin formed a network of hollow tubular steel columns linked together like lattice sheathing to protect the building against horizontal loads, like wind. Finally, webbed

steel floor trusses spanned the area from the center core to the perimeter steel lattice. You might envision this as similar to placing a small cooking oil can inside a larger cooking oil can, then connecting the outer can to the inner can with layers of spaced sheet steel. As a result of Yamasaki's design, for their size, the Twin Towers were very strong but light in weight (Roberts, 2003).

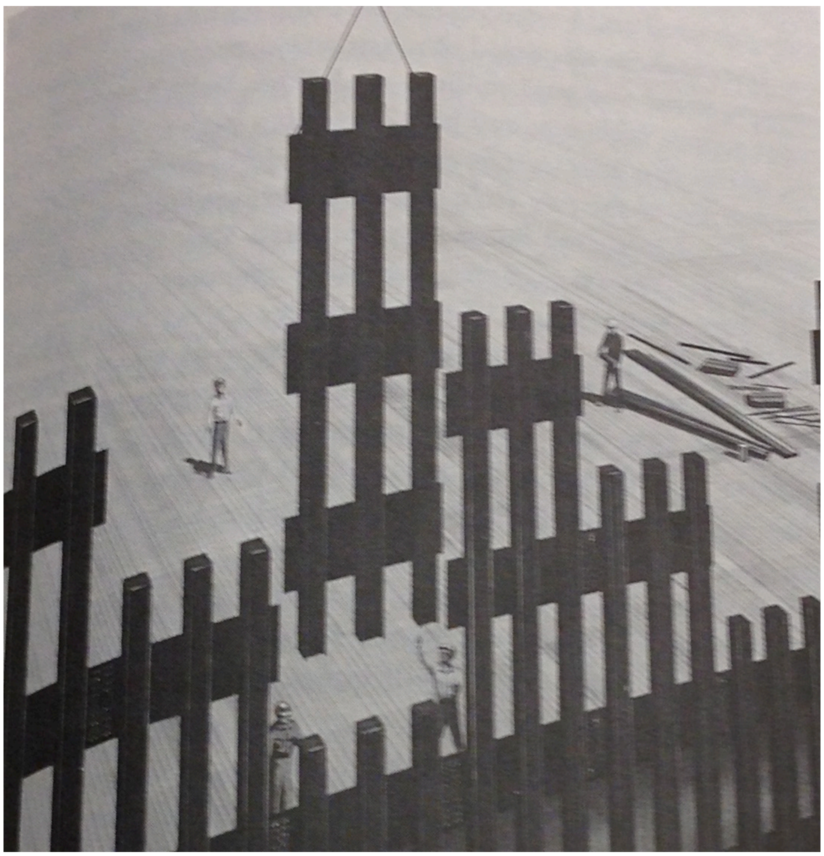


Figure 20: Three Column System (Gillespie, 1999)

Typically, skyscrapers had a network of interior supporting columns, which was the skeleton that supported the structure. However, this plan for a frame allowed for more open floor plans than the traditional design of columns throughout the interior, supporting building loads. The perimeter steel columns were called Vierendeel trusses that were spaced close together, to form a strong wall structure, resisting the lateral loads of wind and sharing the gravity loads with the core. This was the trick in getting the outer wall to carry the vertical loads, by closely spacing them together. They were placed three feet, four inches apart from each other. The exterior frame contained 59 of these columns per side, each piece being prefabricated with three columns together, three stories high, all being brought together with spandrel plates. This design can be seen in Figure 20**,** where the three column sections were being lowered into place by crane. The column and window spacing is clearly defined in this image, as well as the spandrel plates. The spandrel plates were located at each floor, to transmit shear stress between the columns, allowing them to work together in resisting the lateral loads. Since Yamasaki wanted narrow windows, Skilling's firm developed this steel bearing wall system, which required using large amounts of structural steel in the tower walls, which worked perfectly with the preference for narrow windows. At the base of the towers, there were special members, called the perimeter column "trees." These members were fifty-one feet in length and weighed fifty tons each. They were in the shape of a three-pronged tuning fork, as they brought the three feet, four-inch space columns down to ten-foot column spacing at the plaza level. In regards to the tight column spacing around the windows, "they serve as dramatic frames for the floor-to-ceiling windows which are only twenty-two inches wide. Such narrow windows give a feeling of complete security, even for most people with a fear of heights. In addition, the narrow windows partially shielded by the outer ribs reduce the heating and cooling loads" (Gillespie, 1999). The latter portion of this quote will prove to be highly beneficial when the heating and cooling systems and techniques of the World Trade Center are discussed in the services and machinery portion of the paper.

As aforementioned, Yamasaki had a unique style of architecture so he wanted to somehow incorporate this in his design of the World Trade Center. He gave the bases of the towers a gothic look. "Each group of three columns in the towers merged into one at the base, forming a Gothic-like arch and opening the wall with glass and light" (Gillespie, 1999).

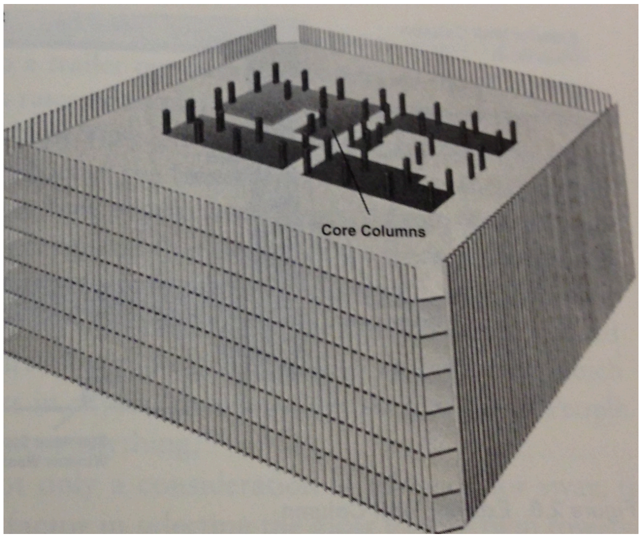


Figure 21: Core System (Gillespie, 1999)

Within the core frame system, were the elevators, utility shafts, restrooms, stairwells and other spaces. The core in the World Trade Center was a rectangular area of 87 feet by 135 feet. The core consisted of 47 columns within it, from the base of the foundation to the top of the tower. Between the core and the exterior frame, were the prefabricated floor trusses. From Figure 21, you can see the interior column system in the rectangular area described as well as a depiction of the exterior columns, so you can visualize how the system had tube-like functionality, where the trusses spanned from the interior system to the exterior load-bearing wall. These floors support their own weight as well as any live loads. The floors, themselves, as seen in Figure 22, on the following page, consisted of 4 inches of lightweight concrete slab, laid on a fluted steel deck. The bridging trusses spanned to the main trusses, which spanned to the perimeter and connected to the columns, at a 6 foot 8 inch center. The trusses were bolted to seats welded on the spandrels beams on the exterior side as well as a channel that was welded to the core columns on the interior side. The floors also used viscoelastic dampeners where connected to the spandrel plates, to reduce the amount of sway in the building. Chief Engineer, Leslie Robertson, was in charge of developing these viscoelastic dampeners, to reduce the building sway to an acceptable level, where the occupants would feel comfortable and be able to tolerate the level of sway (Gillespie, 1999).

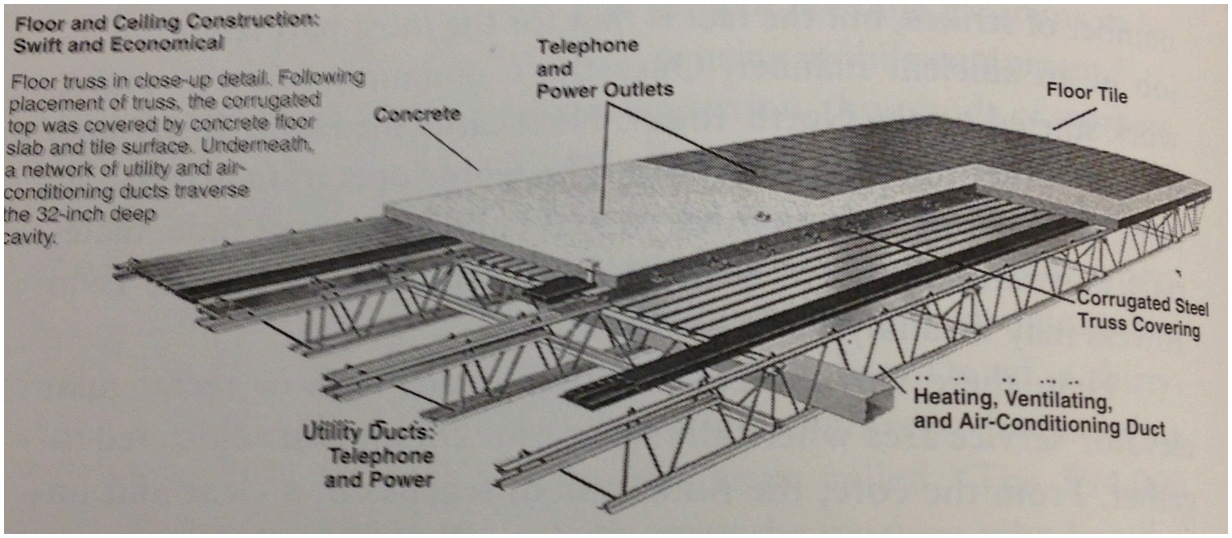


Figure 22: Floor System (Gillespie, 1999)

The bracing against wind was one of the biggest problems for the World Trade Center, because of it's tall, 110-story frame. Skilling's novel solution of having a much lighter structure, by abandoning the steel cage and going back to the load-bearing wall, with the modern material of reinforced concrete was one of the main reasons this idea was taken from design to construction. "The steel load-bearing walls required closely spaced columns to form the rigid box, and that fit nicely with Yamasaki's narrow windows. It also provided a good rationale for his sheathed-in-steel design" (Robins, 1987). Along with the closely spaced columns providing the window space that Yamasaki originally wanted, the outcome of the frame was as follows:

> The result was a rigid, hollow box, no cage inside, with floor trusses extending straight across to the central core housing the services. The steel walls, fabricated in sections three columns wide and two stories high, hoisted into place and welded together, became the supporting structure. Wind loads were simply carried down the walls to the

foundations. As an added benefit, the structure produced column-free interiors for maximum flexibility in floor layouts (Robins, 1987).

