

Integrated Design: Everything Matters

The Development of Burj Dubai and The New Beijing Poly Plaza

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ABSTRACT

Architectural design and structural engineering have a symbiotic relationship: a close and essential union in which one heavily relies upon the other. In the ideal structure, the lines between science and aesthetic are blurred. By reviewing the development of Burj Dubai Tower and the cable wall of the New Beijing Poly Plaza, this paper will highlight examples of how the successful interplay between architects, structural engineers, MEP engineers and their various consultants influences the design process and ultimately, the structure as a whole. In particular, it will explore how a structural engineer approaches this essential collaboration which, in the best instances, results in situations where one cannot describe the structure without also describing the architecture, and the architecture without its structure.

BURJ DUBAI

THE STRUCTURE AND ITS PURPOSE

In the case of Burj Dubai, the building's architecture is derivative of its structural aspirations for height. Consequently, we cannot understand its form without first examining the structure's engineering; as in all cases, form is driven by function: the team of engineers and architects must first address the function of the building, as well as the needs of the client.

From the conceptual stage of the project as presented in competition, it has been intended that the Burj Dubai be the World's Tallest Building (Figure 1). While currently under construction, the structure has exponentially grown in height from Skidmore Owings & Merrill's originally submitted design at about 1,800 feet. The tower has reached over 160 stories, and while the final height of the building is "a well-guarded secret", the multi-use skyscraper will "comfortably" exceed the current record holder, the 509 m (1671 ft) tall Taipei 101. The 280,000 m² (3,000,000 ft²) reinforced concrete tower is utilized for retail, a Giorgio Armani Hotel, residential and office.



FIGURE 1 – RENDERING

HOW FUNCTION INFORMS DESIGN

The primary concern in the engineering of tall buildings is the effect of the wind on the building's structure. The profile of the Burj Dubai is the result of collaboration between SOM's architects and engineers to vary the shape of the building along its height, thereby minimizing wind forces on the building while keeping the structure simple and fostering constructability. Necessity aside, however, the basic Y-shaped plan is also good for the residential function of the building itself, as its wings allow for maximum outward views and inward natural light (Figure 2). The shape, or massing, of a tower is often viewed in architectural terms, but is the single most important structural design parameter in ultra-tall towers. The overall shape is an extremely efficient solution to the potentially conflicting structural requirements of a supertall residential tower. Starting from a slender top, the building spreads out as the gravity and wind forces accumulate. The tower shape is a graphical representation of the structural tall building problem. As a result, even though the global forces are large, the forces in the individual members are not. These ideas led to the structure's tripod foundation, while its twenty four major setbacks produce a spiraling reduction as it ascends in height.

Furthermore, Burj Dubai's architectural concept is also represented within its tri-axial geometry, as the building's location within the United Arab Emirates drove the inspiration behind its form. Architects aimed to incorporate the region's particular culture and history into its design, and were influenced by traditional Middle Eastern domes and pointed arches, as well as by spiral imagery within Middle Eastern architecture.

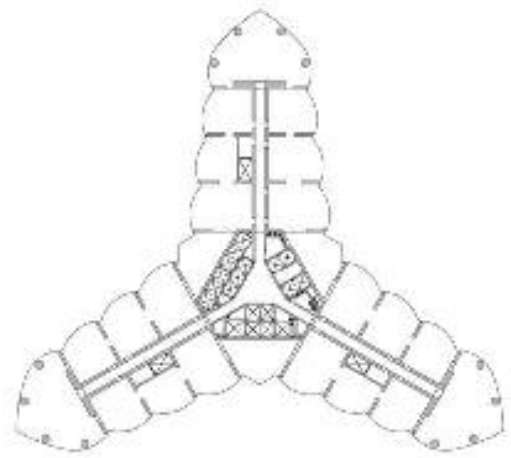


FIGURE 2 – TYPICAL FLOOR PLAN

BUTTRESSED CORE SYSTEM

SOM engineers describe their Y-shaped structure as a “buttressed” core system. As evidenced above, the buttressed core is where engineering necessity meets aesthetic inspiration. Simply put, Burj Dubai would not stand without it.

