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Challenges in the Architectural Technical Design of the New Generation of Supertall Buildings

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Abstract

The design of a supertall building poses many challenges to the architect and engineer. Using Jeddah Tower as a case study; this paper intends to discuss a few of those challenges specifically related to the arrangement of programmed spaces in the tower, their functional connection by means of the vertical transportation system and physical connection with shafts which introduces the potential for stack effect in the building. The measures applied in response to and mitigation of these issues are discussed.

Keywords: Supertall buildings, Vertical transportation, Stack effect, Jeddah Tower

1. Introduction

This paper follows on from an article first published in Issue 1 of CTBUH Journal 2013 entitled "Meeting the Challenges of a One Kilometer Tower" and is intended to be the second in a series of articles authored by members of the design, construction and ownership teams responsible for Jeddah Tower, the next number one "tallest building in the world", currently under construction in Jeddah, Saudi Arabia.

But first, let me start with a short story.

Representatives of a prominent US developer arrived at the offices of Skidmore, Owings & Merrill in Chicago very early on a beautiful late summer morning. They had flown in from New York to kick-off the design of a new supertall, mixed-use project to be located on the Chicago River, just off of Michigan Avenue. The project, was discussed in terms of superlatives. Not only would it be the most ambitious and luxurious mixed-use project yet to be undertaken by the developer, but it would also be the tallest they had ever attempted. As a matter of fact, it was possible that this building could be the tallest building not only in Chicago, the city of the Sears (now Willis) Tower but, the tallest building in the world at that time. It would be HUGE.

As it happened, Donald Trump's team arrived on the morning of September 11, 2001. As events of that morning unfolded, it became obvious that the world had changed. The project immediately went on hold and was quickly re-conceived with reduced program to be the second tallest building in Chicago as was finally built.

No one in the U.S. who was watching on TV that day will ever again look at a tall building without having the images of the events of 9/11 in the back of their minds. Within a month or two, there were several articles written and public forums organized at which even the most prolific practitioners (my boss Mr. Smith included) declared the tall building a thing of the past.

It was not hard to think that the era of tall buildings had ended forever.

Having said that, here we are in 2017, now in the midst of a period of unprecedented tall building construction worldwide.

When my generation began their careers, there were only five (5) buildings in the world, all in the US, which could be considered as "supertall," that is to say, exceeding 300 meters (about 1000 feet). Although two of those five came down on 9/11, there are now one hundred eleven (111) supertall buildings in the world plus almost the same number of supertalls under construction! As is generally known, the vast majority of these buildings are in areas of the world that only recently have seen the social, economic and technological development that allows the construction and management of projects of this magnitude.

2. Challenges of the Supertall - Jeddah Tower Case Study

This new paradigm that has fostered this the new age of the supertall building; that is to say the creation of a landmark as a catalyst for economic development, both a symbol of prestige and the expression of mankind's ego is

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exemplified by the **Jeddah Tower**, It is literally the center-piece of a more than 2 square mile development called **Kingdom City** and will be the first building to exceed one kilometer in height, not only the tallest building in the world, but the tallest structure ever built.

"Meeting the Challenges of a One Kilometer Tower" discussed the process by which the architectural aesthetic design was developed over an 8 ½ month competition phase period; based a program provided by the client for a very tall (height), but very small (area) building. The competition brief asked teams to design a 290,000 m^2, multi-use tower containing a five-star hotel, serviced apart-

