Title: **A Postcard from Dubai - Design and Construction of Some of the Tallest Buildings in the World**

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Subjects: Architectural/Design
Construction

Keywords: Concrete
Construction
Seismic
Steel
Wind

Publication Date: 2008

Original Publication: CTBUH 2008 8th World Congress, Dubai

Paper Type:

1. Book chapter/Part chapter
2. Journal paper
3. **Conference proceeding**
4. Unpublished conference paper
5. Magazine article
6. Unpublished

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Design and Construction of Some of the Tallest Buildings in the World

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Biography

Andy Davis is a Director of the global consulting engineering practice ‘Hyder Consulting’, and serves on the Hyder global professional board. They are headquartered in London UK, and manage about 3,000 staff in 20 offices around the world, including over 900 staff in the Persian Gulf.

He is the Chief Engineer of the Hyder high-rise design ‘Studio’ which is now based in Dubai and is responsible for many of the high-rise projects undertaken by Hyder around the world, including the beautiful Emirates Towers in Dubai, which are the tallest buildings in the Gulf. Andy’s ‘Studio’ currently has 7 towers between 60 levels and 160 levels under various stages of design and construction for Clients in the Gulf and around the globe. Andy is responsible for the structural design certification of the 160 level Burj Dubai Tower, currently u/c in Dubai, UAE. When completed in 2008, it will be the tallest manmade construction in the world.

He is an Australian Engineer by training and passion, but also holds a PhD in Engineering and an Adjunct Chair in Architecture at the University of Sydney, and serves on several International Code Committees. He received the RW Chapman medal and Engineering Excellence Award from the Institution of Engineers for his work, and was recently cited as amongst the 100 most influential Australian Engineers.

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Abstract

This paper presents an overview of the design and construction of some of the tallest buildings in the world, currently under construction in the Gulf region. The paper explores some of the key natural and commercial forces at work in the region, and how these forces shape the design of these super high rise projects. The key natural forces of regional seismic activity and the wind environment of the Gulf are highlighted as having characteristics which are unique to the Gulf, and their effects upon the design of these tall buildings must be carefully considered in design. Typical subsurface conditions in the Gulf are outlined, and the ability of this marine sediment material to degrade under cyclic loading is highlighted. Finally, a series of postcards of mixed use towers in the height range of 450 metres to 600 metres currently under design and/or construction in the Gulf are used to illustrate the observations offered in the paper.

Keywords: Tall, Design, Construction, Concrete, Steel

The Gulf Scene in Context

As Architects and Engineers we are in the business of creation, but before turning our hand to that task we need to ask the question….what motivates this creation, and what is the context? A casual observer in Dubai would say that this was simply a shallow display of wealth fuelled by selling oil. However, living and working in Dubai we discover a more startling reality, that it is an act of Nation Building. For a nation being born, these built forms can be as important as grains of sand to an oyster. They provide a sense of place where such a sense did not exist, and something to share where a wider sense of community has no roots. This is the real context of our work here as Engineers and Architects.

Figure 1. A Collection of Images of the Gulf Context

Subsurface Conditions in the Gulf

Much of the existing settlement and new development in the Gulf is located around the coastal areas. The subsurface conditions along the coastal areas are characterized by a relatively thin surface layer of sand overlying layers of conglomerate, sandstone and various marine sediments such as calcarenite and calcisiltite. Water tables are often within a few metres of the surface, with the groundwater containing significant proportions of chloride and sulphate. Overall, this configuration provides a reasonably competent material to found large building works, although it is a highly corrosive environment. A typical geotechnical profile is shown in Figure 2.

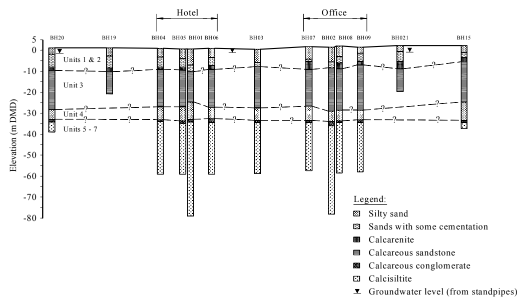

Figure 2. Typical Geotechnical Profile in a Gulf Coastal Area

Typical Deep Foundation Systems in the Gulf

Super high rise buildings in the Gulf are often constructed upon piled rafts. These foundation systems typically consist of several hundred 1.5m diameter bored and cast insitu piles extending about 50m to 60m in depth, capped by a 3m to 5m thick cast insitu raft covering the footprint of the tower. The load of the building is shared between the piles in shaft friction and the raft in direct bearing, with the pile system typically carrying about 80% of the total load directly into the deeper strata. The marine sediments have an ability to carry quite high static loads, but such capacity reduces under cyclic axial loading in some conditions. For this reason, full scale pile testing is often undertaken as shown in Figure 3. A typical 1.5m diameter pile 50m long in this material can carry a static working load of 3,000 tonnes with a settlement of about 30mm.