Another effect that needed to be considered, even though it did not directly affect the design of the structures, was the wind effect on pedestrian comfort, on ground level. "It was one of the first large-scale projects where the impact of the wind on pedestrian comfort was taken into account through aerodynamic analysis" (Gillespie, 1999). The buildings could only be placed so close to each other, due to the "tunnel effect" that was produced when gusts of wind blew between the buildings. This design component made it evident how much of a role wind could play in the design of a structure, and how it is very commonly the controlling load for design in tall buildings.

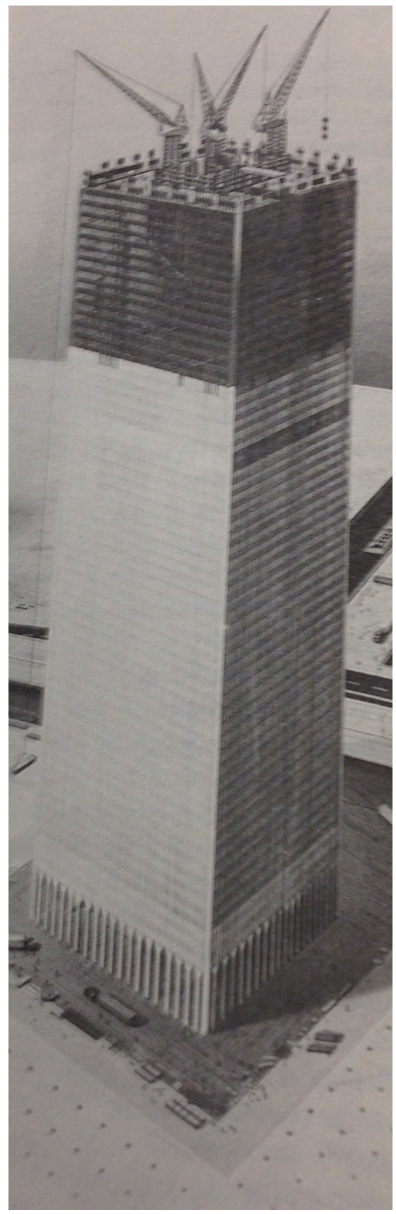


Figure 23: Kangaroo Cranes (Gillespie, 1999)

When considering statistics for the structural elements and components of the World Trade Center buildings, they are most often grouped together as "Tower One" and "Tower Two" or the "North Tower" and the "South Tower." This being said, the discovered numbers have been halved to compare the amounts of a single tower to the other buildings being analyzed. One World Trade Center tower consisted of approximately 100,000 tons of structural steel. As mentioned, this was mainly in the outside structural wall, the core columns and the trusses, which ran under the floors of the towers. Also, on the outside frame, there were about 21,5000 windows, which totaled approximately 300,000 square feet of glass. This astonishing number, however, was only about 30% of the building's surface area, as Yamasaki did not want the towers to be a high percentage of glass, which he thought was the dying trend in architecture and construction.

For construction of the frame, a newer invention was used to raise and lower heavy structural elements. They were called Kangaroo cranes, which can be seen in Figure 23**.** Normally, derricks were mounted to the building, to lift the steel with ease. However, with the height of tall buildings, derricks had to constantly be lifted to a higher position, one floor at a time. This process of lifting a derrick normally took, on average, a day and a half. This option was clearly too time consuming, especially for the massive height that this skyscraper would be reaching. Another available option was the crawling cranes, which were staged on the street. The main problems with these types of cranes were their safety, regulatory issues, and of course the fact that they could only lift anything that was less than their own height. With the building rising to well over one thousand feet in height, a different type of crane was needed that would be able to move up with the building, because it would not be able to reach from the ground, but also one that could move quickly:

> What was needed was a crane that could carry its own power aloft and could be equipped with hydraulics to raise itself atop the building as it went along. It would also have to be irrefutably safe. Such an ideal crane was found in Australia, manufactured by Favelle Mort, Limited, of New South Wales. It was officially called a Favco Standard

> 2700 Crane, but because of its Australian origins it was quickly nicknamed the "kangaroo crane". At first glance it looked rather ordinary. It had a 110-foot boom painted red and white for aircraft safety, a red cab, and a counterweight at the rear. Less ordinary was its mounting. It sat atop a thin steel structure, 12 feet by 12 feet, which was 120 feet high. The lower 80 feet of this tower fitted into the elevator core "like a sword in a sheath," according to Austin Tobin. There were four of these kangaroo cranes, one at each corner of the elevator core (Gillespie, 1999).

The kangaroo cranes were capable of lifting themselves up, three floors at a time, powered by diesel motors, which drove hydraulic lifts. The process took a mere two hours, which was incredibly shorter than the other types of crane mechanisms.

As mentioned with the column and window arrangement in the World Trade Center towers, "the columns are twelve inches deep from the outer skin of the aluminum to the glass, shading much of the glass of these narrow windows. This is particularly important on the south and west facades, saving energy for air-conditioning during daylight hours in the summer. Similarly, the low amount of glass saves on heating in the winter" (Gillespie, 1999). The windows being twenty-two inches wide and the columns being eighteen inches wide created a module of three feet and four inches for the frame construction. In the following figure, Figure 24, an example of one of the exterior columns can be seen. The window-washing track, discussed in the Machinery or Services portion of the report, can be seen on the lower part of the picture. Also, discussed later, the fireproofing system around the steel column can be seen in this image. As previously discussed, the "Aluminum Column Cover" or panel can be seen in the image below as well. This part of the frame was repeated hundreds of times, through the hundreds of columns that existed in the World Trade Center. The only variable in the repetitious process of the column system was that the higher the building rose, the smaller the sections of steel would get, in terms of thickness and in weight.

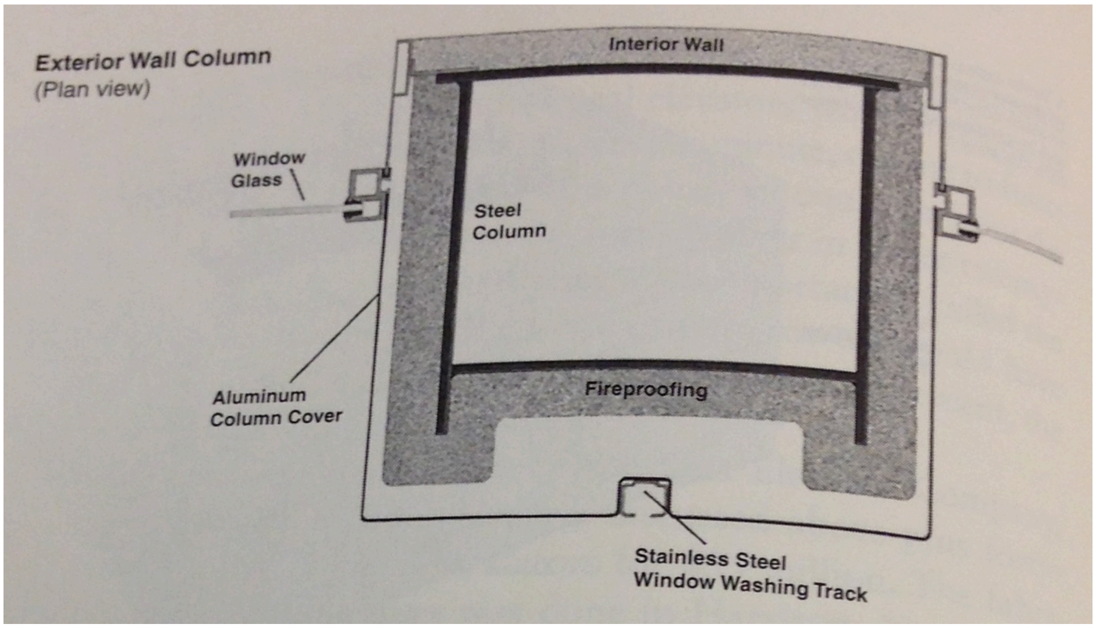


Figure 24: Exterior Column (Gillespie, 1999)

A different innovation that occurred with the building of the World Trade Center was the use of multiple providers of steel. The two giant companies at the time, Bethlehem Steel and U.S. Steel were originally going to receive the proposals, however, the two companies had betrayed, Austin Tobin. Over the course of the design process, the two companies had sent estimates to Tobin, as well as Guy Tozzuli, the directing leader of the World Trade Center operations, which seemed reasonable, especially as the estimates came closer to the time to make a deal on the proposal. However, the low costs, which seemed promised by the manufacturers, came in a full 50 percent higher than they had expected. This set the stage for Tobin to take the unconventional method of looking for numerous other companies, by separating the project into smaller "packages." This required a lot more work on the side of the Port Authority, as they tried to find fifteen different companies to fulfill their fifteen different packages. In the end, this unconventional method of hiring manufacturers was a lot more work for the Port Authority, however, it ended up saving tens of millions of dollars. Steel came from all parts of the country, under this new method of contracting with fifteen different companies, but to Tobin and the Port Authority, it was worth the future headaches in keeping track of all fifteen of them as a pose to just two companies, to prove that they could find ways to save money on their own and not have to rely on the large companies, who had betrayed them with astronomical costs.