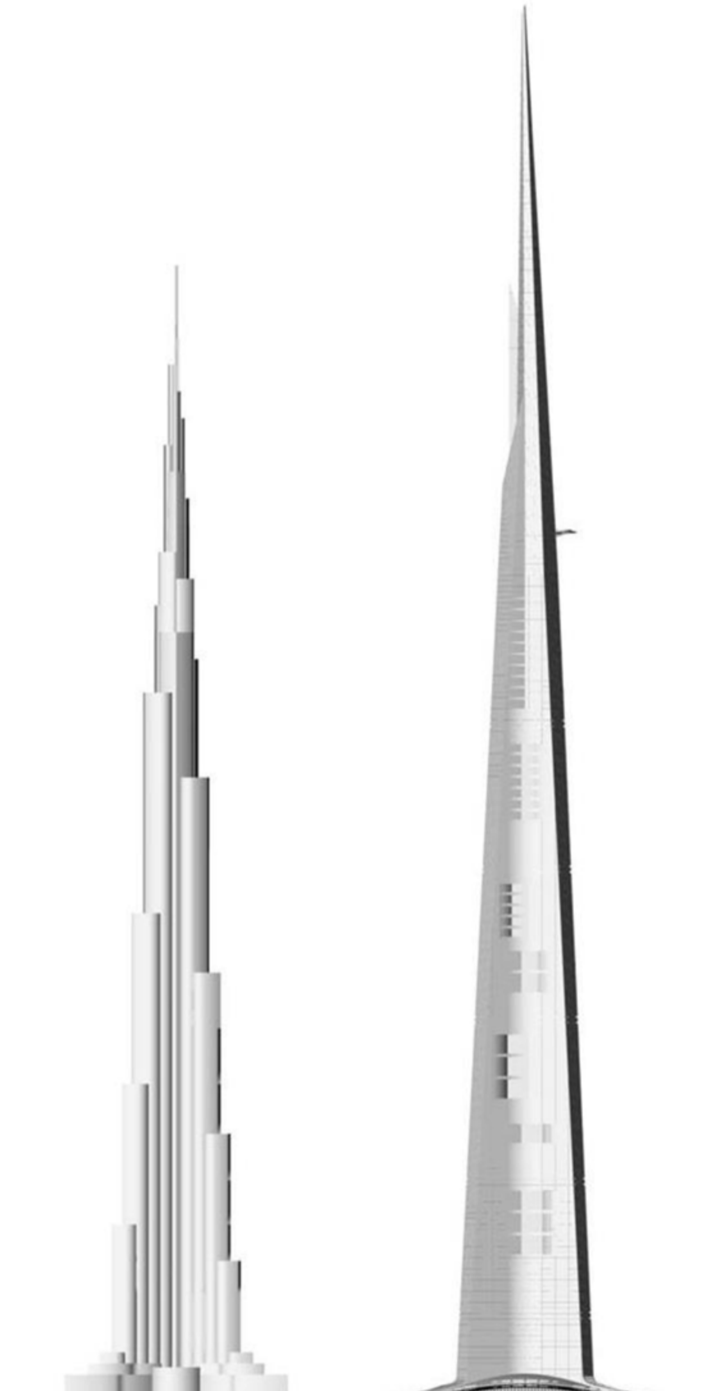

Figure 1. Burj Khalifa and Jeddah Tower Height Comparison.

ments, office and residential units. The proposed design would make Kingdom Tower the tallest in CTBUH's three categories for maximum heights. All three are currently held by the Burj Khalifa.

- Highest occupied floor (level 154 at 584.5 m or 1918 feet)
- Highest architectural top (elevation 828 m or 2717 feet)
- Highest tip (elevation 829.842m or 2723 feet)

3. Mixed-use Program Accommodation

In the case of Jeddah Tower, although it will be the tallest "structure" ever constructed, it is first and foremost a "building" designed to safely and comfortably accommodate it occupants and at the same time make a profit for its owners.

The design process therefore starts with the accommodation of the clients' program. That is to say, the spaces allocated to each of the revenue generating functions. From the bottom up, the tower is "stacked" as follows (Refer to Fig. 2):

Podium (level B3 up through Tower level 4) contains 191,420 m^2 with parking for 2,400 cars, loading dock and central mechanical spaces as well as the lobbies and public areas for the offices, residences and hotel.

Office (levels 7-13) contains 22,464 m^2 of commercial office space.

Hotel (levels 20- 26) contains 20,776 m^2 with 168 guestrooms for a five star hotel operated by Four Seasons.

Serviced Apartments (levels 27-37) contains of 30,699 m^2 with 121 serviced apartments operated by the hotel.

Residential Groups 1-4 (levels 44-120) contains 99,791 m^2 with 318 luxury residences and two sky lobbies containing residential amenity spaces.

Void or Flex Space (levels 126-153) was originally envisioned as "flexible" space. Potentially 28 floor levels with 37,800 m^2 of space that could be developed as the building was being constructed, should sales go well enough to warrant the expense.

Observatory / Sky Terrace (levels 157-159) contains multiple levels and an outdoor sky terrace of more than 500 m^2.

Refuge Floors (levels 18, 38, 56, 71, 86, 104, 124 and 154).

Technical Floors (levels 15/16, 39/40, 68/69, 95/96, 121/122, 161/169).

