

A Report on a Concrete Frame Structure

THE BURJ KHALIFA



(EMAAR)

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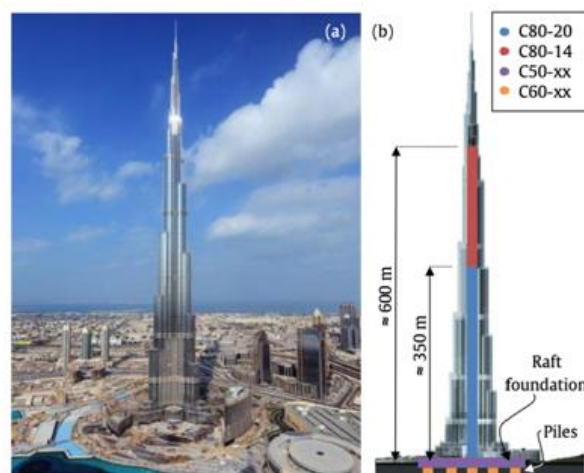
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1. ORIGINAL DESIGN

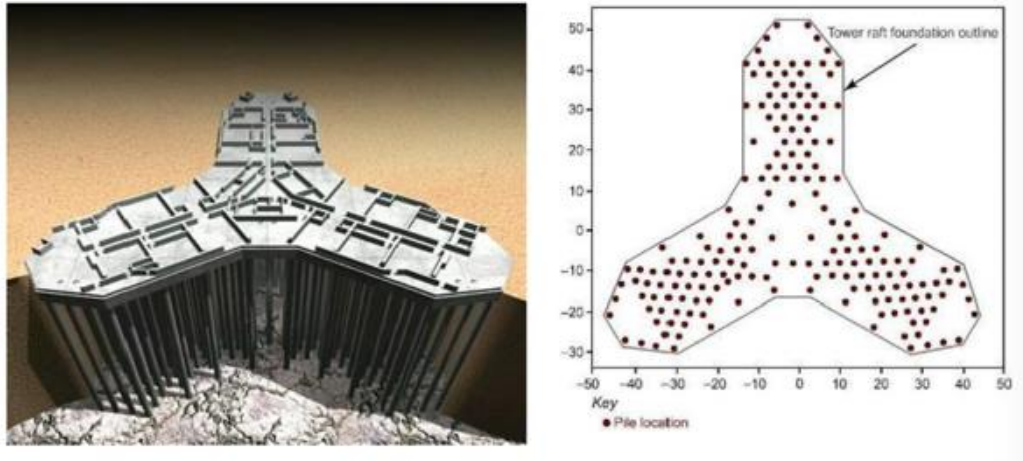
Standing at 828m high the Burj Khalifa is the world's tallest building. The Burj is a 'Y' shaped structure comprising of reinforced concrete to the first 586m with a structural steel spire accounting for the remaining 242m (*figure 1*). The 'Y' shape enables a central hexagonal core column to be connected to the three exterior wings by a 200-300mm thick reinforced concrete slab (*Yusuf et al., 2023*), with every 7th floor of the wings subtracting inwards towards the core creating a representation of the indigenous desert flower (*Abdelrazag 2012*).



(Figure 1.1: (a) An image of the Burj Khalifa and (b) a diagram displaying the grades of concrete used from foundation level to 586m. Bester 2013)

1.1 Foundations

The Burj Khalifa rests upon 460,000m³ of land supported by reinforced foundations (*Abdelrazag 2012*). High performance concrete was used to form the 3700mm thick raft foundation seen in *figure 2* (*El Gendy and El Gendy 2018*) which lays over 100mm of blinding with a waterproof membrane, and all supported by 194 x 1500mm diameter rebar concrete piles (*Russo et al., 2012*) driven ~50m below the surface.



(Figure 1.2: Burj Khalifa foundation system (a) cross sectional diagram and (b) birds-eye view of pile placement. El Gendy and El Gendy 2018).

1.2 Concrete

250,000m³ of self-compacting concrete was used to complete the Burj. To achieve the highest strength concrete (80 MPa), a 77/13/10 combination of cement, fly ash, and condensed silica fume with a water/binder ratio of 0.34 was mixed (Bester 2013). This combination generated a high workability mixture to facilitate its navigation around high-density reinforcement whilst maintaining its homogeneity (Illston and Domone 2001).