In comparison to the Empire State Building, the framing system of the World Trade Center was more advanced, however, it used more structural steel. One of the World Trade Center towers used approximately 100,000 tons of steel. One of the World Trade Center towers also consisted of approximately 4.3 million square feet of floor space. This equaled out to there being about 46.5 pounds per square feet of structural steel in the World Trade Center. Compared to the Empire State Building, as discussed earlier, this value was approximately 41.18 pounds per square foot for that building. The structural framing system that the World Trade Center used with the exterior columns and the floor-spanning trusses proved to be a more economical solution, as far as using steel was concerned than the steel column system that the Empire State Building used throughout the frame of the entire building. These numbers were fairly similar to the amount of structural steel used in the Empire State Building. Although one would think the amount would be lower due to efficiency in design, the magnitude of the building required larger sections to be used, so although efficiency was attained, more steel was needed to compensate for the dead load of the structure, due solely to it's enormity.

Envelope

The sheathing of the World Trade Center building was supposed to look like metal. Minoru Yamasaki thought the days of the all-glass building were over, such as the Seagram and Lever House buildings. The twenty-two inch wide glass windows, between eighteen-inch wide columns were unusually narrow. Columns projected about twelve inches out from the glass to the outer face. Figure 25 shows what the envelope system of the World Trade Center looked like. The three-pronged system that was discussed earlier can also be seen in this image.

Figure 25: Structural Framed Envelope (Craven)

One thing that was unique about the World Trade Center was that the steel bearing walls on the outside were predominantly used for the structure. This need worked nicely with Yamasaki's preference for narrow windows. He made the windows run from the floor to the ceiling. Yamasaki only felt comfortable if the windows were narrower than his own shoulder span. There was also a depth of the windows from the column, which served practically to shade the glass, thus saving energy for air conditioning and heating.

As far as the outside envelope is concerned, the following quote was taken from a reading:

> When the World Trade Center was being designed, Fritz Close, then chairman of Alcoa, called me one day and said, “Yama, I understand you are going to use stainless steel for the curtain walls of the towers.” I laughed and said I was thinking of it. He asked, “Why? Aluminum is significantly cheaper.” So I told him I did not like the color of standard aluminum, since it was so cold looking. He said he could change the composition of the alloy and provide exactly the warm color of aluminum I wanted, using new technologies to overcome problems of color consistency from panel to panel. I told him I did not want a coating, but a new alloy to give us the color throughout the panel. He agreed, so Alcoa’s labs went to work and gave us several trials of pink, brown, and other shades (Robins, 1987).

The building ended up with a sparkling silver alloy because of the colors that were added to the original aluminum. In the end, the envelope was made up of large panels of anodized aluminum. Minoru Yamasaki kept a very close eye on this construction and installation process. This was mainly due to the fact that there could be slight variation in the coloration of the panels, based on how it was made with the specific alloys, so he did not want there to be panels that were discolored from the other panels and wanted quality assurance and control of uniformity.

Another source stated:

> As long as these “curtain walls” were waterproof, they could be made of just about any permanent material. Earlier skyscrapers might have had walls of brick or terra-cotta or even blocks of stone. Cost considerations dictated the use of some lightweight metal. At

> first Yamasaki contemplated the use of stainless steel. According to his own account, he got a call one day from Fritz Close, who was then chairman of the Aluminum Company of America, the dominant producer of that metal in the United States (Gillespie, 1999).

In the end, they finally settled on a silver alloy that had an amazing ability to reflect different shades of sunlight throughout all different times of the day. As part of the visible envelope, the columns were very much a part of the scene, but they have already been discussed in detail in the Frame portion of the report.

The percentage of glass in the World Trade Center was only about 30 percent. This was about half of that of an International Style Building:

> Yamasaki's distancing himself from the International Style stemmed from his dislike of the "all-glass" building, which was actually about 60 percent glass. In such buildings, Yamasaki had intense feeling of acrophobia, especially when standing next to a large pane of glass in a tall building. Instead of having the secure feeling of being inside a building, he felt as if he could just tumble through the glass and fall. At the same time, he realized that with no windows at all occupants would have a sense of claustrophobia. The challenge was to provide people with the pleasure of looking out the windows and enjoying the view, while still having the security of being side a structure and enjoying its protection. By the time he designed the World Trade Center, Yamasaki had worked this problem out to his satisfaction. He gave the building windows that were shoulder-width

> and spanned from floor to ceiling. A person could lean right up against the frame of the windows and look out and down with no fear of falling (Gillespie, 1999).

This played a large role in his column design for the structure. The columns, being a large part of the envelope were designed in such a way to get this ratio to what Yamasaki wanted. Skilling and Robertson worked closely with Yamasaki to achieve the correct architectural look on the outside of the building, as well as gain the needed structural strength. Another goal of the floor to ceiling windows was to achieve the maximum advantage of the change in light from sunrise to sunset. This allowed the most natural lighting inside the building, from the widths that were allowed for the windows between the columns. Studies showed that office workers like working in natural light conditions to fluorescent lighting. As discussed in the Empire State Building section of this paper, the office buildings previously had to be designed with natural lighting in mind, before fluorescent lights were created. It controlled how deep offices could be, which was a huge technological advance in the World Trade Center, as the office space between the center core and the outer walls was ultimately limitless, thanks to limitless amounts of artificial lighting.

Interior

One of the main elements that Yamasaki wanted to incorporate in a lot of his previous building designs, were the raising and lowering of the ceiling heights of various spaces to vary the spaciousness of rooms. This design was difficult to incorporate with the World Trade Center, as the floors and design were pretty standard. However, like Frank Llyod Wright would like using "the element of surprise" in any of his designs, this was one of Yamasaki's marquee selling points. The place he was able to use this design scheme was in the concourse and in the plaza of the World Trade Center, but not in the interior of the building.

The building itself, which the structure could be seen in the Frame section of this paper had an interior issue based on the structural layout of the interior core:

> On any given floor there are some desirable spaces and some undesirable spaces. Each floor is basically a square with 207 feet on each side, but inside that square at the core is a service rectangle with elevators, air shafts, and so forth. Thus the square floor plan with rectangle at the core yields two desirable shorter sides, not as deep, that provide office space closer to the windows Conversely, the two longer sides are much less desirable because fewer offices, usually desks with cubicles, can be near windows. Thus, if the goal is to place a group for businesses on a given floor, one in the group is bound to be shortchanged (Gillespie 187).


Figure 26: World Trade Center Lobby ("WTC – Interior," 2009)

In the lobby, as mentioned in the framing section of this paper, the first fifty one vertical feet of columns were spread out much more than the columns for the rest of the tower. This was to create a more spacious and uplifting interior area where the lobby and mezzanine area were. As seen in Figure 26, the lobby was very open and the widely spaced columns could be seen as they merged at the top, to form the "three-pronged" forks, to allow for the more narrowly spaced windows higher up the building. The colors of white present a very clean look to the interior of the lobby. The combination of the large windows and the white created the most open appeal to anyone entering the building.

Figure 27: World Trade Center Interior ("WTC – Interior," 2009)

In addition to Figure 26, being the "World" Trade Center, in Figure 27, there were flags representing all of the countries in the world that were involved in world trade within the buildings. This added an aesthetic contrast to the white look of the lobby, making the interior look friendlier than the bold exterior demeanor that the World Trade Center was more traditionally known for.

Another important part about the interior of the building, which runs in coordinance with the structural design, is the typical floor layout of the interior. In Figure 28, the interior layout of the World Trade Center is shown. As mentioned in the framing and service section, to follow,

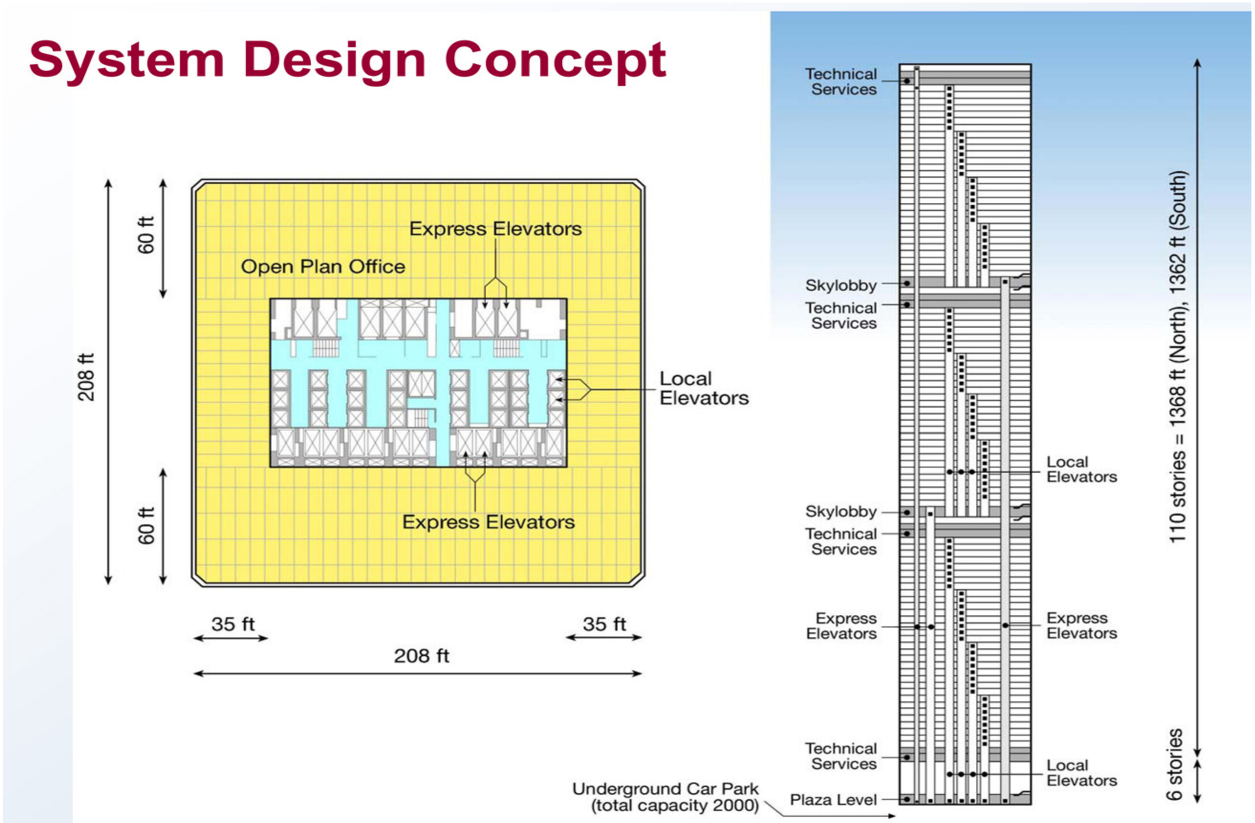


Figure 28: World Trade Center Interior Layout ("Video: 9/11 WTC," 2010)