Spire approximately 300 meters of "aspirational" height.

4. Vertical Transportation

A **Mixed-Use Tower** like Jeddah Tower can be likened to a small city, but it is arranged vertically. It contains residences, places of work, hotels, restaurants, retail shops, amusement areas and all ancillary spaces and equipment

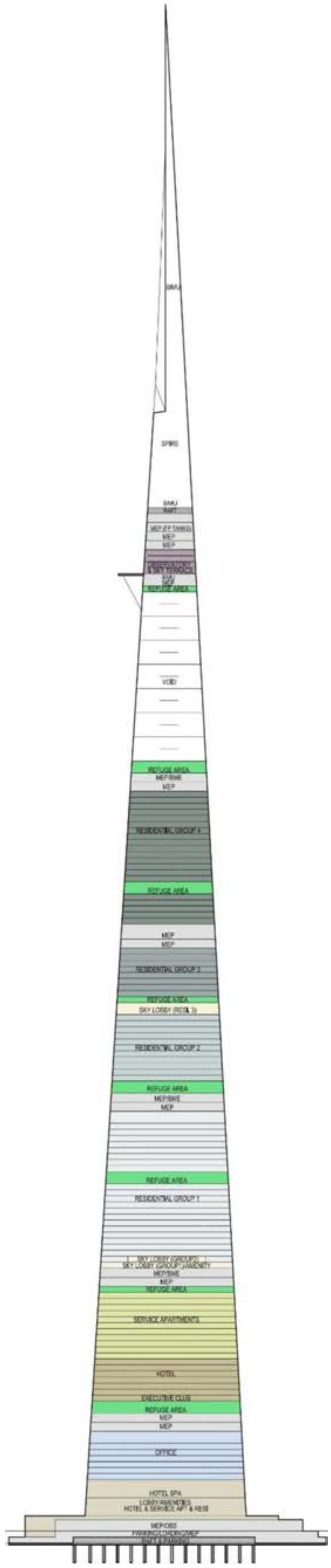

Figure 2. Jeddah Tower Program Stacking Diagram.