The concrete was pumped in-situ to form the concrete skeleton, as this avoided transporting heavy prefabricated material up the skyscraper Bester (2013). To reduce the occurrence of blockages pumping tests were executed to achieve the desired workability mix with the addition of a special superplasticiser to induce a prolonged setting retardation to reduce blockages when pumping.

1.3 Lateral and Gravity Loads

The lateral and gravity load imposed on the land had to be accounted in the design. Figure 3 presents the designed lateral load resisting system, which relies on a high performance reinforced concrete core connected to concrete reinforced shear panels and exterior reinforced columns (Abdelrazag 2012). Moreover, the steel spire that rests on top was structurally designed with diagonal bracing system to mitigate wind resistance. The quantity of material required to equilibrate the gravitational load equates to the amount needed to neutralise the lateral load, which is testament to the impressive structural design (Yusuf et

al., 2023) as the imposed loads are successfully transmitted through the structural concrete (Figure 4).

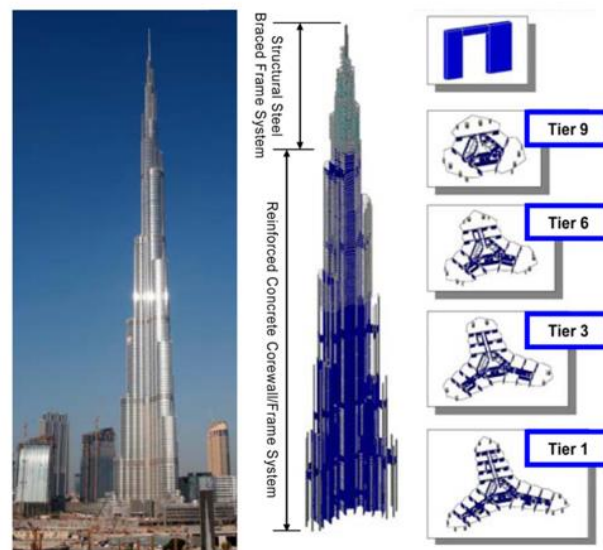
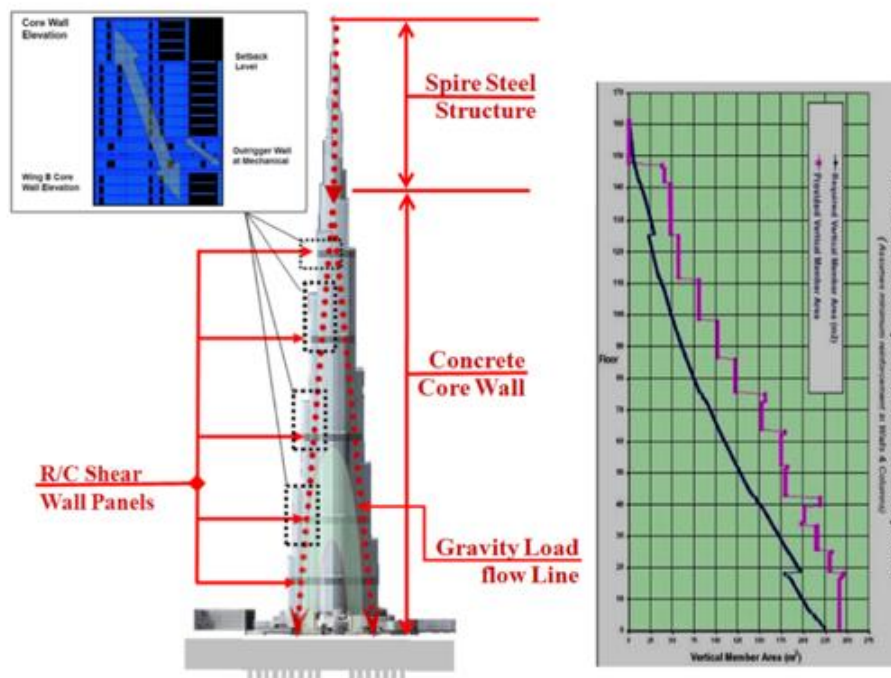


Figure 2. Lateral load resisting system and photo of the completed tower.

(Figure 1.3: Diagram of the lateral load resisting system. Abdelrazag 2012)



(Figure 1.4: Lateral load resisting system. Abdelrazag 2012)

2. CLIMATIC RESISTANCE

The two major climatic forces that poses structural challenges to the construction are extreme temperatures and high winds.