the interior office space was not exactly square, as the floor plan was. This was due to the rectangular core space taken by the elevator and utility space. The yellow space in the image represents the open office plan area. It can be imagined or pictured that some space may end up being wasted or deemed as hard to use space in the open plan office, as partitions would need to be made by the tenants, and due to the large open areas, it may be hard find the best use for the space. In the right side of the image, the skylobby elevator system can be seen, which will be discussed in great detail in the following section, services. The rest of the profile elevation of the building can also be seen in this image, with components such as the technical service floors and the lobby plaza, which has also been discussed.

Services

From Carol Willis' book, *Form Follows Finance*, she noted that the original office buildings were no deeper than between 20-28 feet deep, for the natural lighting to provide enough lighting to efficiently work. Windows in these buildings were also allowed to be open to provide the fresh air inside, or comfort. Although air conditioning was not around in the early 20th century, when skyscrapers were beginning to be built, there were some cooling systems for circulating the air and for heating systems (Willis, 1995). As stated in the section of the Empire State Building, the services were always one of the most technologically influenced parts of the office building, as time progressed, and in regards to lighting and air conditioning or refrigeration units, among other advancements, the services in the World Trade Center did not disappoint in their technological evolution, from the time the Empire State Building was constructed. Advancements were always looking to be made in the working space, in such areas of building safety, maintenance, transportation and comfort, to name a few. Many of the different items that the building showed significant advancement in were in the conveying systems (elevators), heating, ventilation, and air conditioning (HVAC), fire protection and many others.

As far as the elevating system in the World Trade Center, the pending issue was that with the taller you design a building, the more people are in the building. The more people that are in the building, than the more elevators you need to transport the people. The more elevators that you have in the building, the less floor space that you have for rentable area, which in turn, substantially decreased the profitability of tall buildings. This problem was usually one of the driving factors for determining what the height of an office tower will be. This was the reason why skyscrapers seldom exceeded eighty stories, which was determined to be the peak of optimization and profit for rentable area, before it became counterproductive.

There were numerous ideas discussed with the World Trade Center and what would be the best elevating or vertical transportation system. Ultimately, the following ideas were drawn up and taken to be the final outcome for the design, and the following is what ended up happening:

> We could divide each tower building into three parts, or zones. For express elevators from the lobby, we will construct the biggest elevators in the work each carrying 55 passengers. Then we will stick the three local parts on top of one another. Each zone will have its own lobby. People will transfer from express to local in the second and third zones by crossing the lobby. Therefore, all the locals will sit on top of one another within a single shaft, and it will solve the problem of usable space (Gillespie, 1999).

Another source stated:

> Each tower is divided into three zones, entered at the first, forty-fourth, and seventy-eighth floors. Very large express elevators, traveling seventeen hundred feet per minute, take passengers to the forty-fourth or seventy-eighth floor skylobbies, where they transfer to local elevator service. By having three sets of local elevators, one serving the first through the fortieth, another serving the forty-fourth through seventy-fourth stories, and a third serving the remainder. As a result, elevators take up only 25 percent of any floor.

Even among the local elevators, service is staggered, with each local rising nonstop to serve a specific group of half-a-dozen floors in its zone. The result is a very fast ride from lobby to office" (Robins, 1987).

The Port Authority and Otis Elevator, together, created this so called "skylobby" system. Each of these large elevators had a 10,000-pound capacity, with a climbing speed of 1,600 feet per minute. Each of the towers were given twenty-three of these express elevators, seventy-two local elevators and nine freight cars. The freight elevators ran a total of 116 floors, down six floors in the basement, so they were by the far the highest-rise elevators ever installed up to that point. The local elevators ran at a more conventional speed of anywhere from 800 to 1,200 feet per minute, or nine to fourteen miles per hour. As can be seen in Figure 29, there were three zones, each with their own lobby, where transfers from the express elevators to the local elevators would be made.

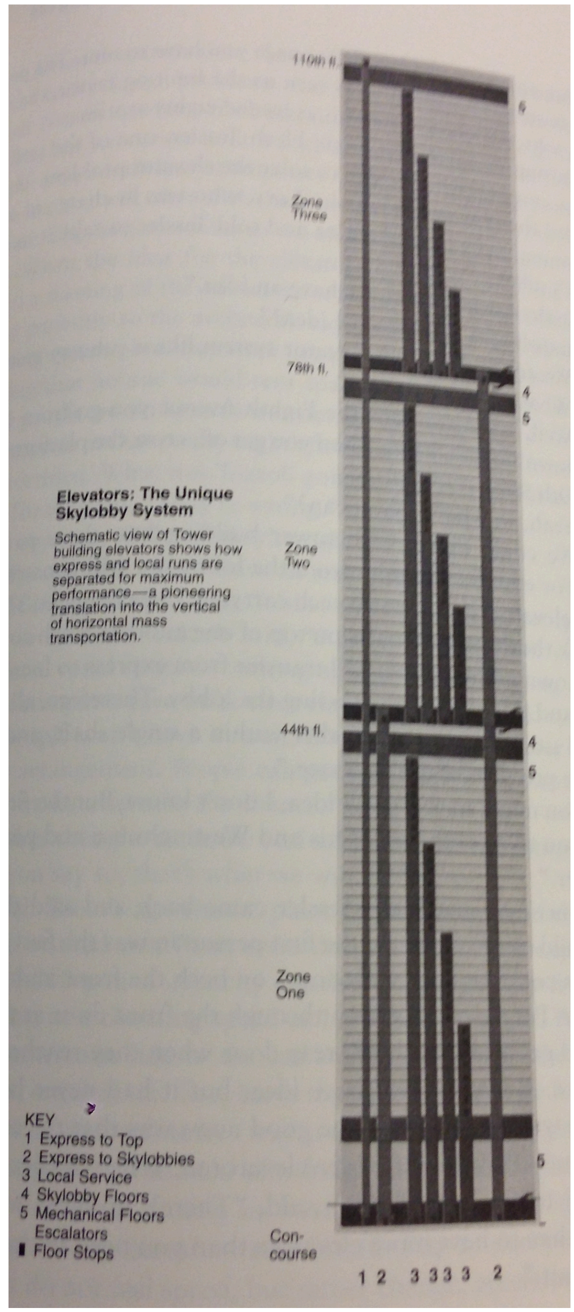


Figure 29: Skylobby System (Gillespie, 1999)

Another innovation to these elevators, whose main purpose was to save space, was that people would get in the front door at the lobby levels of the express elevators and get off through the rear doors when they reached the desired floor. It was an attractive idea, which in the case of the World Trade Center saved space. It was going to be the first time that this was done in an office building.

Ultimately, due to the skylobby innovative system, the twin towers were to have 75% usable space per floor, rather than the 62%, which was the best that had been previously installed in a tall skyscraper. The building actually was said to be over-elevatored, which was nothing but good news. One of the main issues is that people hate to wait for elevators, so this would eliminate this issue. Along with these methods of transportation within the building, they also had forty-nine heavy-duty, high-speed escalators:

> Elevators in the Twin Towers have to be in good working order. Engineers estimate conservatively that there are about 450,000 "passenger movements" per day in these elevators. A passenger movement is defined as one person going on one trip. But because of the skylobby system, two-thirds of the people have to make double trips. This includes all those in the second and third zones, because in effect each tower is made up of three skyscrapers, stacked one on top of another (Gillespie, 1999).

The entire World Trade Center complex, of all of the buildings, consisted of 254 elevators. Each of which had their own drive motor plus a motor-generator set. These were the big electric motors, each were the size of a small van, having approximately 450 horsepower, which was compared, at the time, to more than a 911 Porsche, which only had 280 horsepower (Gillespie, 1999).

Another advanced service that the World Trade Center's design incorporated was the cooling system. The system was linked to the Hudson River, by way of sixty-inch diameter pipes. This project was to be the largest in the world in this regard. All of the refrigeration equipment was placed in a two-acre area, five floors beneath the street level of the World Trade Center. The plant that was designed and later installed in the World Trade Center was a 49,000-ton central refrigeration system. The plant was located between the two towers, housed in an enormous room that was three stories tall and about the size of a small airplane hangar. In this room there were seven 7,000-ton machines, which were called "centrifugal liquid chilling units." There were an additional two 2,500-ton parallel compressors that came on line when there were lighter loads to be handled (Gillespie, 1999). The plant pump station had the capabilities to take in water from the Hudson River at a rate of 80,000 gallons per minute and the station was said to be enough to be capable of cooling 15,000 homes. The river water was pumped into the building through the aforementioned pipes, where it circulated through the refrigeration plant and went through the equipment to transfer the heat back out to the river. At the peak of the summer, the system was capable of using 100.7 million gallons of river water per day. This system was definitely one of the more groundbreaking technological advances that the World Trade Center included, for the time in which it was built.