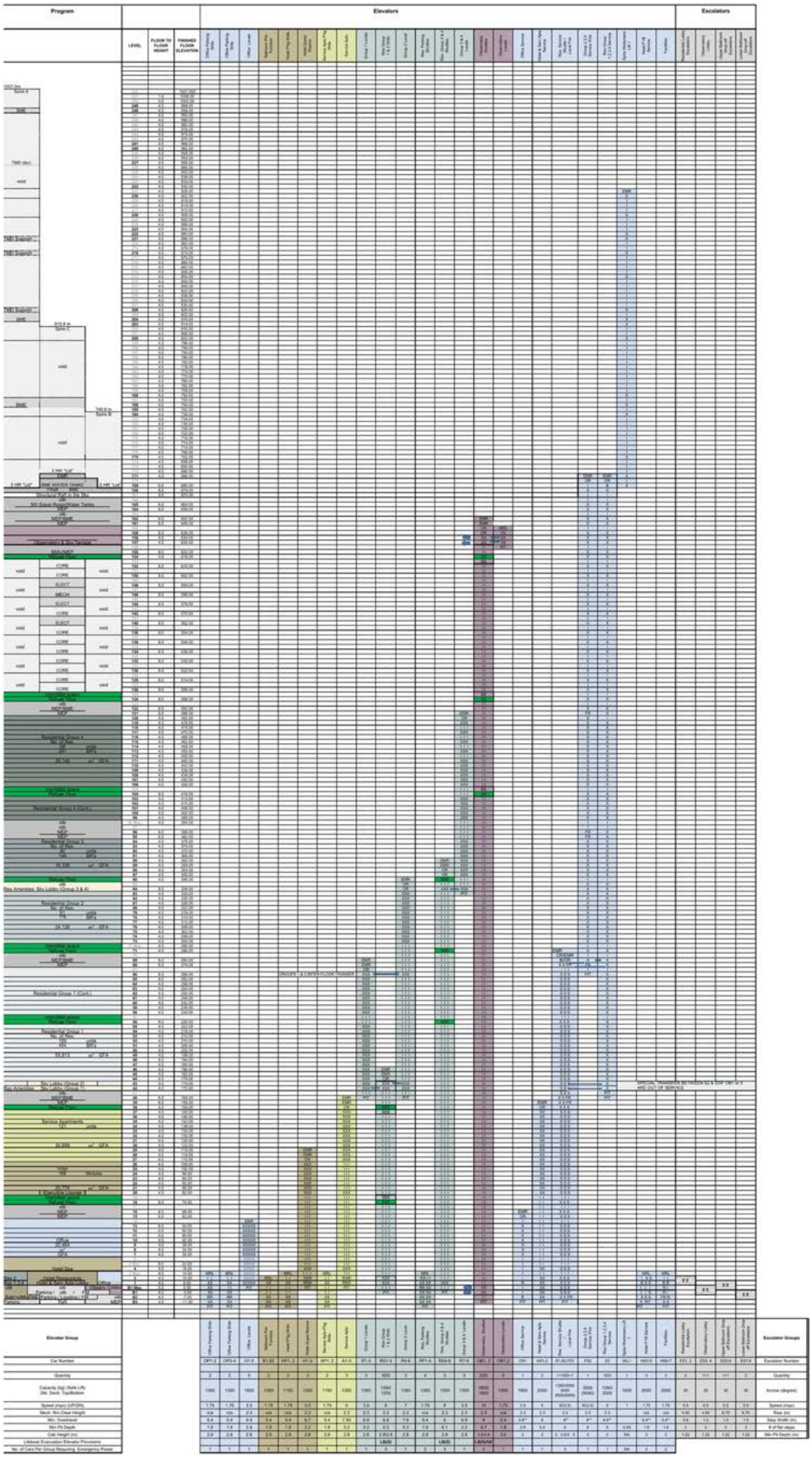

Figure 3. Jeddah Tower Vertical Transportation Diagram.