2.1 Heat

Firstly, the concrete under these temperatures would be subject to premature setting and shrinkage which occurs when the rate of evaporation increases under intense heat causing weaknesses in the concrete. Although high temperatures could increase short-term strength of the concrete, consequently it reduces its long-term strength (*Illston and Domone 2001*). To combat this the pumping of concrete was conducted at night, however temperatures could still surpass the maximum temperature limit of 32°C therefore flaked ice was added to concrete mix for retardation (*Aldred 2010*).

2.2 Wind

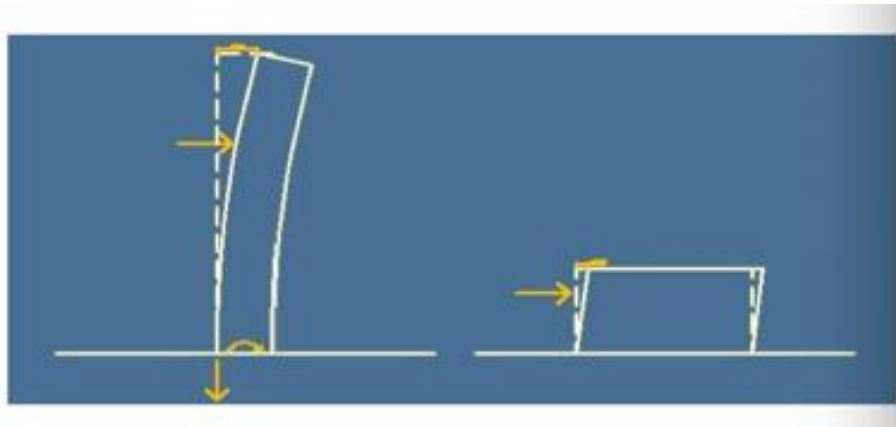
Taller buildings are more susceptible to overturn (*Figure 5*). Therefore, enhanced wind modelling was conducted on various models of the Burj to determine the most effective orientation and to incorporate the wind effects on gravity and lateral loads to withstand overturn/collapse. *Abdelrazag (2012)* outlines 4 methods used to resist wind forces:

Resistance to overturning is predominantly executed through the building's own gravity and effective structural concrete frame.

Columns are aligned equally to distribute equal stress to minimise column shortening.

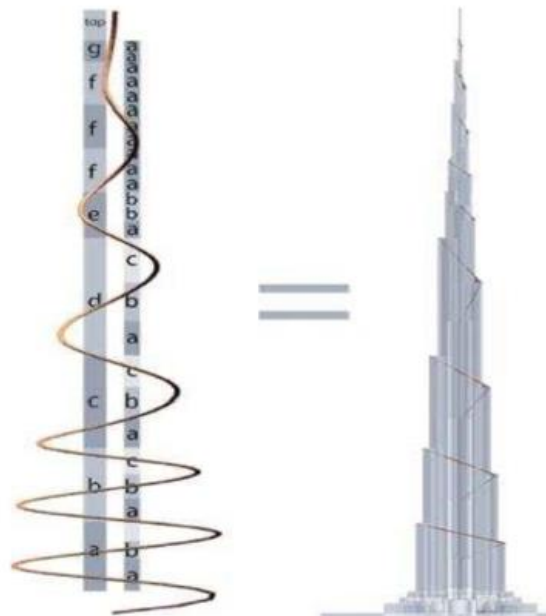
The shape and the position of the building is utilised to deflect wind.

The reduction of the Burj's girth as elevation increases reduces the potential area for wind to apply force.



(Figure 2.1: How wind effects tall-long buildings versus short-thick buildings. Nirmal 2017)

Nirmal (2017) also draws attention to how the initial design of the Burj could create a wind vortex phenomenon (Figure 6). Having identified the risk early, the cutback of layers on the three wings with the thick base of the tower confuses the wind and pacifies any vortex build-up.



(Figure 2.2: Wind vortex phenomena. Nirmal 2017)

3. DURABILITY

The durability of the concrete ultimately permits the development of concrete buildings, especially when these buildings are constructed in extreme climates.

3.1 Load pressure

To ensure the building could support the heavy load, high strength concrete (HSC) was utilised. To formulate HSC a reduced water/binder ratio and superplasticiser was combined to reduce the porosity and generate a higher packing density to support the building (*Bester 2013*). However, the increased compactness applied additional stresses to the aggregates used in the concrete mix therefore high quality, high strength, and low water tolerating aggregates were needed to absorb the compressive pressures.