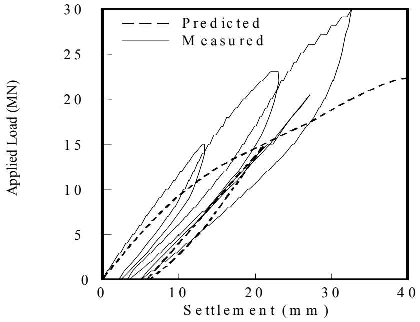

Figure 3. Typical Deep Pile Testing in the Gulf

Seismic Conditions in the Gulf

The Gulf is located along the northern edge of the Arabian plate, which is currently moving northwards at about 20mm per year. This plate is slowly colliding with the Asian plate, forcing the edge up and creating the extensive Zagros mountain range along southern Iran. The outcome of this tectonic motion is a region to the north which has significant seismic activity. An overview of the seismic activity in the Gulf region is presented in Figure 4. Design seismic spectra for the Gulf is strongly related to the proximity to the plate boundary. The seismic design spectra derived for Doha is presented in Figure 5, for various return period events. In general, cities such as Doha, Dubai and Abu Dhabi which are several hundred kilometers from the plate boundary have a seismic design spectrum which is similar in magnitude to Zone 1 in UBC. Approval Authorities often ask for major building projects to be designed to Zone 2A, which is significantly higher than probably required for cities along the southern shores of the Gulf.

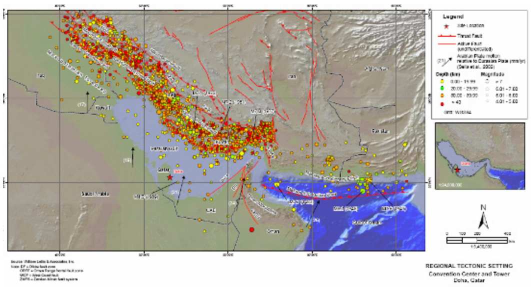

Figure 4. Overview of Seismic Activity in the Gulf

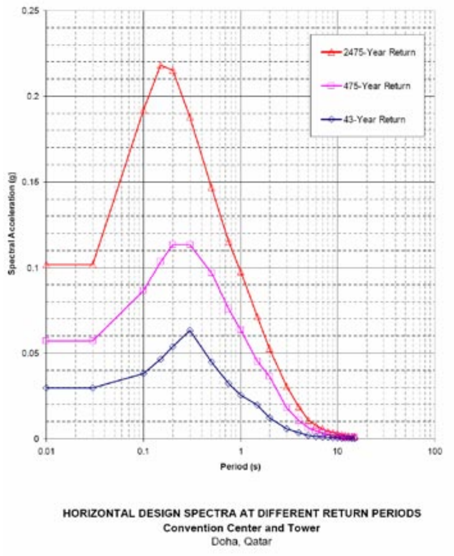

Figure 5. Seismic Design Spectra for Doha

Wind Conditions in the Gulf

The wind climate of the Gulf is characterized as a 'mixed climate' and consists of influences from synoptic, thunderstorrn, shamal and Indian Ocean cyclonic events. Each of these events has a different wind velocity profile, probabilities of occurrence and duration, and their associated effects upon very tall buildings in the Gulf should be individually contemplated during the design process.

A typical synoptic event is shown in Figure 6. It is characterized as a low pressure system which could be several hundred kilometers in diameter, moving slowly across the region from a well predicted direction. The wind velocity profile associated with this type of event is well documented, and a typical velocity profile is also shown in Figure 6, where the wind velocity reaches a stable peak at above 600 metres, which is towards the top of many tall buildings currently under design in the Gulf.