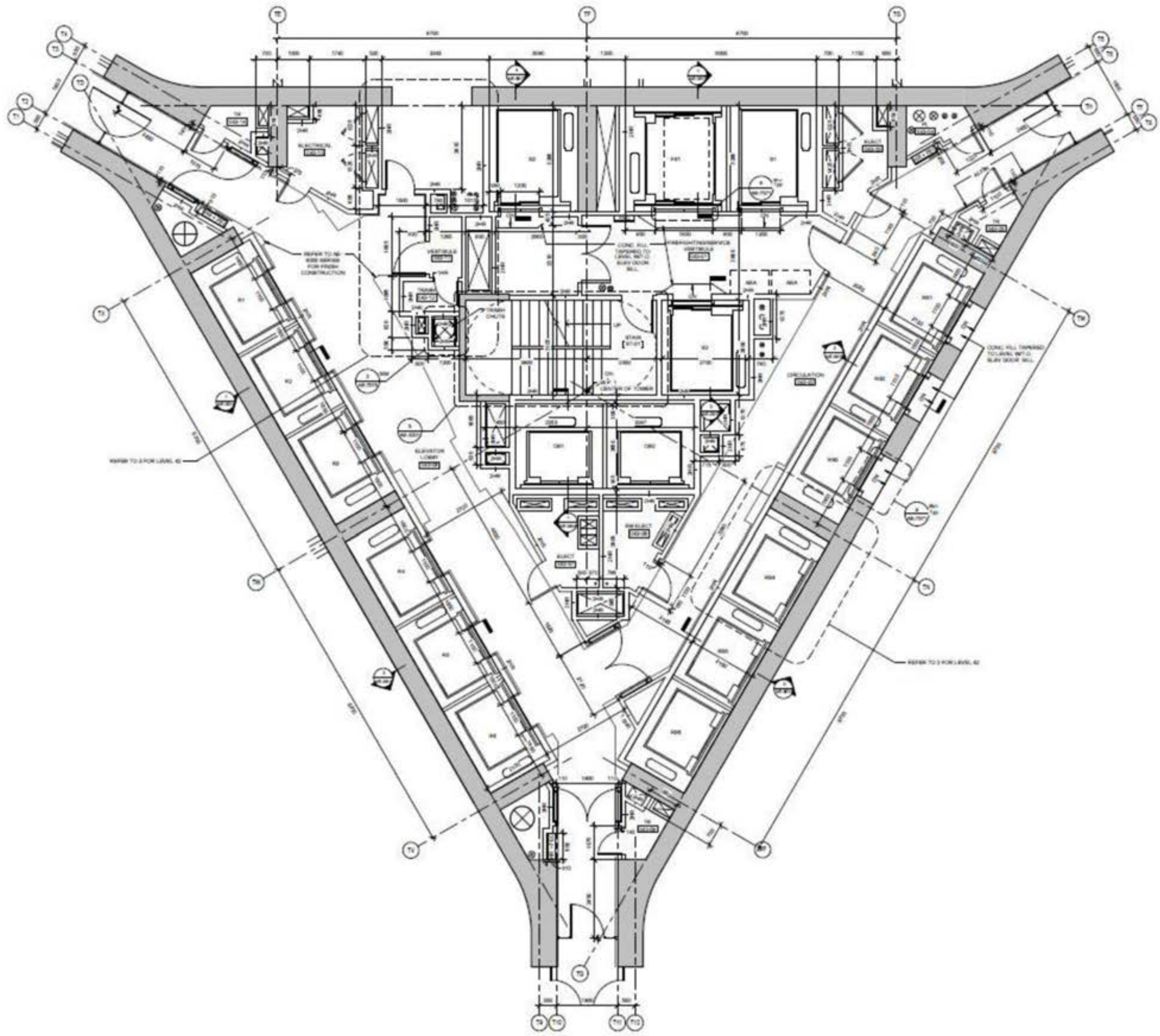

Figure 4. Jeddah Tower Core.

necessary for the revenue generating program to function properly. Furthermore, similar to, but beyond the needs of a small city; the arrangement of the various functions must be rationalization along with the means and methods of transportation of occupants, emergency responders, services, goods and materials both into and out of the tower. Therefore, the efficient design of the vertical transportation system is essential to the functioning, safety and economic success of the project.

Refer to Fig. 3. The Jeddah Tower VT system is comprised of the following:

- 57 Elevators
- 44 passenger elevators (5 of which are double decked) and 13 service and/or firefighting elevators (2 of which are double decked)
- 64 Cabs (50 single decked and 7 double-decked)
- 8.025 km (5 miles) of hoistways
- 8 Escalators
- 1 workmen's lift

Specific **challenges** include:

Design of the Core: Every square foot on the typical floor counts, especially if you repeat those floors more than 100 times! Furthermore, as noted above, Jeddah Tower requires 57 elevators, however the core only has space for 18! Therefore, efficiency in the **Design of the Core** is essential and the answer for Jeddah Tower resides in the stacking of elevators in the same order that the program of the building is stacked. Groups of **High Speed Shuttle Elevators** originating at the bottom of the tower serve the Residential **Sky Lobbies** where passengers transfer into groups of **Local Elevators**, serving each Residential floor. The Locals in the upper zones are in the same posi-

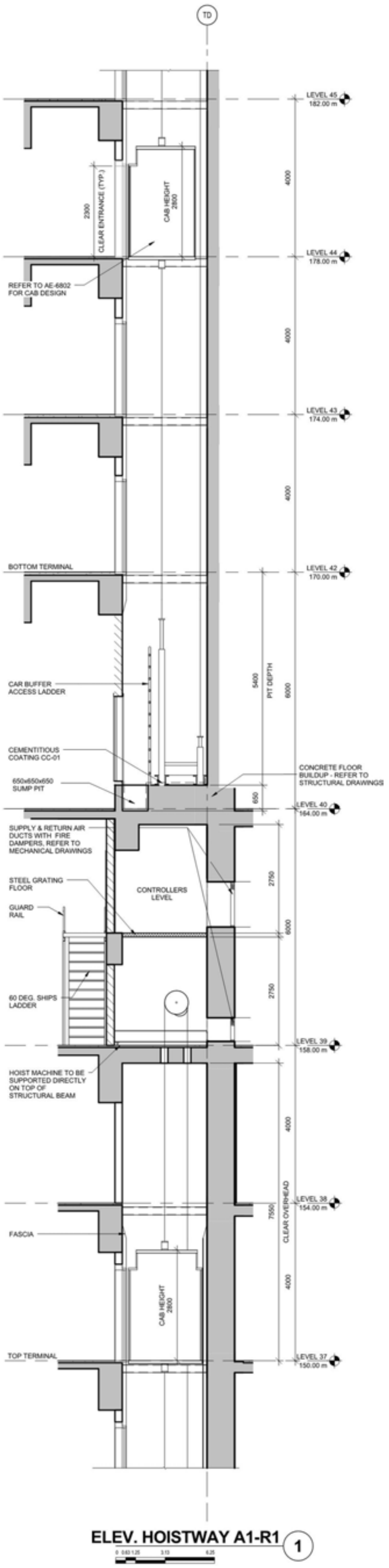

Figure 5. Stacking the Elevators in Jeddah Tower.

tion as the Locals in the lower zones because we have located multi-story **Technical Floors** below each **Sky Lobby**. The height of the Technical Floors allows for the pit of the upper Locals to be positioned directly over the machine room serving the lower Locals. In this way, we recapture the shaft space as we go up the tower, allowing the 50+ elevators to be located in the 18 shaft spaces in the Core. See Figs. 4 and 5.