Furthermore, HSC typically discharges heat at greater rates to that of normal concrete but produces lower overall temperatures during hydration which could result in thermal cracking. *Bester* stresses the importance of attention during the curing process and the engineers determined that night casting in combination with water curing and flaked ice would mitigate thermal cracking. Tests were conducted to determine the climatic and methodological effects on the rate of hydration such as climate and pumping prior to pouring, resulting in the addition of fly ash to the mix accordingly to offset hydration.

3.2 Chemical Attacks

Chemical attack can be catastrophic for concrete buildings, as water and sulphates will attack the concrete causing weaknesses in the structure. Alternatively, the chosen aggregates in the concrete mix could be contaminated which will produce sulphates that attack concrete, and being the Middle East is notorious for

contaminated aggregates (*Illston and Domone 2001*) it was paramount that the engineers selected high quality aggregates which will be discussed in due course.

The development site of the Burj Khalifa is located 2 miles from the sea, but surrounded by watercourses which feed and are fed by the sea creating a potentially hazardous sub-terranean chemical environment for concrete and steel foundations. To protect the foundations a cathodic protection system was placed to prevent corrosion of the rebars within the waterproofed concrete foundations (*Abdelrazag 2012*).

4. CONSTRUCTION METHOD

4.1 Sub-terranean

The initial site analysis uncovered that there were high water tables (2.5m), and horizontal beds of very weak lithospheric layers (*table 1*) which influenced ground's ability to bear heavy concrete structures resulting in deep foundations to stabilise the Burj (*Russo et al., 2012*) and reduce the risk of liquefaction.

(Table 4.1: Geotechnical site analysis)

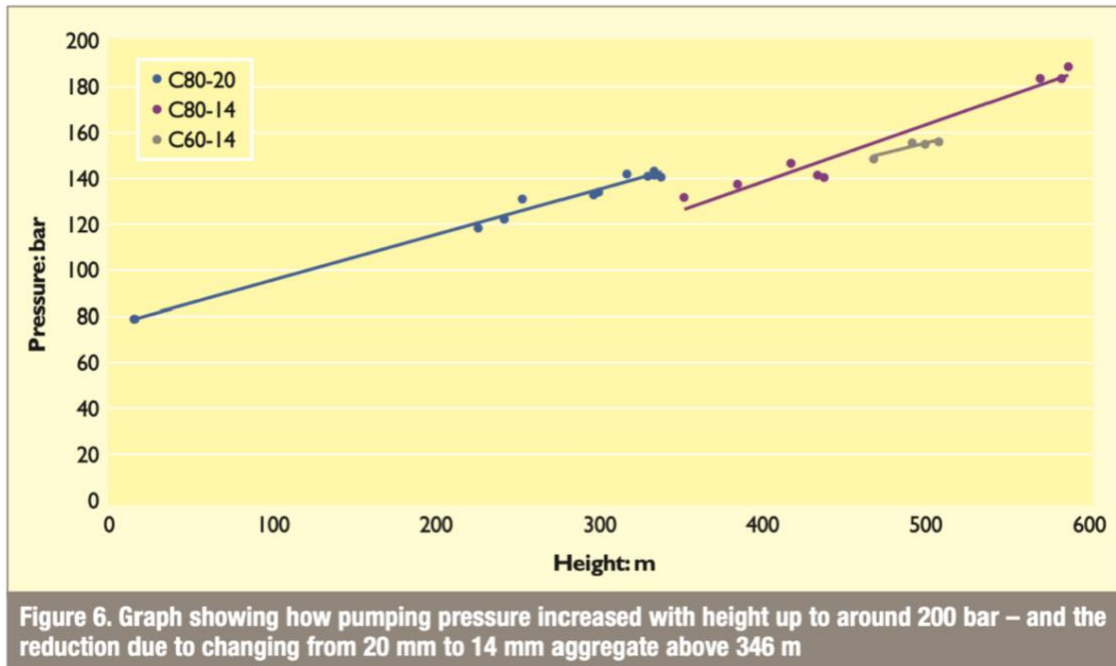
Strata	Sub-Strata	Subsurface Material	Level at top of stratum [m DMD]	Thickness <i>H</i> [m]	UCS <i>q_s</i> [MPa]	Undrained Modulus <i>E_u</i> [MPa]	Ult. Comp. Shaft Frict. <i>f_s</i> [kPa]
1	1a	Medium dense silty Sand	+2.50	1.50	-	34.5	-
	1b	Loose to very loose silty Sand	+1.00	2.20	-	11.5	-
2	2	Very weak to moderately weak Calcarene	-1.20	6.10	2.0	500	350
3	3a	Medium dense to very dense Sand/ Silt with frequent sandstone bands	-7.30	6.20	-	50	250
	3b	Very weak to weak Calcareous Sandstone	-13.50	7.50	1.0	250	250
	3c	Very weak to weak Calcareous Sandstone	-21.00	3.00	1.0	140	250
4	4	Very weak to weak gypsiferous Sandstone/ calcareous Sandstone	-24.00	4.50	2.0	140	250
5	5a	Very weak to moderately weak Calcisiltite/ Conglomeritic Calcisiltite	-28.50	21.50	1.30	310	285
	5b	Very weak to moderately weak Calcisiltite/ Conglomeritic Calcisiltite	-50.00	18.50	1.70	405	325
6	6	Very weak to weak Calcareous/ Conglomerate strata	-68.50	22.50	2.50	560	400
7	7	Weak to moderately weak Claystone/ Siltstone	-91.00	>46.79	1.70	405	325