Within the buttressed core, each wing, equipped with its own high performance concrete corridor walls and perimeter columns, buttresses the others via a six-sided central core, or hexagonal hub. This hexagonal core is absolutely essential to the building's structure, as it acts as an axel and thereby prevents the building from twisting. From an architectural standpoint, this system also monopolizes on usable floor space, as the hub houses the structure's elevator banks.

It is easy to theorize the buttressed core as three slab buildings that are fused to form wings, so that one wing braces the others against the forces of wind. However, engineers stress that one must view the Burj Dubai as a lateral system; one in which a giant concrete beam cantilevers out of the ground so that the system works together as a single unit. Every piece of vertical concrete (and thereby every gravitational force) is part of this giant beam, used to resist the wind. The gravitational load then helps stabilize the structure by utilizing the weight of the building to resist the wind. Because gravity is an invariable constant, it's nature's best inhibitor in resisting wind's overturning loads.

ESCALATING HEIGHTS, HARNESSING NATURE

The modular, Y-shaped structure, with setbacks along each of the three wings, was part of the original concept design entered in an invited design competition at the beginning of the project. It was immediately apparent that for a building of this height and slenderness, wind forces and the resulting motions in the upper levels, would become dominant factors in the structural design of the Burj Dubai. Over several months, the SOM team would refine the tower's shape with extensive wind tunnel tests (Figure 3). These studies were undertaken under the direction of Dr. Peter Irwin of Rowan Williams Davies and Irwin Inc.'s (RWDI) boundary layer wind tunnels in Guelph, Ontario. The wind tunnel program included rigid-model force balance tests, full multi-degree of freedom aeroelastic model studies, measurements of localized pressures, pedestrian wind environment studies, and wind climatic studies. Through these tests, the team determined the harmonic frequency of wind gusts and eddies under various wind conditions. This information was used to set targets for the building's natural frequencies, thereby "tuning" it to minimize the effects of the wind.

As a very tall tower, Burj Dubai requires a wide footprint to provide sufficient stability to resist high wind loads. This footprint, along with the buttressed core structural system, allowed the architects to continually adjust their design to allow for unprecedented heights.

Several rounds of force balance tests were undertaken as the geometry of the tower evolved and was refined architecturally. Initially, the tower setbacks occurred in a spiraling counter-clockwise manner, then the setbacks' direction was reversed to a clockwise direction and the shape of the individual setbacks were refined. After each round of wind tunnel testing, the data were analyzed and the building was reshaped to minimize wind effects and accommodate unrelated changes in the client's program. In general, the number and spacing of the setbacks changed as did the shape of wings. This process resulted in a substantial reduction in wind forces on the tower by 'confusing' the wind, in effect, encouraging disorganized vortex shedding over the height of the tower (Figure 4). The mullions that hold the glazing act as 'fins' around the perimeter of the building. These fins, similar to the dimpled surface of a golf ball, create surface turbulence and reduce the lateral drag forces on the building. Based on a separate set of sectional wind tunnel tests, blades were added to the pipe at the top of the spire. This simple move greatly reduces the wind forces on the spire due to vortex shedding.