Travel Distance, which in the case of Jeddah Tower's Observatory Shuttles is over 640 meters or more than 2100 feet. At a speed of 9 mps or 1800 feet a minute, it will still take more than a minute and a half to get from the B1/B1Mez lobby to the Observatory at 157/158. Spurred on by the newer generation of taller buildings, the manufacturers have been developing technologies that allow for faster and higher elevator service. Recent developments include larger machines and light weight composite material rope technology. When we were doing Burj Khalifa, we were limited to a travel distance of about 500 meters due mainly to the weight of the steel cables or rope. The weight of the multiple strands of rope exceed one half kilometer in length is several times to weight of the cab, passengers and counterweight; therefore, requiring larger and larger machines as travel increased. With the development "UltraRope" (a cable with a carbon fiber core); Finnish manufacturer Kone, has cut the weight of the cables to a fraction of what is required for steel; thereby opening the possibility of elevator travel distance of one kilometer and beyond. Furthermore, non-conventional technologies that may actually permit not only travel to extreme heights but also permit travel in all directions are being investigated. Refer to Fig. 6.

Windage is concerned with the issue of ride quality for passengers in an elevator cab traveling at high speed within an enclosed shaft. The cab itself acts like a piston in an automobile engine cylinder. Creating high pressure in the direction of travel and low pressure behind. As the

Figure 6. High Speed Elevator Machines and Kone Ultra-Rope alongside Conventional Steel (Kone).

air rushes past the cab going from high to low, buffeting and noise can make the passengers uncomfortable. We therefore pay a lot of attention to the aerodynamics of the high-speed cabs as well as designing ways to ease the movement of air and generally reduce the amount of noise within the cab. Mitigation measures include the following measures:

- Proper sizing of the shaft
- Aerodynamic cab shrouding
- Cladding the inside surface of the shaft
- Specifying active roller guides
- Providing pressure relief between shafts

Building **Sway** is another issue that must be addresses at an early stage in the design. All buildings move when lateral loads are applied. Lateral loads include wind and seismic events. Seismic events, being rare occurrences, are responded to by temporarily shutting down the elevators to prevent damage to the equipment. Wind, being a daily occurrence and high winds, especially at the extreme heights of these Supertalls, must be dealt with in the fundamental design of the system. We start by analyzing the buildings behavior under wind through the use of computational models and wind tunnel testing. A building Sway Report, describing the fundamental modes of movement, including both amplitude and period, is issued along with the contract documents to the elevator manufacturer. An elevator system is essentially a pendulum; the cab is a weight hung on a cable from a fixed point. Given the advanced knowledge of building sway, the manufacturer will analysis his design in order to prevent it from reaching resonant frequency. That is to say, the cab and cables excited to the point that their movements ae amplified to the point that they slam into the walls of the hoistway, guide rails, etc. Even with the best design and mitigation measures, we will still install accelerometers in certain locations up the tower to monitor lateral movements. If the building movements approach that equipment resonance or exceed a certain amplitude, the elevators will be slowed down or temporarily stopped to prevent damage.

4.1. Fire and Life Safety: "In Case of Fire Do Not Use Elevators"

There were many lessons learned from the tragedy of MGM Las Vegas Fire in 1980, where 85 people lost their lives. Arguably, following that event, the two most important changes reflected in the Codes were the requirement for automatic sprinklers in high rise buildings and the recognition that the use of elevator systems during fire emergencies, as were then designed, should be discouraged. At that fire, three elevators became jammed in their hoistways. The use of heat sensitive call buttons was also prevalent, which resulted in the elevators answering a call from a fire floor, the door opening, even if passengers were occupying it, and death from asphyxiation due to smoke. However, since the World Trade Center tragedy of **September 11, 2001**, there has been much discussion about speeding up the process of full building emergency evacuation. Specifically, the use of elevators to supplement the exit stairs, under certain circumstances, has been perceived as a no - or low - cost **enhancement**. As it stands now, both US Model Codes (IBC and NFPA) recognize the use of elevators, if properly designed and protected from fire and smoke, for supplemental building occupant evacuation.