It is interesting to note how demands on the mechanical engineers in tall building construction have increased over time. For example, Karl Sabbagh, author of *Skyscraper*, explained:

> Over the last fifty years air conditioning in office buildings has been transformed from a luxury to a necessity as buildings have grown larger. Before World War II even the most famous skyscrapers such as the Woolworth Building and the Empire State Building did not have central air conditioning. The only way to stay cool in your office on a hot summer day was to open a window – always assuming you were close enough to a window to obtain the benefit. This was fine in, say, the Empire State Building, where no office was farther than twenty or thirty feet from a window, but as ambitions became grander and buildings became wider, this was impossible (Gillespie, 1999).

As mentioned in the previous portion of this paper, about the Empire State Building, the structure did not have any air conditioning system installed in it originally, so the windows were used for ventilation. The magnitude of the refrigeration unit that was used for the World Trade Center was something that was extremely advanced, so it was easy to see why the Empire State Building did not include a refrigeration system at all. Later on it's life, however, with the evolution of technology, the Empire State Building did become equipped with a central air conditioning system of its own.

Offices generally focused on having very large windows and tall ceilings for the natural light to be provided adequately. However, as mentioned before, the World Trade Center only consisted of about 30% windows, on the exterior face, as the technology improved, allowing manmade light to be used as the norm throughout the building.

Another technological evolution, at the time the World Trade Center was created was the window washing system. Guide rail tracks were built into the towers' metal columns originally, to be able to accommodate the window-cleaning units. These units rode down these tracks and sprayed both the glass and the metal surfaces with a detergent solution. A nylon brush agitated the surfaces and a clear water rinse was sprayed on, which came from a twenty-gallon tank. There was also a squeegee system that accumulated any debris from the building and the excessive amounts of detergent material and took care of it through a series of vacuums that removed it all from the surfaces. The passersby on the street level did not get wet because of this feature, which sucked up the dirty water, filtered it and returned it back to the tank for reuse (Robins, 1987). There were two of these window washers, which were automatic and unmanned; one for each tower. Each of the two towers had fifty-eight vertical columns of windows per side and each of the columns is numbered. Each side of a tower took about a week to clean, or four weeks for all four sides, thus taking about a month to clean all of the windows in the building (Gillespie, 1999). In Figure 30, the rotating device is shown at the top of the World Trade Center. The mechanism that washed windows was only one window width wide and moved along the track, taking twenty minutes to go down one pass of the building. It took an

Figure 30: Window Washing Device (WTC: OCC, 2012)

additional ten minutes to go back up the building, where it moved horizontally over the track, to the next column spacing. In the figure, the rotating device is how the window washer made a ninety-degree turn at the top of the tower, to switch sides of the building. Both buildings were equipped with this system, which took up the perimeter of the roof space of the buildings.

The World Trade Center was not originally equipped with a sprinkler system, however in 1981, the Port Authority decided to install fire sprinklers throughout the entire World Trade Center complex. This afterthought of a project was projected, at the time, to take three to five years to complete. The New York City requirements stated that sprinklers or an alternative method of fire safety measures were to be installed in all office buildings that were taller than 100 feet, or about 10 stories. However, being a state owned building, by New York and New Jersey, this requirement could be bypassed. Guy F. Tozzuli, the director of the World Trade Department, decided that the Port Authority of New York and New Jersey decided to comply with the city law. A sprinkler head was installed every 2,500 square feet, and as the buildings each consisted of 100-stories, at 43,560 square feet/floor, this was a massive undertaking to enhance the security of the World Trade Center. In areas where sprinklers were not going to be used, the law permitted that open areas had fire retardant walls and pressurized stairways to keep the smoke out of them. However, given the building's height, pressurized stairways were voted against, and sprinklers were installed throughout the entire building and access and egress routes (Goodwin, 1981).

Another method of fire protection that the World Trade Center incorporated was the use of fire protection on the columns. The insulation material was considered passive and applied to any structural member of the World Trade Center. If we recall the image of the Exterior Wall Column, in Figure 24, the fireproofing material encased the structural columns, between the steel column and the aluminum column cover.

One World Trade Center

After the tragic events that occurred on September 11, 2001, the previously discussed Twin Towers no longer existed. There was a void left in the New York skyline, millions of square feet of office space were lost and America wanted to fight back and prove that it could not be broken. This being the case, the idea for a new skyscraper was initiated. The building would redefine the skyline and reestablish the architectural icon for the country.

The world-renowned company, Skidmore, Owings and Merrill, LLP, designed One World Trade Center. The architect, David Childs, was responsibility for the majority of the design. The building was designed to reach 1,776 feet into the air, at the top of the antenna tower, significant of the year in which the country signed the Declaration of Independence into fruition.

The One World Trade Center began construction in the first quarter of 2006. The building began with a square base at the bottom and turned into an eight-sided building, with chamfered corners. In other words, the exterior looked like it had eight isosceles triangular faces, four with the tips up and four with the tips down. The roof height was planned to be at an elevation of 1,362 ft and the glass of the parapet would be 1,368 ft, each significant of the roof heights of the original twin towers. Above these, there will be a 400-ft tall antenna mast, secured by cables, to bring the height to 1,776 feet. Since the original World Trade Centers were destroyed by terrorist attacks, the proposed safety systems for One World Trade Center were going to be above and beyond any of the state requirements, to try to fend off any of the same means and methods which caused the destruction of the original World Trade Center. The building will have 3.1 million square feet of office space when it is finished later in 2013. One World Trade Center started out as a relatively affordable undertaking, but it is now projected that the building will take $3.19 billion in total to complete (Gonchar, 2011).

The technological evolution will be distinguishable from the time the original World Trade Centers were created in the late 1960s to the present, and especially from the methods used in the creation of the Empire State Building, from the late 1920s into the early 1930s. Although One World Trade Center has yet to be completed, the technological evolution is evident, as the building continues to rise and be completed. These methods will be discussed in much further detail in their appropriate sections of the paper to follow.

Substructure

The substructure for One World Trade Center was going to be the same size, dimensionally, as it were for the original World Trade Center. It was a 200-foot by 200-foot square podium. From the article "World Trade Center Projects Move into Construction" by Nadine M. Post, at the time she said, "On the civil side, work is under way to extend the slurry wall 'bathtub' around the entire 16-acre-site. The east slurry wall should be finished in three years" (Post, 2006). This was in regards to the entire World Trade Center site. Such as the slurry wall system that was created for the original World Trade Center, the new design was going to have a similar water retention system, using the repaired original system. The proximity of the site to the Hudson River, along with the depth of excavation, the slurry wall system proved as the most efficient system to hold back water, under the surrounding water table, without affecting adjacent structures.

An advancement of the substructure as well as any other concrete used in the structure was that a high strength mix of 12,000-psi reinforced concrete, which the developer of One World Trade Center, Larry A. Silverstein, remarked was above code (Post, 2005).

Frame

The frame of One World Trade Center was very unique, unlike any other structure ever designed. At the base, an almost cubic pedestal existed, being a 200-foot wide by 187-foot tall pedestal. This area consisted of a 50-foot-tall lobby, with mechanical floors stacked on top of it and was known as the "blast-resistant zone." The design of the frame changed a number of times, from its original inception in 2003, when it was then introduced as the Freedom Tower (Gonchar, 2011). Eventually, the structure was set to be a 104-floor structure, with five additional stories going into the basement. The "cubic base gives way to an octagonal plan at center whilst the glass parapet is square in plan and rotated 45 degrees from the base. The mid section's octagonal plan is achieved by façade planes which are comprised of eight alternately inverted isosceles triangles with beveled edges" (OWTC: *Emporis*, 2012). Another source described the structure as such that "the corners are chamfered back, creating progressively smaller floor plates that gradually shift from a square above the podium to an octagon at midsection. At the top, it is once again square, but 150 feet on a side and rotated 45 degrees from the base" (Gonchar, 2011). The tapering and twisting of the floors does produce a tower with a very complex geometry, but it was much easier to design and construct than the earlier version, designed by SOM:

> Its designers point out that it will have enhanced security and life-safety systems, including a robust, reinforced shear-wall core surrounded by a steel moment frame spanning 45 feet to perimeter columns. The building is part of a post-September 11 trend for New York City office towers to move away from all-steel structures toward composite systems. And although concrete shear-wall construction is just one way to design and harden a core, in the case of One WTC, the approach was deemed the most appropriate due to the tower's height and slenderness (Gonchar, 2011).

This concrete core was designed for security to be three feet thick. Such as the foundation of the building uses 12,000-psi reinforced concrete, the core, which ran the entire height of the building, as well as the pedestal did the same.

Where the original World Trade Center combined the frame system with the envelope system, One World Trade Center has two distinguishably different systems. The frame, as mentioned before, was quite similar to that of the original World Trade Center, however, technologically advances have been made in the reinforcing, rigidity and overall strength of the structure. This is how the system of One World Trade Center has advanced from the design of the WTC of the 1960s. In Figure 31, the pedestal is shown, where the concrete frame exists. Above the concrete encased lobby, the exterior frame can be seen, consisting of steel columns and the lateral bracing system on the exterior. As aforementioned, the concrete core served as a lateral bracing system as well, so there was a lot of repetition and stability measures that were made for One World Trade Center. The large area shown, in Figure 31, is where much of the towers mechanical floors were housed, directly above the lobby.