FIGURE 3 – WIND TUNNEL TESTING

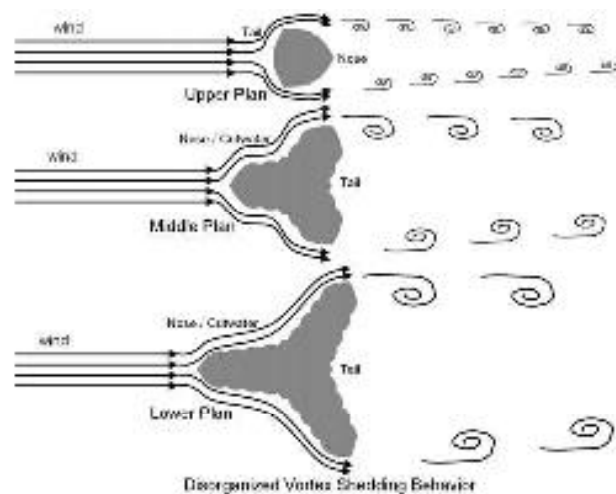


FIGURE 4 – WIND BEHAVIOR

THE SWISS WATCH PART I: DESIGNING THE CENTRAL CORE AND CORRIDORS

Like a Swiss watch, the components of a supertall building must precisely and efficiently fit, arranged so as to maximize the usefulness of the interior space as well as the efficiency of the structural and building services systems. The central hexagonal core and corridors of the Burj Dubai went through a long and difficult process of design and coordination so as to achieve this machine-like precision. The central core is not only the hub of the structural system, but of the building itself. In addition to performing a vital structural function, it also houses the building vertical transportation as well as all building services closets and express risers. As such, its size and geometry needed to be sufficient to perform these tasks, while still being respectful of the usage of the surrounding interior space. Given the Y-shaped floor plate, a hexagonal core arrangement proved to be the optimum design (Figure 5). This geometry allowed for creating three zones of space within the core, while complimenting the spatial requirements for the adjacent residences, guest rooms, and offices. The three zones of space within the core were formed by secondary reinforced concrete wall elements, aligned with the axes of the three Tower wings. Located within these zones are elevators, stairs, vestibules, lobbies, and building services closets. The final layout of spaces within the core as well as the geometry of its perimeter and interior core walls were arrived at after several permutations, including some earlier versions which located some functions outside of the core (Figure 6). The interior face of the perimeter hexagonal core wall was kept constant throughout the height of the Tower, as was the thickness of the interior core walls, so as to standardize the design of the interior core spaces.

Just as important to the success of the Tower as the refinement of the central core was the arrangement of the corridors in each of the three wings. It is necessary to have a pair of walls extending from the core to the end of the wing, to broaden the Tower's structural footprint and buttress the core. These walls were originally located so as to align with the core perimeter walls (Figure 6). This alignment allowed for a smooth transition between the core and corridor walls, in both load flow and reinforcement detailing. However, this alignment also placed the corridor walls within the middle of the floor plate, intersecting the interior space and essentially dividing each unit or guest room. The first architectural floor plans of the residential and hotel floors placed bathroom and closet spaces within this intersected space, which provided a workable if not