4.2 Aggregates

The aggregates required for the construction had to meet the specific restrictions imposed on the project by the size of the building and local climate. Dolomitic limestone was selected for its high strength and low water properties (*Bester 2013*) to coincide with the low water mix and high strength requirements. The size of the aggregate also held significance, as coarser aggregates require bigger pipes and increased pressure. A 150mm pipe pumped a maximum 20mm aggregate up to 346m which enabled the pipe to provide $40,000m^3$ of concrete (*Aldred 2010*). Furthermore, the size of aggregate could reduce the durability of the pipeline therefore an average 20mm aggregate which decreased in diameter at higher levels of construction to permit the usage of smaller pumps with reduced pressure requirements (*Bester 2013*). Finer aggregates also increase the cohesiveness of mixtures, binding the water tighter to aid transportation through the pipeline. Consequently, if aggregates were too big the water would separate and advance without the mix causing blockages.

Higher finer aggregates are common in HPCs, and these comprised 50% of the HPC used in the construction of the Burj (*Aldred 2010*) with fly ash and condensed silica fume at a 13-20% and 5-10% replacement level respectively (*Bester 2013*). A bespoke superplasticiser was tailored for the Burj, coined as 'workability aids' these plasticisers enhance workability and permit the reduction of water which increases strength (*Illston and Domone 2001*). Nevertheless, these plasticisers delay set and thus decrease early strength, however this effect was intentionally manipulated to delay the setting time and reduce the risk of blockages as the concrete was pumped up to 350m.

The pouring of concrete required static booms (Putzmeisters) that were mountable to the Doka climbing system that raised with the formwork (*Aldred 2010*). *Figure 7* presents the required pressure used to pump each concrete mixture during the construction. The decreases in pressure between the mixtures respond to the reduction of aggregate diameters (C80-14) and water-cement ratios (C60-14) enabling greater pumpability.



(Figure 4.1: Graph displaying the required pumping pressures of concrete for the Burj Khalifa. Aldred 2010)

5. ENVIRONMENTAL

5.1 Material Impact

Concrete produces high quantities of CO². The manufacturing of limestone, called ‘*calcining*’ involved heating calcium carbonate to form the essential ingredient in cement ‘*clinker*’ which is then used in concrete. Not only does the fuel used to heat the limestone emit CO², but also the bi-product of the reaction itself produces CO² as a bi-product. Accounting for the 460,000m³ of concrete used to construct the Burj Khalifa, it is difficult to comprehend the immense CO² output that was produced by the concrete alone.

Positively, the self-compacting concrete (SCC) used attributed to positive health and environmental factors when compared with non-SCC. The use of SCC reduces the vibration exposure of workers (*Illston and Domone 2001*) because SSC does not require the vibration machinery used to compact the non-SCC. Furthermore, the elimination of vibrating machinery reduces the noise pollution to surrounding areas protecting the environment and health of workers.

5.2 Method Impact

The method of construction requires significant quantities of natural resources, such as water. Natural water is not abundant in Dubai, in fact the UAE heavily relies on desalination plants that provides 80% of its water (*Marashi and Bhinder 2008*). The desalination plants require carbon to function and despite this report not acquiring the project’s precise quantity of consumed water, the amount of cement used suggests a high-water consumption on cement alone generating a high carbon output.