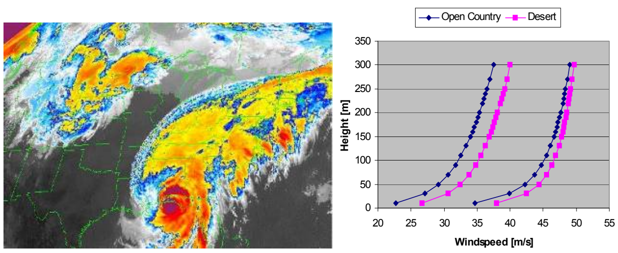

Figure 6. Typical Synoptic Wind Event and Velocity Profile

A typical thunderstorm cloud and associated wind velocity profile is shown in Figure 7. Thunderstorm downbursts occur when the cloud collapses, ejecting a high velocity jet of air from the base which descends vertically to strike the ground. The jet of air then runs out horizontally at or near ground level, creating a high velocity flow at low levels, as shown in Figure 7. These wind events are responsible for the peak wind gusts in the Gulf as recorded by standard anemometers located at 10m height at airfields. They have a significantly different velocity profile to a synoptic event shown in Figure 6, with a significantly different effect upon the response of a tall building in the Gulf.

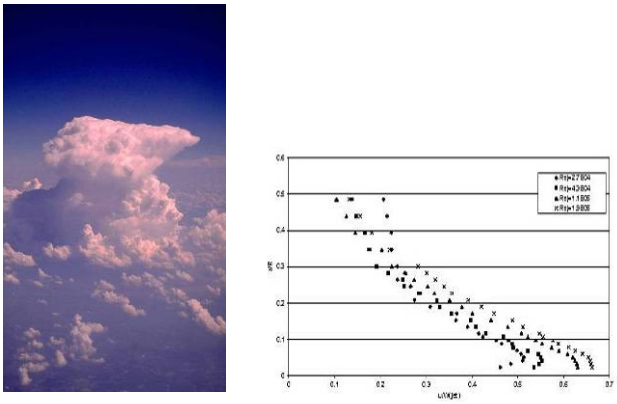

Figure 7. Typical Thunderstorm Wind Event and Velocity Profile

The eastern shores of the Gulf region can be affected by cylones generated in the Northern Indian Ocean. These cyclones are infrequent, but can be very intense. They can form in the warm waters towards the Indian subcontinent and travel westwards, increasing in strength until making landfall on the Arabian peninsula. Their air pressure systems are characterized as being several hundred kilometers in diameter with upto Cat 5.5 winds at the centre, but unlikely to produce extreme winds in the cities along the southern shores of the Gulf. An image of cyclone Gonu which occurred in 2007, and it's track are shown in Figure 8.

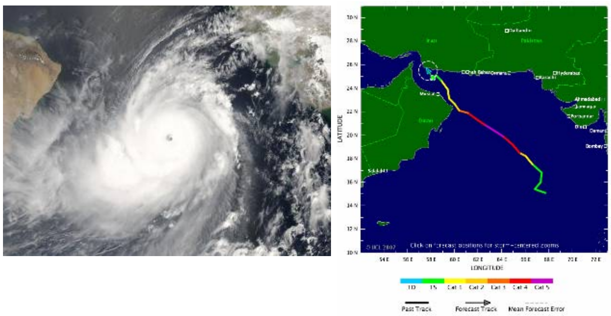

Figure 8. Tropical Cyclone Gonu and it's Track, 2007

A wind event which is unique to the Gulf is the 'Shamal', which is an Arabic word for north. These winds occur during late summer as a result of temperature inversions over the Arabian desert. They come from the northwest down the Gulf and are very strong at low levels. Satellite images of the Gulf on a normal day and during a shamal are shown in Figure 9.

Figure 9. Typical Clear Day and Shamal Wind Event in the Gulf

The velocity profile of a typical shamal event is shown in Figure 10. It is seen that the peak velocity occurs at about 300 metres height, which is at approximately mid-height of many of the super tall buildings currently under design in the Gulf. We also note that the velocity measured at a typical anemometer mounted at 10m height will not be a good indicator of shamal strength at height. The velocity profile is significantly different to that of a synoptic event for Gulf buildings over about 300 metres height.

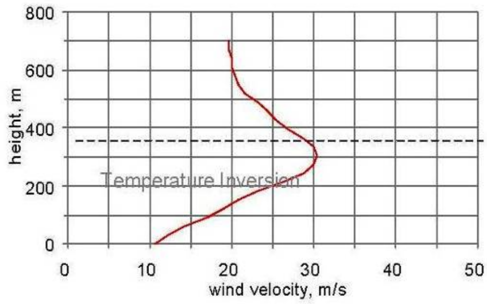

Figure 10. Typical Velocity Profile of a Shamal Wind in the Gulf

Advanced Wind Tunnel Studies in the Gulf

It is seen from the preceding discussion that the wind environment in the Gulf is a complex mix of events which are each generated by differing physics. The strength, direction, duration, probability of occurrence and in particular the velocity profiles of the various wind events are significantly different. Each of these events will have a different effect upon the response of a super tall building in the Gulf. Results of a recent wind tunnel investigation conducted at RWDI's test facility for a 450 metre tall building in Doha are shown in Figure 11. The project is the Dubai Tower Doha, described later in this paper. In this investigation, the various wind velocity profiles of synoptic, thunderstorm and shamal events were simulated in the tunnel in order to determine the response of the tower.