In the case of Jeddah Tower, the local applicable codes do not recognize the use of elevators for means of escape. However, due to the great height of the building, the use of elevators to augment evacuation, primarily for "extraordinary" events, has been a fundamental aspect of the fire and life safety enhancements incorporated into the design. Partial or phased evacuation due to a "normal" emergency event, such as a fire in the building, would be handled in a normal manner via the exit stairs, without the use of elevators. However, in the case of "extraordinary" events, which could include, but are not necessarily limited to, district power outages, seismic events and general or specific security threats to the development, a tenant or to the building itself, would call into operation "Lifeboat" Evacuation.

4.2. Fire and Life Safety: Lifeboat Evacuation Elevators

The intent is to reduce the time it would take for Full Building Evacuation.

Design Approach is to employ Shuttle Elevators with Protection Features to insure operation.

- Resistant to Water Infiltration
- Emergency Power
- Operated from Each Cab
- Video inspection of hoistway shaft
- Limited stops – Lobby to Refuge Floor
- Operated by Trained Staff
- Part of Emergency Management Plan
- Full Building Evacuation in Less Than 2 Hours
- Fire Service Elevators remain dedicated for Firefighting and Disabled rescue assistance

5. Stack Effect

The Phenomena: To a person from a temperate climactic zone, stack effect is sometimes called "chimney" effect. It is the draft of air up the chimney in winter time due to the difference in temperature and density of flue gas within the chimney and that of the outside air. The height of the chimney will also influence this phenomenon. In the case of Jeddah Tower however; this effect is reversed. The high outdoor temperature and cool indoor condition create a difference in density that makes the indoor air want to travel downward out the bottom of the building.

This pressure difference is proportional to the temperature difference and building height and can be calculated mathematically. The design team enlisted the advice of RWDI our wind engineering consultants, with respect to this issue.

5.1. Stack Effect Mitigation Measures:

- Well-constructed exterior wall with minimum openings
- Well-constructed shafts, isolated from exterior wall
- Revolving doors, air locks and gaskets on door openings
- Mechanical system mass volume sensing and balancing
- Interruption of and/or offsets of continuous shafts
- Operational measures

Architectural Mitigation measures were incorporated into the architectural design with the intent to mitigate the negative impact of stack effect:

- The infiltration/exfiltration rate of the exterior wall is designed to a very tight standard. Operable doors/windows are minimized. Terrace doors are "alarmed" so that they are discouraged from being open at the same time that the unit entry door into the corridor is open.
- The sky lobby elevator system is an advantage in that the shuttle and local elevator shafts are separated and air locks provided at the entries. In effect, the building tends to act as a series of shorter buildings, separated, but stacked on top of one another.
- The service elevators have door openings at every floor. They are, however, provided with vestibules at each floor with tight fitting doors. Also, the elevator doors themselves have been provided with additional gasketing to improve the air tightness of the shaft. Furthermore, the elevators are located within the heart of the core, separated from the exterior wall (source of infiltration or location of exfiltration) by at least two additional sets of doors.
- Vestibules, with revolving doors, are provided at the entry level to each of the highly-trafficked passenger shuttle elevators.
- The exit stair transfers at Area of Refuge floors acts in a similar fashion as the sky lobby elevator system. The stairs are not in a continuous shaft, each shaft is much shorter and each is separated from the other by at least two doors.
- The service shafts between mechanical floors are separated where the risers from the lower zone meet those descending from the upper zone.
- Additional sets of doors were placed in the corridors between the elevator lobby in the core and the Residential corridors.
- The perimeter of the floor slab is sealed at every level to the inside surface of the exterior wall.
- The pipes and other services within the service shafts are sealed off at every floor.
- The Residential unit entry doors are provided with adjustable door bottom seals so that the air flow due to stack effect can be adjusted seasonally and under operating conditions, if necessary.