Figure 31: Pedestal (OWTC: SOM, 2012)

In the following images, plan views of the structure are shown, from three different rise levels, where the exterior columns can be see, represented by the small black squares. As the building progressively rises, as mentioned earlier, the four-sided building becomes an eight-sided building, which can also be seen in the images. As far as the core part of the frame is concerned, the black areas represent the concrete core, which is typically three-foot thick sections, surrounding the elevator and stairways. In Figure 32, the low-rise floor plan is shown, which has the most elevators. This plan looks very similar to that of the original World Trade Center, with the large expanses of open floor space. There are only four sides to the building at this point, until the building began to taper to the eight-sided, isosceles triangular sided structure. In Figure 33, a typical mid-rise floor plan of One World Trade Center is depicted. In the four corners, the chamfered edges can be seen, where the

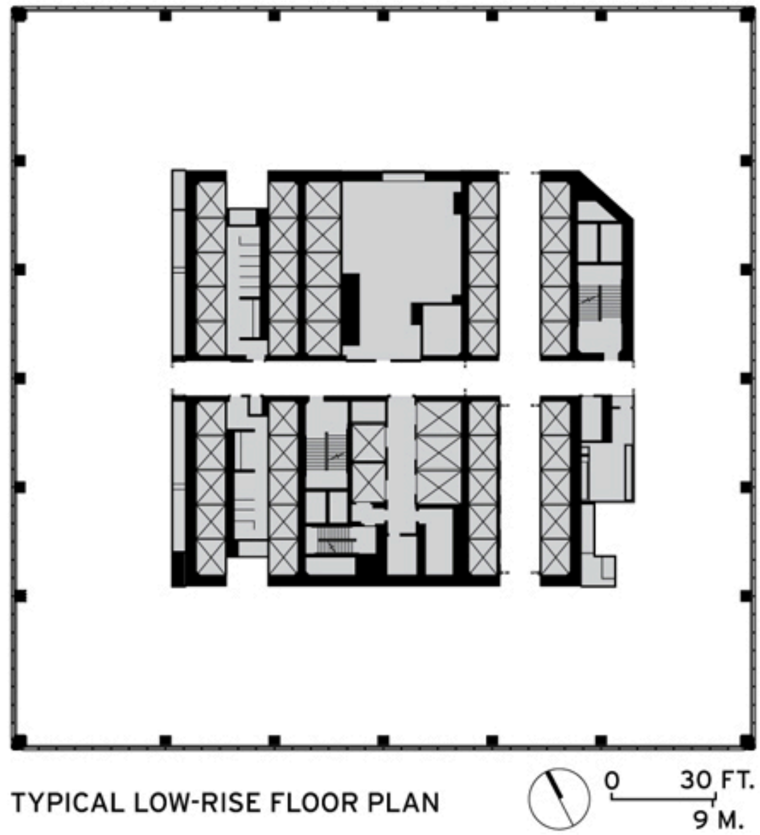


Figure 32: Typical Low-Rise Floor Plan (OWTC: SOM, 2012)

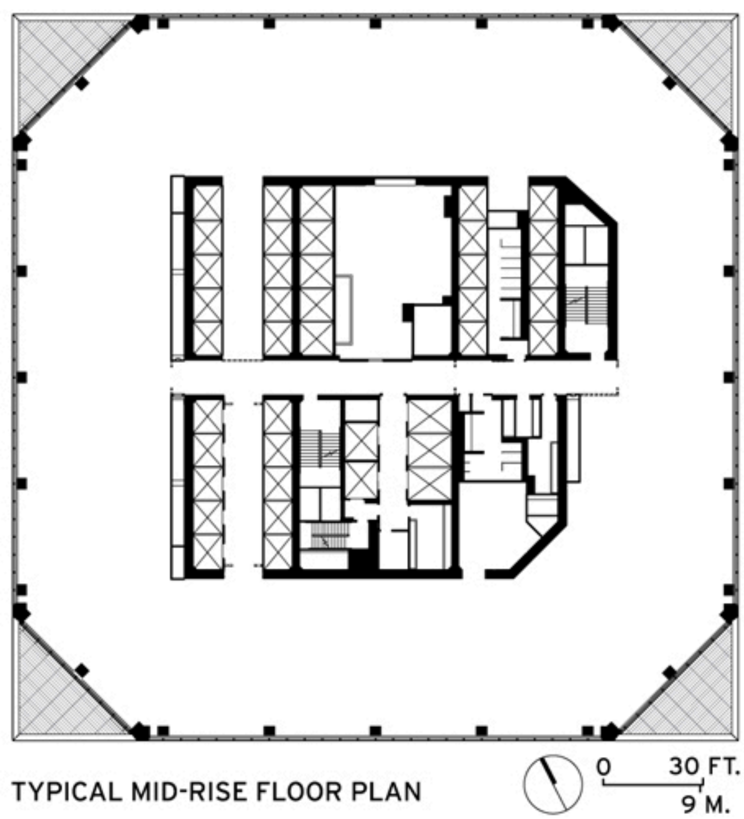


Figure 33: Typical Mid-Rise Floor Plan (OWTC: SOM, 2012)

triangles begin. The overall frame of the concrete core has only changed by becoming smaller, as the footprint of the floors gradually decreases. A similar system as the original World Trade Center was also used in the elevating system, like the skylobby system, but that will be discussed in further detail in the Services portion of the paper. In Figure 34, the high-rise portion of the building is shown, where the floor plan of the building has been rotated 45 degrees, and there are still eight sides of the building. The concrete core of the frame has changed in its plan view, as elevator amounts have greatly diminished, as well as the open floor space. As far as the frame of the new One World Trade Center, the structural frame did not really advance too much from the basics of the original design of the World Trade Center from the late 1960s into the 1970s. The open floor space plan remains very similar, however the technology evolved to create a more complex structure, not purely the same design, floor by floor.

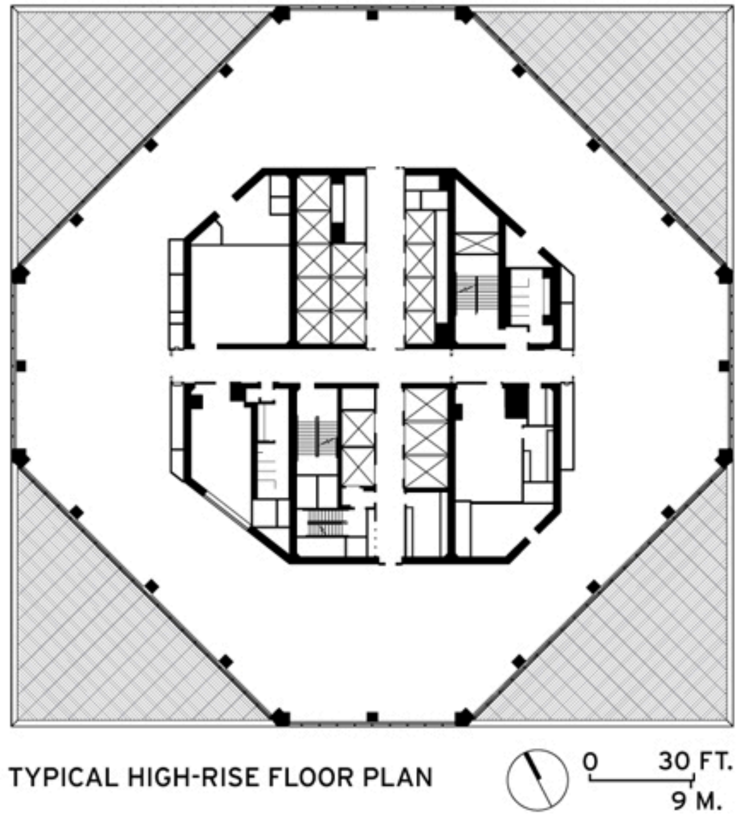


Figure 34: Typical High-Rise Floor Plan (OWTC:SOM, 2012)

The advances that are really seen are more in the services and envelope parts of the structure. The tube-in-tube structure has been a highly successful building structure type over the last forty-plus years, so there has not been much advancement or a particular type of new framing system that has been designed and use very often. Changes such as the concrete strength and types of lateral bracing are really the drivers of the frame technological evolution.

Envelope

As mentioned earlier, the envelope of One World Trade Center is separate from the frame of the structure, unlike the combined system used by the World Trade Center. At the time the World Trade Center was constructed, the designer, Yamasaki thought the days of the fully glassed structures were over, which is why his building was about 30% glass and 70% frame on the exterior envelope system. However, this was not nearly the case as many buildings constructed between then and now have used a glass façade.

Beginning with the lower portion of One World Trade Center, the "podium" that was mentioned earlier was originally going to be clad in glass. In 2010, "PPG Industries announced it had received an order to supply STARPHIRE[R] ultra-clear, low-iron glass for One World Trade Center in New York City" (PPG, 2010). "STARPHIRE glass was selected for its ability to maintain the highest levels of clarity at thicknesses of up to 1 in. (25 mm)" (PPG, 2010). The vice president of PPG Industries stated:

> Glass is a signature element in the design of One World Trade Center, not just because of its beauty and functionality, but because it is symbolic of our country's commitment to openness, transparency, and freedom … as the first commercially successful plate glass manufacturer in the U.S., PPG is proud to provide material that will help reinforce those ideals on an iconic structure that will soon be recognized around the world (PPG, 2010).

Although this idea seemed iconic and beautiful, it was not practical:

> The architects had planned to camouflage the podium with tempered and laminated prismatic glass panels that would reflect, refract, and transmit light, in order to "establish a relationship with the water cascading in the memorial pools," says Childs. However, after discovering that tempering caused the panels to bow, interfering with the laminating process, the project team devised another solution. The alternate, whom sources describe as glass fins projecting from the facade at various angles, is now in the bidding phase but has yet to be finalized (Gonchar, 2011).