FIGURE 5 – TYPICAL CORE

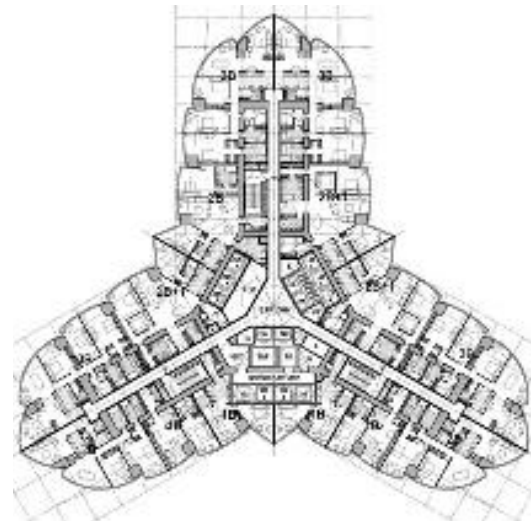


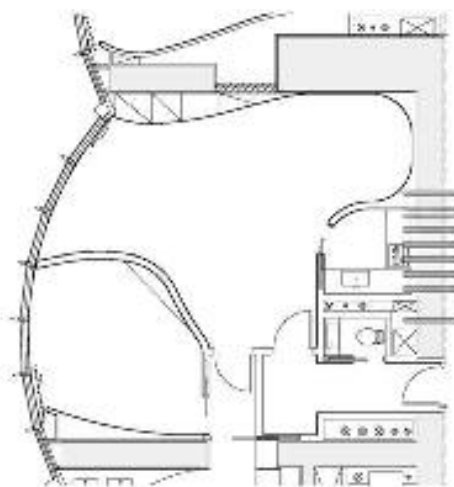
FIGURE 6 – EARLY FLOOR PLAN

ideal solution. However, the presence of these walls severely limited the flexibility of the layout of the individual units and guest rooms. A better solution was to locate these walls so as to form the faces of the corridor, allowing much more flexibility for space planning. The structural concern for this location was related to the intersection of these walls with the central core; however, aligning the corridor walls with the core interior walls solved issues relating to force transfer and detailing. Additionally, locating these walls at the corridor instead of mid-unit created too long a span for the flat plate structure; this was solved by providing “nib” walls perpendicular to the corridor walls, which aligned with the perimeter columns. The presence of these nib walls had a minor effect upon flexibility of the interior spaces, as their module was selected so as to match the preferred module for demising partitions for the residential units and hotel guest rooms.

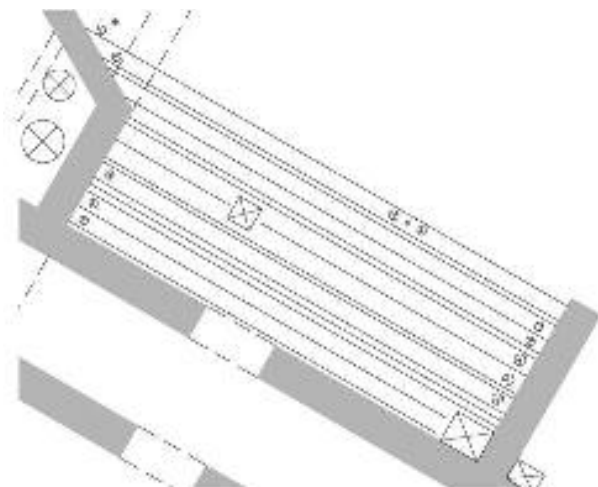
THE SWISS WATCH PART II: COORDINATION AND BUILDERS WORKS

Determining the location of the primary structural elements and the layout of the architectural interior spaces and functions was only part of the exercise required to fine tune the building. The next step was to integrate all of the building services requirements. There were two primary factors which drove this effort: the need to minimize the ceiling sandwich so as to maximize the number of floors, and the thickness of the core and corridor walls and the density of the concrete utilized. The need to minimize the ceiling sandwich meant that services needed to be routed through, not below structural elements; otherwise, the building would have to grow in height to house the same area, or sacrifice area to maintain overall height. The thickness and density of the concrete walls meant that coring the structure after its construction would not be practical, thus requiring the horizontal distribution of the building services to be laid out in detail during the design process. This effort resulted in the coordination of over 25,000 wall penetrations and over 100,000 slab penetrations.

As such, it was very important to develop a strategy early in the coordination process for the routing of the building services, particularly those services that were being distributed to each floor from the closets contained within the central core: domestic water supply, fire protection, electrical, and information technology. Services left the core via the corridors, then penetrated the corridor walls to access the units and guest rooms. Penetrations were provided within the