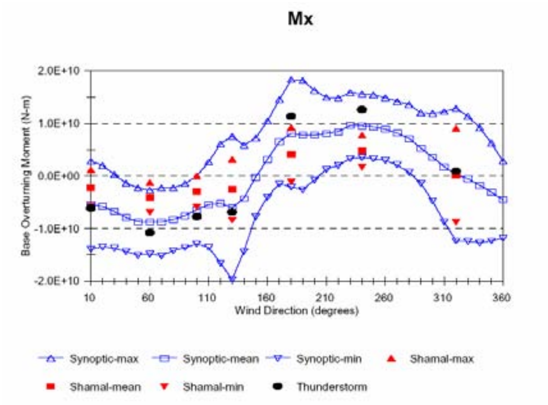

Figure 11. Investigation of the Effect of Various Winds the Gulf

Economic Conditions in the Gulf

The cost of construction in the Gulf has traditionally been significantly lower than in Europe, North America and much of Asia. Most building products and processes are imported into the region, including labour, and the cost of imported labour has traditionally been modest even with high demand. However, the rate of inflation in the construction industry in the Gulf has peaked at more than 1.5% per month recently, meaning that construction time is now the most critical design parameter for these super high rise projects. This is a key point to understand about the most appropriate design of a super high rise in the Gulf at present. The very high level of inflation has also lead to a change in the way contractors are appointed, with a clear trend away from lump sum contracts towards GMP type contracts, in which the owner and contractor share the risk of time extensions.

Figure 12. World Best Practice Construction Techniques the Gulf

In general, the quality of contractors and their work is on parity with the best available elsewhere in the world. All construction materials and methods which are available on the global market are readily available in the Gulf, including conventional and post-tensioned concrete, high yield structural steel, precast floor panels and composite construction beams and decking. Typical example high rise buildings which employ these various construction technologies in the Gulf are shown in Figure 12. High strength concrete in grades upto 80Mpa is commonly produced locally for super high rise projects, especially in Dubai. As with all leading edge technologies, careful planning, testing and site supervision is essential.

Postcard Case Study – Emirates Towers, Dubai

The Emirates Towers project in Dubai was completed in 2000, and represents one of the first in the new breed of high rise buildings in the Gulf. It was conceived as a flagship nationbuilding project to mark Dubai's aspirations for the new century, and the story since then in Dubai is self evident. The completed project is shown in Figure 13.

Figure 13. The Emirates Towers, Dubai, 2000

The project consists of a 355m tall office building and 305m tall hotel over an extensive podium accommodating retail and carparking. The office building was constructed using conventional slip forming techniques for the central and corner cores which supported precast floor planks spanning between the core and a perimeter steel edge beam. A series of concrete filled steel tube columns around the perimeter supported the edge beams. Building stability was provided by coupling the central RC core to the perimeter columns using outrigger and belt trusses at plantrooms which ran around the perimeter of the building and connected back to the core. The outrigger and belt trusses were fabricated at ground level using grade 460 rolled steel sections, and strand jacked into place. To accelerate construction, the cores were initially slipped up 75m to the location of the first typical tower floor, jumping past the more complex podium. This allowed two construction fronts to proceed at the same time, one above the podium and one from ground level. This configuration was called a 'çonstruction jump start', and is shown in Figure 14.

Figure 14. The Emirates Towers Office u/c, Dubai, 1999

The Hotel building was constructed using conventional jump forming techniques for the central and corner cores, which supported conventionally reinforced flat plate RC floor slabs. The central and corner cores were initially jumpformed upto 75m height to reach the first typical tower floor, jumping past the more complex podium. Steel trusses were then placed around the perimeter to support the independent perimeter self-climbing jump form system, which was used to construct a cast insitu RC perimeter frame. This perimeter frame provided stability to the completed tower. This technique also allowed two construction fronts, one above the podium and one from ground level, to operate at the same time which yielded significant savings in time. This configuration was called a ‘çonstruction jump start’, and is shown in Figure 15.