Figure 35: Original One World Trade Center Podium Design (OWTC: SOM, 2012)

The rendering in Figure 35 depicts the original design of the podium and what was described in the original architectural idea. The façade design was to help the base of One World Trade Center look more open at the windowless base, which was designed to withstand a truck bomb. The Port Authority of New York and New Jersey had already spent $6 million on the custom-made panels, but the glass broke during the off-site testing. An agency spokesman, John Kelly said, "the replacement material will be glass that is more typically used in construction, but the design is still being finalized. 'The design will be practical while being distinctive'" (Zraick, 2011). The priority is to stay within budget for this material. As of February 14, 2013:

> Specialized, green technology is coming into full view at One World Trade Center in Lower Manhattan. Construction workers at the Port Authority's 16-acre World Trade Center site are installing new state-of-the-art, 'green technology' glass panels at the street level podium wall of One World Trade Center. The base of One World Trade will feature 2,000 specially made frosted glass panels designed with a high-performance, low-admittance coating to maximize sunlight and minimize heat gain (Press Release Number 22, 2013).

For the remainder of the building, above the podium pedestal, the curtain wall system was going to be made out of low-iron insulated glazing units (IGU's):

> The IGUs are 5 feet wide and 13 feet 4 inches tall – the largest production IGUs available. They have thicker than typical outer lites (3/8-inch thick versus the more standard ¼ inches) and laminated inner lites whose thickness varies depending on location (some are thicker than others due to security concerns). Although the IGUs are heavier than standard units, which complicates installation, the panels' size allows them

> to span the full floor-to-floor height without intermediate mullions or spandrels. The thickness of the outer lites, along with inner lites' lamination, should also prevent "oil canning," or pillowing of the glass panels, says SOM managing director Kenneth Lewis. The goal is to create a "uniform and crystalline" surface – or one that appears to be "shaved and carved," adds Childs, again alluding to the form of the Washington Monument (Gonchar, 2011).

The system described can be seen in Figure 36, where the large pieces of glass span the entire height of a floor and are hung from the compact wall system, shelving off of the column and

Figure 36: One World Trade Center Façade Rendering (ONWT: SOM, 2012)

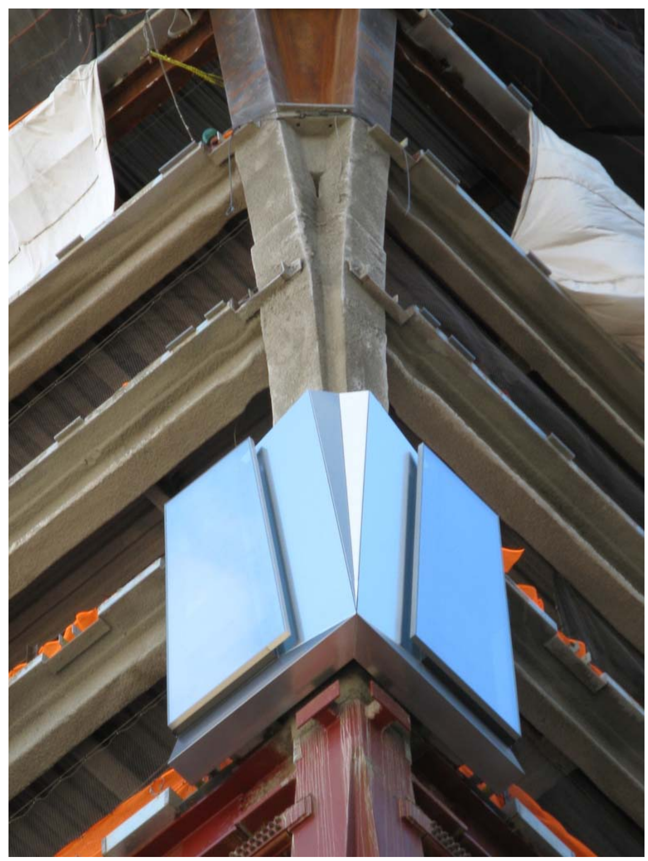


Figure 37: One World Trade Center Facade (Shapiro, 2010)

beam structural system.

Also, as seen in Figure 37, the first stainless steel and glass panels were captured being installed in late 2010. The tower, in all is going to feature 12,000 of the panels, which formed the eight triangles, in combination with the steel. The overall design was purposed to refract light and change its appearance depending on the weather and the viewer's position, which when compared to the original World Trade Center, seems to offer a much more technologically advanced and pleasing solution as to what to have on the exterior of the highly viewed building (Shapiro).

Interior

As far as the interior for One World Trade Center goes, much of the details are visible in the lobby, through rendered images. As shown in Figure 36, Figure 37, and Figure 38, on the following page, the modern details, spacious lobby with fifty-five foot high ceilings, and nine foot tall typical office space are a few of the interior items that One World Trade Center has to offer. The technologically advanced items in the interior of One World Trade Center will be discussed in the services portion of the paper, as they are more relevant to the machinery and advancement that it offers.

Figure 36: One World Trade Center Lobby Rendering (OWTC: SOM)

Figure 37: One World Trade Center - Lower Lobby (OWTC: SOM)

Figure 38: Typical Office Floor Rendering (OWTC)

Services

The services of One World Trade Center may be where the most technological evolutions occur, as far as differentiating it from the other two office buildings. Numerous items such as the elevating transportation system, life-safety systems and HVAC are a few of the main evolutions that One World Trade Center incorporates and will be discussed in this portion of the paper.

To begin, the elevating system of One World Trade Center is similar to that of the original World Trade Center, with a similar "skylobby" approach to save floor space, so there is more rentable area. There will be five large service cars that service all of the office floors, as well as fifty-four high-speed destination dispatch passenger elevators (ONE WORLD TRADE CENTER). The express cars were going to be capable of reaching a top speed of 2,000 feet per minute. This means that a trip from the bottom of the tower, to the top, could take less than forty-five seconds. In relation to the original World Trade Center, these elevators were twenty-five percent faster than those that were in the World Trade Center. The five service cars are going to be the fastest elevators in "the Americas" but will not be the fastest in the world, as Taipai 101 in Taiwan holds that record, traveling at 3,314 feet per minute. The original World Trade Centers elevators were said to "shake, rattle and roll" but the new building has "advances in several areas, including improved alignment of the guiderails along which elevator cars travel and computerized roller guides that can compensate for what few bumps there are in the guiderails by exerting force in the opposite direction" (Dunlap). The original specifications for the elevator contract was to only have them be 1,800 feet per minute elevators, but the Port Authority increased this to be able to maximize the number of tourists and others who wanted to access the observation deck (Dunlap).

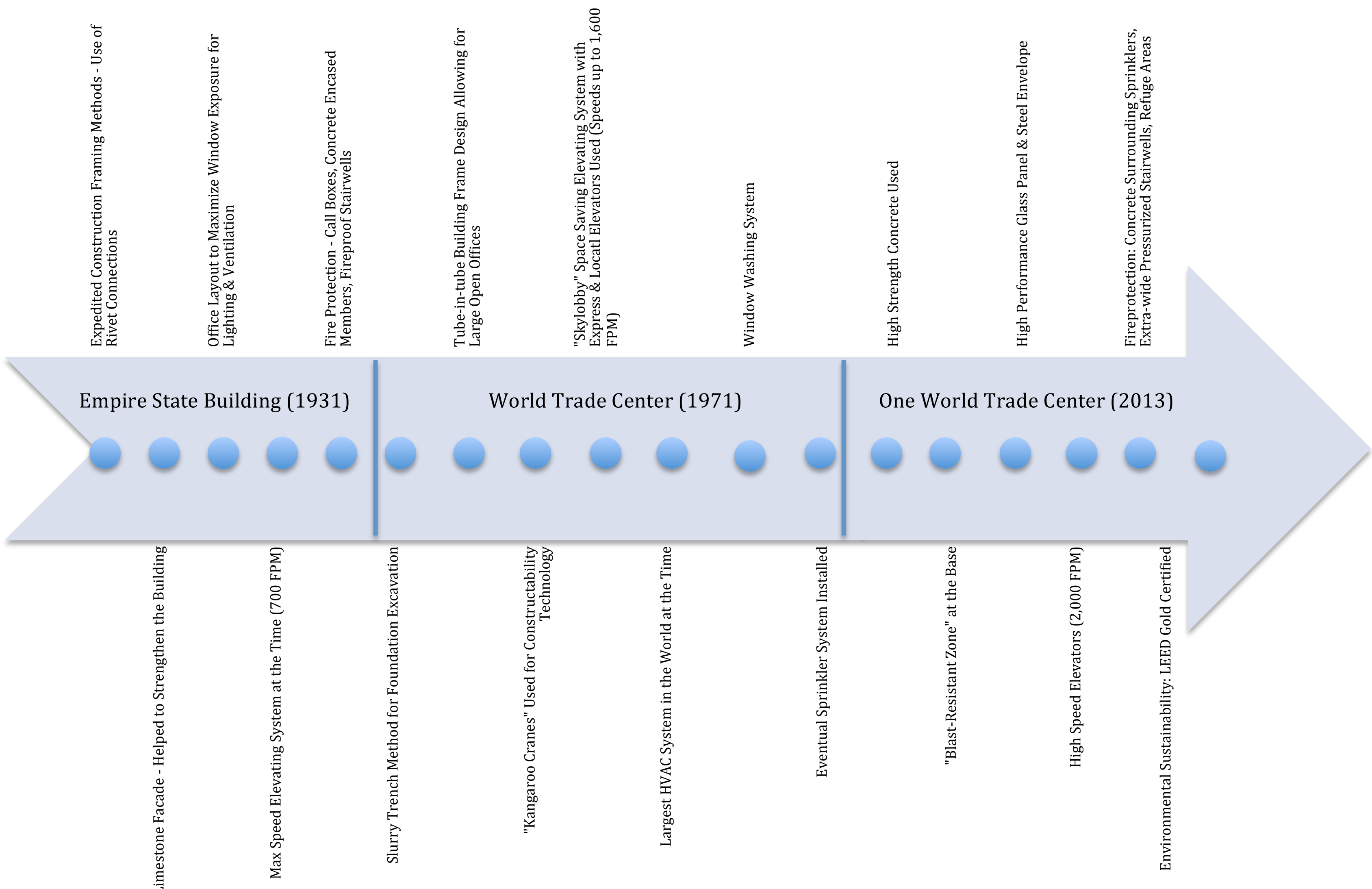
Another service item that One World Trade Center offers is an "extra-strong" fireproofing system. This system includes many different facets of safety. There will be concrete protection for all sprinklers as well as extra emergency risers. The main stairwells are going to be extra-wide as well as pressurized so smoke does not enter in the case of a fire. Within many of these exits, some will be interconnected as well as redundant with each other. There will be additional stair exit locations at all of the adjacent streets and direct exits to the street from tower stairs. All of these life-safety systems are going to be housed within the concrete core (Post 2). There is one emergency stairway that is dedicated solely to firefighters. Also, going along the lines of safety, an advancement that One World Trade Center has over the original World Trade Center is that every floor has a refuge area, within the core. The air supply system will incorporate chemical and biological filters for further fire protection and warning (One World Trade Center: *Emporis*).