WALL VS. SLAB PENETRATIONS

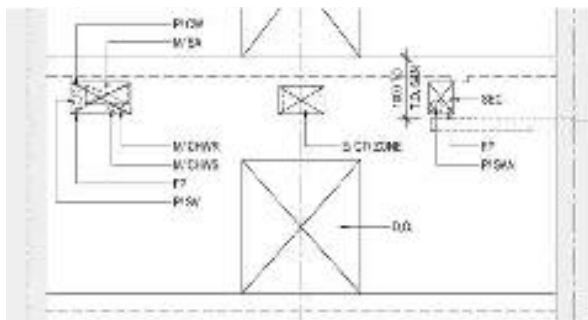


PENETRATIONS AND REINFORCEMENT LAYOUT

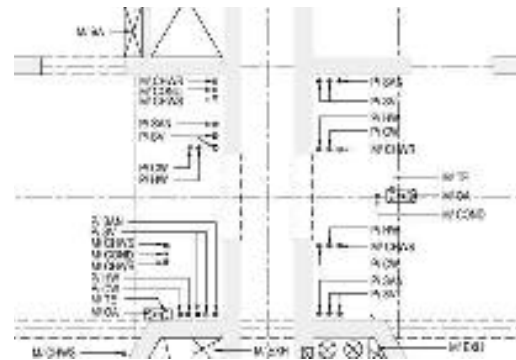
FIGURE 7 – LAYOUT OF BUILDING SERVICES PENETRATIONS

hexagonal core link beams so as to accommodate these services. Doors were present at these locations to separate the core from the main floor so as to better control stack effect issues; this also provided an opportunity to run some of the services below the link beams. From this location, the services ran down the corridor, turning to enter the residences and guest rooms by penetrating the corridor walls. A series of five penetrations were provided at each bay for this purpose: two utilized for plumbing requirements, and one each for fire protection, electrical, and information technology. No penetrations were allowed within the corridor wall link beams. Careful consideration was given as to the location of these penetrations within the corridor walls; they must not conflict with the location of vertical services risers on the other side of the wall, nor enter the residence or guest room in a zone where high ceilings are planned (Figure 7). Similarly, an additional effort was made when locating the interior vertical services so that they not only avoided the incoming horizontal services, but also were arranged in plan so as to minimize the amount of reinforcement interrupted by their placement (Figure 7).

An additional level of refinement of this coordination was required for the first 40 stories of the building. The main superstructure contractor was not brought into the project until after the foundations had been built. As such, there was not much time to complete the detailed dimensional coordination of the building services that would normally be performed by the contractor. The Owner asked SOM to produce detailed Builders Works drawings that could be used by the contractor immediately once on board. These drawings were intended to be utilized as a supplement to augment the Construction Documentation drawings, by providing a blueprint for locating all of the building services' horizontal and vertical distribution through the structural walls and slabs. Accordingly, the scope and detail of these Builders Works drawings went well beyond what typical Construction Documentation type drawings would provide. Every individual wall and slab penetration, no matter how small, was labeled as to which service was going through, in both plan and elevation (Figure 8). This effort was coupled with a concerted effort to precisely dimension and locate each penetration on the structural drawings. The result was a set of drawings which provided a significant jump-start for the contractor, as well as a confirmation of the viability of the coordination strategies implemented by the design team.



BUILDERS WORKS ELEVATION



BUILDERS WORKS PLAN

FIGURE 8 – BUILDERS WORKS DRAWINGS

THE NEW BEIJING POLY PLAZA

The client's goal was for a new headquarters building that represents the company's disparate subsidiaries as a unified whole. The program for the building contains a wide range of spaces including office, retail, restaurants and the Poly Museum. The museum, established by one of the company's subsidiaries, has the unique purpose of repatriating China's cultural antiquities through purchases at international auctions. The site's primary orientation is northeast towards the intersection and beyond to the client's existing headquarters building. The triangular form minimizes the perimeter length exposed to the elements, while a series of interior atriums provide additional interior surface area to give office areas maximum access to daylight. The result is a simple 'L' shaped office plan that cradles a large atrium (Figure 9). The exterior walls of the atrium are comprised of minimal glass membranes supported on two-way cable nets in order to maximize visual and solar transparency.