Figure 15. The Emirates Hotel u/c, Dubai, 1999

Postcard Case Study – Pentominium Tower, Dubai

The Pentominium Tower is conceived as the tallest all residential building in the world, and is configured to provide one owner per level over it’s 120 occupied upper levels. The tower is 615 metres tall and situated in the rapidly developing Marina District in Dubai. The structure is very slender, and incorporates sloshing liquid dampers to provide additional damping to reduce the response to low return period wind events. All of the vertical elements of the structural system have been designed to utilize C80 high strength concrete, and are incorporated into a rapid self climbing jump form system to achieve a minimum construction cycle time. The flat plate floors are designed to be constructed using high early strength C50 grade concrete in order to allow early stripping and reuse of floor formwork. Images of the project design are shown in Figure 16. The project is currently under construction on a 36 month construction schedule.

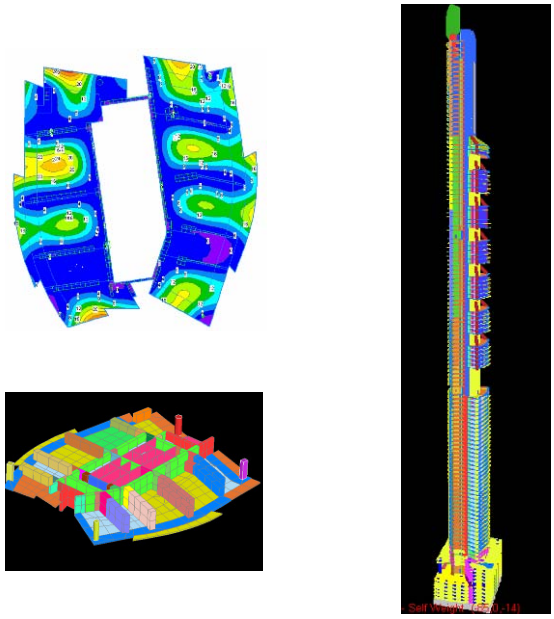

Figure 16. The 615m Pentominium Tower Dubai, 2007

Postcard Case Study – Tatweer Towers, Dubai

The Tatweer Towers project is located on a prominent site on the Emirates Road in Dubai, and is intended to be the landmark gateway to development in the region. The project consists of twin 550 metre tall nominally identical towers with a 170 metre clear span bridge spanning between them over Emirates Road. One tower incorporates office, hotel and serviced apartments within it’s 100 levels, and the other tower incorporates mainly residential accommodation over it’s 100 levels. An image of the project is shown in Figure 17.

The critical path for the construction schedule of the project runs through the ‘fit out’ of the hotel, which is located at mid-height of one of the towers. The tower structural system thus had to achieve speed of erection upto tower mid height in order to minimize the overall project construction cost. The towers incorporate central RC cores and are designed to be built using high strength C80 concrete in a rapid self climbing jumpform system throughout the height of each tower. The perimeter structure of each tower upto mid-height and the whole bridge structure is designed to be fabricated in structural steel due to the need for rapid construction and the complex nature of the perimeter geometry below mid height. In general, the steel fabrication industry is better suited than the RC industry to take 3d engineering design models and create individual items in a controlled process which will bring a complex form to life in the field. This deliberate choice of delivery process was an essential factor in the design of the tower structural systems. Above mid height, the tower structure is no longer on the critical path, and it's design reverted to conventional RC floor and perimeter construction techniques to take advantage of these economies. Construction will begin in January 2008.

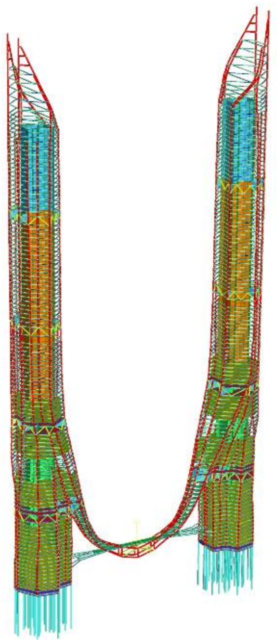

Figure 17. The 550m Tatweer Towers Dubai, 2008

Postcard Case Study – Dubai Towers, Doha

The Dubai Towers project in Doha is a 450 metre tall mixed use development situated on a prominent site on the Corniche in Doha. The tower incorporates hotel, serviced apartments, office and residential uses over it's 92 useable levels, which sit over a 5 level podium and 5 level basement. An image of the project is presented in Figure 18. The tower is of a very unusual and striking elevation and plan shape. In particular, the 'zed' shaped floor plan changes with height as the various parts of the 'zed' shaped plan drop off. The mixed use nature of the project posed special challenges in finding a layout and configuration of the core which imposed minimum penalty on the floor spaces throughout the tower, yet still provides separated lift cores for the various uses with height. The unusual plan shape was carefully studied in the wind tunnel to evaluate the torsional motion of the tower under low return period wind events.