Another innovation that One World Trade Center incorporated was its use of sustainable design guidelines. The building, once completed will obtain LEED Gold Certification. It is going to be the most environmentally sustainable project of its size in the world. The energy performance of the building exceeds the code requirements by over 20% (World Trade Center – One World Trade Center). The consultant who was in charge of making the tower green was the mechanical-electrical-plumbing engineer, because under these breakdowns, achieving a "green" status is most feasible (Post 2). One of these guidelines is of using next generation energy sources, "such as cogeneration and fuel cells, as well as off-site renewable wind and hydro power" (One World Trade Center – World Trade Center). The fuel cells are capable of generating 4.8 million watts of power per hour. Along with forms of power and energy, 90% of occupied spaces in One World Trade Center use natural light (ONE WORLD TRADE CENTER).

All of these machinery items that One World Trade Center incorporates are as technologically advanced as today's technology allows. In summary, a Conclusion has been created to compare each of the major components of the large office building and how they have truly evolved, from what research has been able to been gathered.

Conclusion

Over the course of time, the large office building has taken a different shape. Early in its life, the office building consisted mainly of a foundation, typically steel and concrete structure, some sort of skin or envelope wrapping the outside, interior furnishings and minimal amounts of machinery. In today's office building, you will find similar components as the original office building; however, the emphasis on where the technology has evolved as well as where money allowed for design and construction has been spent has changed substantially. The technology of these components involves changing materials being used, different strengths of materials, overall improvements as well as additional measures being added to buildings, for security, feasibility, and overall user comfort and satisfaction; all while satisfying numerous types of building codes. To conclude this paper, the five major components of a building; the podium, the frame, the envelope, the interior and the machinery will briefly be summarized and compared to show how the building technology has changed from the 1920s and 1930s, through the 1970s, and ending at current day. In summary, Figure 39 shows the most notable items that advance in a building and how they become more and more technical and service oriented in a building, to present date. This figure highlights many of the items discussed in this paper.


Empire State Building (1931)
World Trade Center (1971)
One World Trade Center (2013)
Expedited Construction Framing Methods - Use of Rivet Connections
Limestone Facade - Helped to Strengthen the Building
Office Layout to Maximize Window Exposure for Lighting & Ventilation
Max Speed Elevating System at the Time (700 FPM)
Fire Protection - Call Boxes, Concrete Encased Members, Fireproof Stairwells
Slurry Trench Method for Foundation Excavation
Tube-in-tube Building Frame Design Allowing for Large Open Offices
"Kangaroo Cranes" Used for Constructability Technology
"Skylobby" Space Saving Elevating System with Express & Locatl Elevators Used (Speeds up to 1,600 FPM)
Largest HVAC System in the World at the Time
Window Washing System
Eventual Sprinkler System Installed
High Strength Concrete Used
"Blast-Resistant Zone" at the Base
High Performance Glass Panel & Steel Envelope
High Speed Elevators (2,000 FPM)
Fireprotection: Concrete Surrounding Sprinklers, Extra-wide Pressurized Stairwells, Refuge Areas
Environmental Sustainability: LEED Gold Certified

Substructure

The substructure of the Empire State Building was relatively standard for the time of construction; at forty feet down, it began with pier holes that were dug, where steel supports rested on top of them. All 210 columns were supported at this level for the structure. Over the course of time, the substructure was the element of a tall office building that changed the least amount. It had the same basic function, of supporting all of the weight of the eventual superstructure. The main thing that changed noticeably, was the technology used to construct the substructure. The original World Trade Center, used an excavating technology to excavate the site, keeping water out and creating a retaining wall for the site, so it could be excavated entirely with minimal water disturbing construction. As One World Trade Center was built within the same 16-acre "bathtub" that the original water retention system was used for the World Trade Center, it was easier to begin excavation below the water table.

The only other major change for the substructure was that the strength of the concrete used in the concrete core, which traveled all the way to bedrock, has increased as technology has advanced in concrete evolution. The strength of the material has gone from approximately a 4,000-psi mix used back in the 1920s, to the 18,000-psi super strong mix that is being used at One World Trade Center.

Frame

The frame of the office building, through the three buildings analyzed, has changed greatly. Initially, the Empire State Building was a skeleton of steel framework, with the base columns encased in concrete. At the time, the columns gridded throughout the structure were seemingly the best idea with the known technology. As time and technology advanced, the office building was able to take on a different, deeper shape, due to lighting and ventilation advances. This allowed for the columns to be spaced out along the exterior of the building, connected to the concrete core through truss systems under the floor, and a large column-free floor space span. Materials used for the core also have evolved through time, with stronger concrete mix used, providing both strength and security for the building. The advancement of the frame has allowed all of the vertical transportation systems to be housed in the middle of the building and the rest of the frame along the exterior of the building, known as the "tube-in-tube" design, which is a very common design in large office buildings today, to carry the remaining loads. Beginning with the World Trade Center, this technological evolution changed how buildings were designed, as it allowed for the most open floor spaces, and created a composite frame, where repetition in structural design could be made with the core shear wall as well as moment framing to ensure rigidity.

Envelope

The envelope of the office building has significantly changed through history. Originally, the Empire State Building had a limestone exterior façade. At the time, it was considered a light, thermally resistant enclosure, however, as described in the Empire State Building – Envelope section of this paper, the façade was a very complex, integrated design, difficult to manufacture. It helped with the structural integrity of the building due to its mass, but as technology advanced, it was more feasible to either include the façade as an integral part of the frame, such as the World Trade Center did, or use the envelope simply as a skin, such as in One World Trade Center, where it is used simply for aesthetics. The World Trade Center and One World Trade Center have similar but different envelope systems. The World Trade Center integrates the façade with the frame and One World Trade Center has window panels hung on the outside of the frame. The capabilities of the new system, however, are most innovative. In the past, the façade had to account for allowing natural ventilation inside of the building, as well as natural lighting. The windows in the Empire State Building opened for the former of these purposes and were used for lighting as well, hence the more shallow offices. In One World Trade Center, the large 13’ x 5’ window panels allowed the maximum amount of light in possible, while the HVAC system took care of regulating room temperatures, throughout the office space and interior core space. This advanced HVAC system, which regulated temperature floor-by-floor for user comfort, is one of the Machinery advances that have evolved over time.

Interior

As far as the interiors were concerned, most of the technology advances were been placed in the Machinery for many of the noticeable interior changes. The interior spaces for all of the buildings were state of the art at the times they were created. The Empire State Building finishes in the lobby were created with marble and glass, creating an Art Deco Style. Interior offices were only 28 feet deep and nine feet wide, with each office having its own window, for ventilation purposes. The depths of the offices were limited by lighting, and the core consisted of all of the life-safety systems. In the World Trade Center, the depths of the open office plan are up to 60 feet deep. This increased depth is a huge interior advancement. The overall floor plan of the building could be built larger, due to fluorescent lighting being a new popular technology. The more compact elevating system also increased rentable floor area. A similar design was created in One World Trade Center, with a compact core in the middle of the structure, with up to 45-foot spans for office space surrounding the core. Gradually, as the building rose, the floor space decreased so this number decreased. The technological result was that over time, the interior space for office buildings was able to be increased due to the Machinery advances, thus allowing for more rentable area.

Machinery

The machinery was the part of the office building that changed the greatest amount. Through research, technological advancements had been made in this portion of the office building to include features that were not even imagined in the office building inception period. The "skylobby" elevating system that the World Trade Center introduced was extremely innovative in the sense that it compacted the elevator services to a smaller, more efficient area, allowing for more rentable floor space to be able to be created. In the end, the available rentable floor space was all that mattered for the owner, as it was the factor that determined how much income was generated. The HVAC systems, as discussed previously advanced from being minimal in the Empire State Building, primarily with only heat, all the way to very complicated heating, ventilation, and cooling systems in today's buildings. An entire underground facility in the original World Trade Center and One World Trade Center was used for the cooling system of these structures; costs and considerations that the Empire State Building did not even fathom.

As far as the fire protection systems, the Empire State had minimal safety measures, such as concrete-encased columns and call boxes. Sprinklers were not introduced in any of these buildings until the World Trade Center. A sprinkler system was not even originally installed in the World Trade Center, but an afterthought, as the New York City requirements changed during the life of the office building. Even further advancing the safety technology, One World Trade Center integrated pressurized stairwells and extra stairwells for firefighters to use. Along with three-foot thick concrete core walls, which housed the life-safety systems, One World Trade Center was designed well over code regulations for durability in the event of any incidents of large magnitude.

It is apparent that the office building has truly evolved from the technology used in the Empire State Building to the present day design of One World Trade Center. Through this analysis numerous points have been made as to how this technology has taken place and the purpose for each technology that was used in each building, both at the time they were used and why the technology evolved. Each part of each building served its purpose at the highest level of technological ability, however, as time progressed, newer and better ways of doing things were introduced, thus technology was and forever will be moving forward.

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