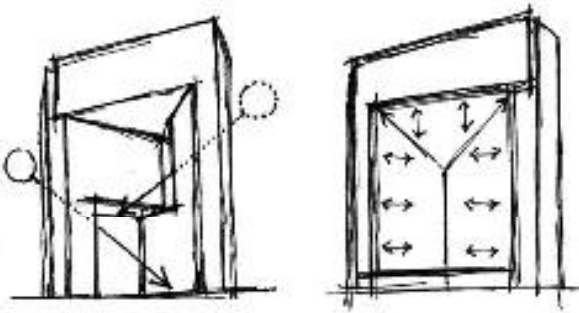


FIGURE 9 - ATRIUM CONCEPTS

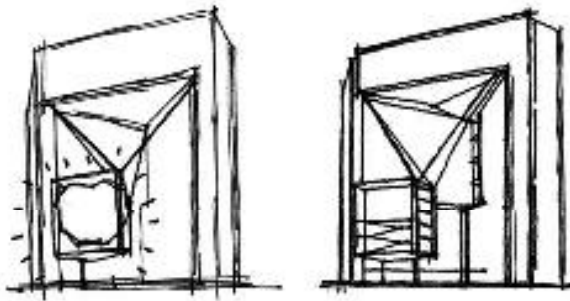


FIGURE 10 - THE 'MUSEUM LANTERN'



FIGURE 11 - NORTHEAST RENDERING

The Poly Museum is suspended within a 'Lantern' in the main atrium space (Figure 10). Its crystalline surface of laminated patterned glass is pleated to increase its light reflecting/refracting qualities (Figure 11). Inside the 'Lantern', exhibit and lease spaces are enclosed by wood walls which control daylight while common circulation areas occupy the void between the solids and the glazed perimeter walls. Secondary 'Sunset' and 'All-Day' atriums cut through the west (Figure 12) and south (Figure 13) legs of the 'L' to act as daylight chambers for bringing direct sunlight into the main atrium. The exterior walls of these atriums are comprised of minimal glass membranes supported by two way cable nets in order to maximize visual and solar transparency. The main atrium's cable-net is stiffened by two 'V'-cables that are in turn counterweighted and kept in tension by the self-weight of the suspended 'Museum Lantern'.