The building has a central RC core constructed using a C80 high strength concrete in a conventional self climbing jumpform. The plan shape provides a large perimeter length per unit of floor space, so it was essential for the perimeter structure to be assembled from a minimum number of pieces in order to ensure overall speed of construction. The perimeter columns are large diameter concrete filled tubes spaced at 12m around the perimeter, and they support a simple steel edge beam. Precast floor planks are economic in Doha, and they are used to span from the core to the simple steel edge beam. The project is currently under construction on a 32 month programme.

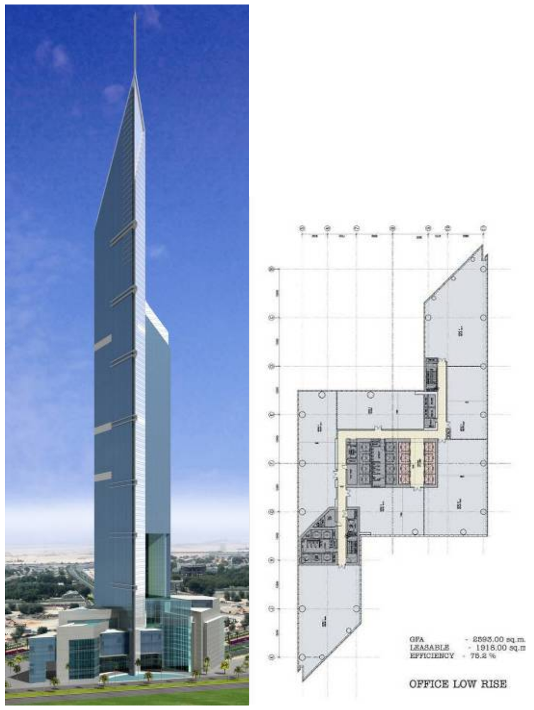

Figure 18. The 450m Dubai Towers Doha, 2007

Postcard Case Study – Al Quds Tower, Doha

The 500 metre Al Quds Tower project is located on a prominent site on the shores of West Bay in Doha. It is conceived as a mixed use project which incorporates hotel, serviced apartment, residential, office and observatory uses within it's 102 levels. An image of the project is presented in Figure 19. Arranging of the various lift sets which serve these individual uses posed a challenge to the core planning. An open architecture core arrangement was developed, which allows modules of lifts to be hung from a pair of intersecting shear walls which span the with of the building and form a simple and organized structural system which carries the majority of the building's gravitational and wind loading. Lift modules are added or deleted as required up the height of the tower to suit operational requirements. All vertical elements will be built using high strength C80 concrete and are incorporated into the self climbing jumpform for maximum speed of construction. The flat plate floors span 10 metres between walls and will be constructed using cast insitu RC with post tensioned reinforcement. Construction will begin in February 2008.

Figure 19. The 500m Al QudsTower, Doha, 2008

Conclusions

Mixed use towers are in favour in the rapidly developing Gulf region, often providing office, hotel, serviced apartment and residential accommodation all in a single building of over 100 levels. Postcard case studies of 5 such mixed use buildings in the 450m to 600m height range currently under design and/or construction in the Gulf by Hyder were used to illustrate the observations. The cores of these towers provide an organizational challenge in order to accommodate the vertical transport systems in the most elegant manner. Such arrangements are largely driven by the vertical stacking of the building uses. The choice of construction system for each building is now driven by minimum construction time due to the high and increasing rate of inflation in the construction industry in the Gulf. Construction systems involving mixed uses of steel and concrete are becoming increasingly common in order to reduce construction times.

As a final observation, it is clear that the demand for iconic super high rise buildings in the Gulf is being driven by a quest for identity and nationhood. These projects are as valuable to this quest as a grain of sand is to an oyster. As Engineers and Architects, it is a great privilege to participate in the act of Nation Building, as currently underway in the Gulf region. We thank the owners and Rulers for their trust in the science and craft of the tall building engineering community.