Building Services Mitigation Measures were incorporated into the mechanical systems design with the intent to mitigate the negative impact of stack effect:

- The building is slightly pressurized or neutral compared to outside.
- Major air systems in the tower have variable speed drives to allow systems to dynamically react to different pressure conditions.
- All air systems in the tower are divided into vertical sections to avoid excess differential pressure between top and bottom of the risers.
- Outside air intake and exhaust systems have air flow monitoring stations to track the amount of air in and out of the building.
- At each air system section, static pressure inside the tower is measured and compared to the static pressure outside to maintain a slightly positive or neutral in the building.
- Smoke exhaust system is doubled up as air relief to avoid over pressurization of the building.
- Air balance is studied to bring in the appropriate amount of outside air and exhaust without over pressurized the building.

6. Construction Update

As of the writing of this paper; the tower is approximately 58 stories above grade or almost one quarter of its' eventual height.

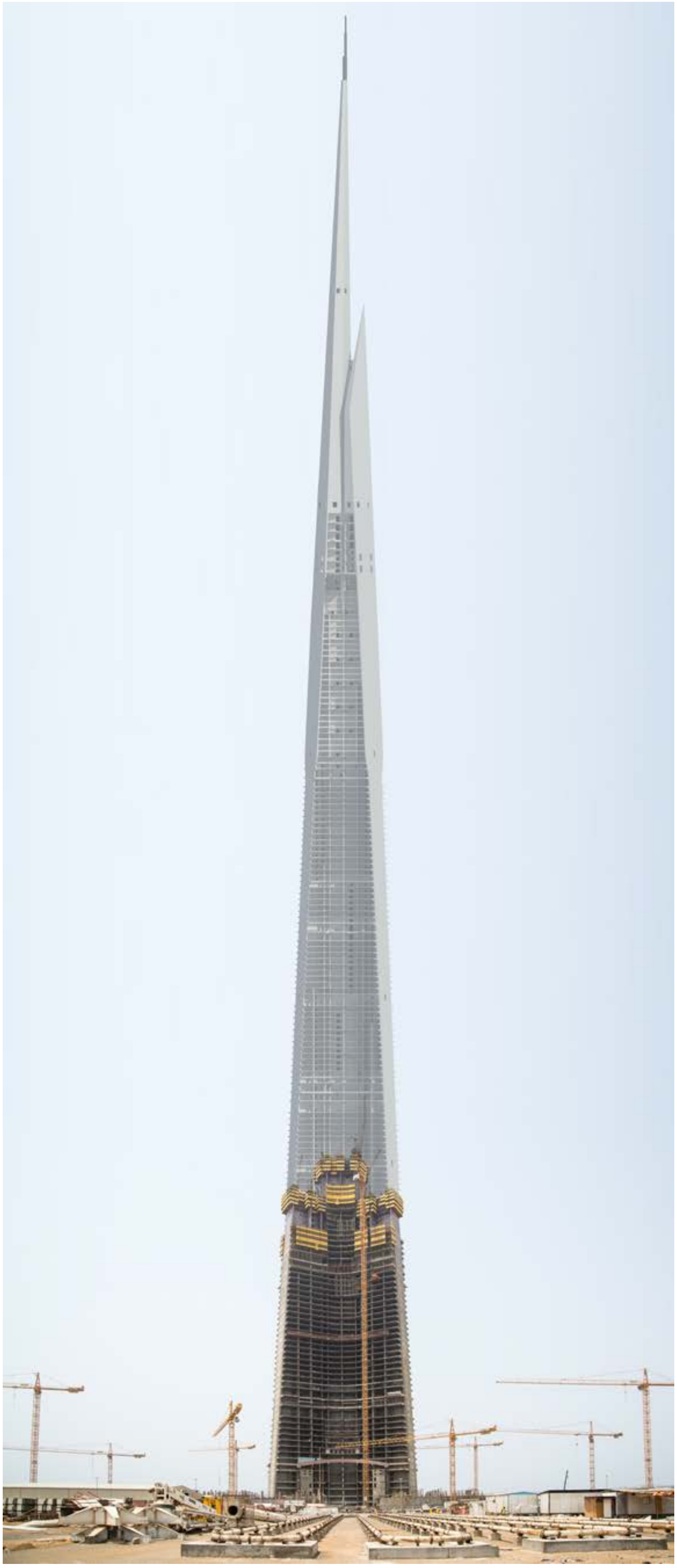

Figure 7. Jeddah Tower as of August 2017, superimposed over an image of the completed building.