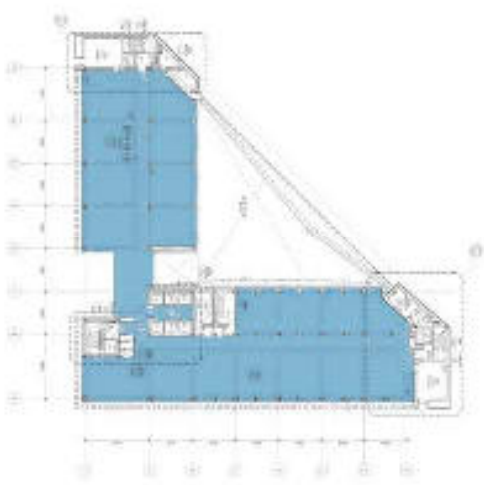


FIGURE 12 - TYPICAL HIGH-RISE PLAN

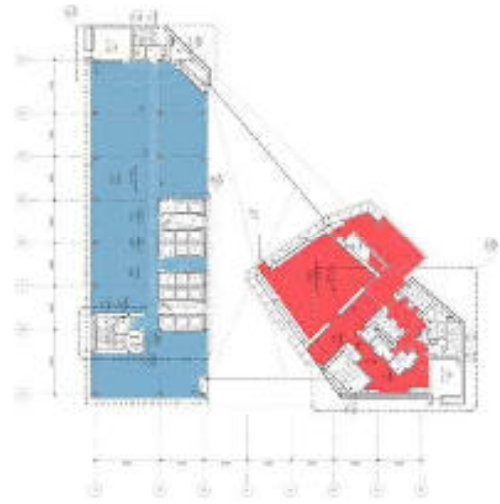


FIGURE 13 - TYPICAL LOW-RISE PLAN

THE CABLE-NET WALL

The New Beijing Poly Plaza project includes a 90 meter-tall atrium enclosed by a cable-net glass wall, 90 meters high by 60 meters wide. The scale of this wall greatly exceeds that which has been built before, introducing specific challenges that are not critical in smaller walls. SOM's preliminary analysis showed that the cable-net spans were too large to be economically achieved using a simple two-way cable-net design. SOM determined however that the cable-net could be achieved by subdividing the large cable-net area into three smaller zones by folding the cable-net into a faceted surface, and introducing a relatively stiff element along the fold lines. The faceted cable-net solution allows the individual sections of the cable-net to span to a virtual boundary condition at the fold line, effectively shortening the spans. Rather than introduce a major beam or truss element to stiffen the fold line, a large diameter cable under significant pre-tension is used. The final design solution was achieved with the largest of the four primary cables 275mm in diameter and consisting of a parallel strand bundle of 199 individual 15.2mm diameter 1x7 strands. The largest cable is pre-tensioned to 17,000kN, and experiences a maximum in service loading of 18,300kN during a 100 year wind event. Using the faceted design solution, the typical horizontal and vertical cables are limited in diameter to 34mm and 26mm, pre-tensioned to 210kN and 100kN respectively. Horizontal and vertical cables are spaced at 1333mm and 1375mm on center respectively.

THE ROCKER MECHANISM

The four primary diagonal cables which support the self-weight of the lantern connect diagonally from the roof of the 'museum lantern' at level 11, to the top of the atrium at level 23. As the base building structure will drift under anticipated seismic loads, the cables will act as braces and attempt to resist the base building drift unless the force levels in the cables are limited in some manner. Designing the primary diagonal cables to resist these brace forces while maintaining an appropriate factor of safety would have significantly increased the primary diagonal cable sizes that as employed in the final design solution. This would also have resulted in the initial level of pre-tension in the primary diagonal cables being a lower portion of the cable breaking strength,

to accommodate the additional brace demands. Pre-tensioned cable systems typically rely on a high initial level of pre-tension to maintain the desired architectural form in the permanent load condition. When cable systems are installed with only a nominal level of initial pre-tension, the tendency of that system to exhibit significant deflections due to the self-weight of the cables is greatly increased. Therefore, it was determined that the design solution required that the primary diagonal cables (the only cables that may act as braces) be decoupled from the lateral system of the base building structure.

The connection between the primary diagonal cables and the roof of the lantern is complicated by the need to decouple the primary cables from the lateral system of the base building structure, and to simultaneously provide a flexible wall system which allows the relative lateral movements between the roof of the lantern and the roof of the building to be incrementally accommodated over the height of the cable-net. Several connection concepts were evaluated before the final design solution was determined. One option connected the main cables to the lantern roof through a sliding connection (Figure 14). This solution was difficult to achieve due to the resulting eccentric load path of the very large primary cable forces through the eccentric connection when the connection was displaced. It also resulted in the upper half of the cable-net moving with the roof of the building, and one course of glass at the roof of the 'lantern' being required to accommodate the full drift between the roof of the building and the roof of the 'lantern'. This resulted in this course of glass likely to fail given any significant lateral displacement of the building, causing a safety hazard in the atrium and street below. A second concept connected the bottom of the 'V' cables to the top of the lantern through a 4m tall, pin-ended' link element (Figure 15). This solved the load eccentricity issue, but still resulted in the relative lateral drift of the upper half of the cable-net being concentrated in a small portion of the wall. This solution also induced tension in the main cables as the building drifts due to the downward movement of the lowest point of the cables caused by the rotation of the link around its base. The concentration of a significant portion of the lateral drift of the building in a 4m high zone still resulted in the high likelihood that glass panels would be lost during the design level lateral drift event, representing an unacceptable risk to the occupants of the building and adjacent outdoor spaces.