The impact of construction on ground settlement provided positive results, which are attributed to the innovative engineering and precise load calculations. The settlement values were “excellent”, column shortening “within the expected range”, and lateral movement had “excellent correlation” between the expected and predicted (*Abdelrazag 2012 pp.45-47*)

6. CONCRETE AND STEEL

6.1 Design

Concrete provides high strength in compressional loading, and although weak in tension this is addressed with reinforcement steel bars as steel is not only strong in compression but strong in tensile stress and provides a better strength to weight ratio than concrete. Controlling the carbon content of steel can increase/decrease ductility, welding, hardness, and ease of casting (*Lyons 2007*) similarly to how aggregates and plasticisers altered the workability of concrete used in the Burj. However, steel frames are more unstable and are prone to twist and torsion, unlike a homogenous concrete frame. To stabilise steel frames 'X' and 'K' braces are required, but even with fixed braces steel frames enable greater spaces between beams to allow penetration of natural light as opposed to concrete frames.

Concrete and steel frames also provide building services. A concrete frame will provide better acoustic and fire insulation up to 500°C before gradually losing strength (*Illston and Domone 2001*). Steel does not provide these services as they require intumescent paint and sound insulation, but steel can absorb and reflect sunlight which was advantageous in building the Burj. An aluminium and steel external cladding reflect the heat from the skyscraper (*Weismantle, Smith, and Sheriff 2007*) along with vents and air-conditioning that extract and displace heat with cooler air (*Yusuf et al., 2023*).

6.2 Construction

Normally steel is prefabricated off-site to be forged/welded to shape on-site. Prefabricated steel can be heavy to handle which requires expensive transport and machinery. Nevertheless, the precision of quality control off-site mitigates on-site work and limits storage needs as steel can be delivered on-site when needed which reduces expenses. Alternatively concrete can be poured in-situ to form desired structures, but pouring concrete requires robust formwork, and testing of cement,

aggregate, and admixtures to determine how these components will perform, therefore concrete is time consuming (*Lyons 2007*) and consequently expensive. In constructing the Burj Khalifa, extensive concrete and pumping testing required valuable time and resources whereas a steel frame would have reduced construction time in this respect.

It is possible to reach greater heights when erecting steel frame buildings, although the Burj displayed innovative methods to build to record heights with concrete. This was achieved by adapting the concrete mix to enhance the workability to be pumped, which is evidence of concrete's flexibility. Of course, precast concrete could have been used, but this would require concrete moulds and craning heavy concrete pieces to significant heights. Although a steel spire completes the Burj, it is not habitable but steel being more flexible than concrete enables greater flex and resistance to strong winds, plus being lighter than precast concrete facilitated its transportation up the structure and eliminated the need for pouring and curing methods.

Despite the advances in concrete innovation, the builders had to protect the concrete from shrinkage and creep through controlling the rate of hydration which is not needed in steel structures. If shrinkage and creep are not controlled, then the concrete can reach a point of no return to its former size 'irreversible shrinkage' (*Illston and Domone 2001*). Furthermore, the balance of aggregates and water content is paramount to encasing any reinforcement and avoiding pump blockages (*Bester 2013*).

6.3 Durability

Steel frames will sustain their strength if maintained correctly and be reused without losing its structural strength (*Marashi and Bhinder 2008*). Alternatively, concrete frames will eventually deteriorate and is subject to external forces impacting its durability which includes but not limited to sulphate and chemical attack and frost expansion. Concrete frames can be reused, however this is limited to producing

hardcore material (*Lyons 2007*) whereas steel frames can facilitate addition or subtraction of steel beams/columns. Nevertheless, steel is subject to external forces such as wind or corrosion causing rust or reduction in strength.

The concrete foundations and cathodic system provided the Burj with a defensive blanket to protect the internal steel reinforced bars, however it is possible over time that the concrete foundation will undergo chemical attacks from sulphates and crystallisation of salts from subterranean watercourses, especially as limestone aggregates are more susceptible to chemical attacks (*Lyons 2007*). Furthermore, the ability of steel to twist and flex was effectively exploited by placing a steel spire at the top of the Burj, rather than a rigid concrete structure that could fracture under strong tensile stress. Naturally the remaining concrete frame will experience tensile wind force, however this was limited by strategic positioning and design of the Burj Khalifa.

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