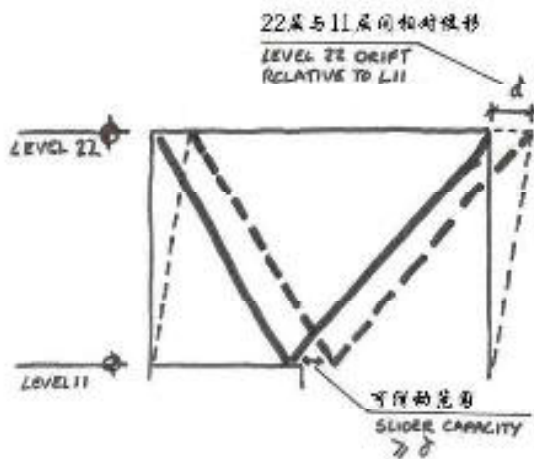


FIGURE 14 - SLIDER CONNECTION CONCEPT

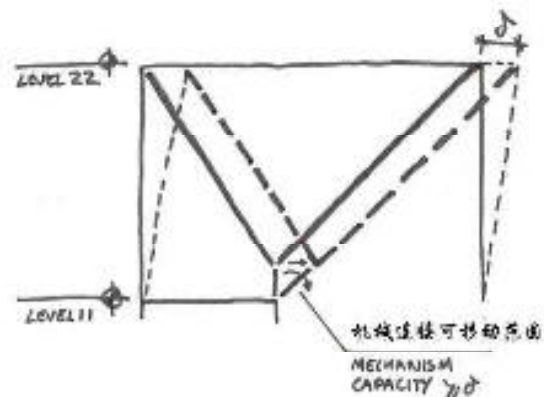


FIGURE 15 - LINK CONNECTION CONCEPT

The final solution is shown diagrammatically in Figure 16. The decoupling mechanism is the equivalent of a pulley at the lower point of the 'V' cables. As the overall building drifts, one half of the 'V' tries to lengthen and the other half tries to shorten. By connecting them together using a pulley or equivalent mechanism, the strains are able to offset each other, without inducing additional load in the cables. A cast steel 'rocker mechanism' was designed to perform the equivalent function of the pulley. By crossing the cables and connecting to the rocker casting arms, the need to provide curved pulley surfaces and curved sections of the main cable were eliminated (Figure 17).

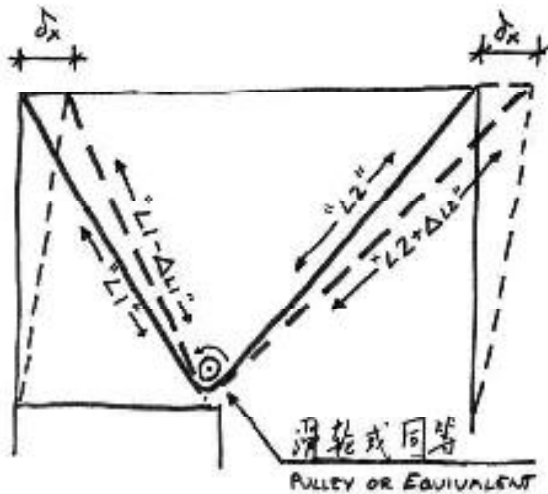


FIGURE 16 - PULLEY EQUIVALENT CONCEPT



FIGURE 17 - THE 'ROCKER MECHANISM'

The effectiveness of the design solution was evaluated by constructing a physical model of the 'rocker mechanism' along with a model of the 'link' concept for reference comparison. The models were installed in a pin-connected frame, with soft springs installed in series with the diagonal cables. By racking the frame backwards and forwards, the relative effectiveness of the two concepts could be visually evaluated. Significant extension of the springs in the 'link' model and negligible extension in the 'rocker mechanism' model, highlighted the ability of this connection to decouple the main cables from the base building lateral system.

CONCLUSION: EVERYTHING MATTERS

The two projects discussed in this paper highlight two different scenarios whereby the integration of the architectural and structural engineering design process has had a direct and significant impact on the final architectural expressions. While the Burj Dubai represents a pure architectural form that was derived from the structural solution to Client's aspiration for height, the New Beijing Poly Plaza cable-net was an initial architectural idea that created specific engineering challenges, the solutions of which were embraced as the architectural focus of the building. Both projects are successful examples of the collaborative working relationship between architects and engineers that results in buildings that can be understood and appreciated by the casual visitor. These are examples of the best instances of the creative process - design where everything matters.