King Abdulaziz International Airport

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ABSTRACT

The expansion of the King Abdulaziz International Airport in Jeddah, Saudi Arabia, includes a 670,000 m^2 new terminal building with a footprint of 1x1.4 km, a 135 m air traffic control tower, tallest in the world, and a number of other auxiliary support buildings. The slabs are designed as reinforced concrete structures, whereas the roofs are steel structures. For the concrete structures, the number of movement joints was minimized, reaching slab lengths up to 290 meters in suspended slabs, and a total joint-less length of 1 km in the Ground Floor slab. The span of the main steel roof reached lengths of 70 meters using 3d space frames that were optimized using parametrical scripting tools.

KEYWORDS: Airport, thermal, shrinkage, optimization, BIM, space-frame, scripting.

1. Introduction

King Abdulaziz International Airport (KAIA) in Jeddah, Saudi Arabia, opened in 1981 and became increasingly strained by the rapid growth in commercial and tourist passenger numbers consequent on Saudi Arabia’s continued prosperity. In 2006, it saw the start of a comprehensive redevelopment programme, including a new terminal. Dedicated experience, innovation and skills contributed to solving the structural engineering design challenges of the new 670 000m^2 international Passenger Terminal Building (PTB), designed to handle over 30M passengers per year.

The 1.4km long facility will house 46 Domestic and International departure gates, 94 boarding bridges, Processor Hall, International departures Hub, internal automated people mover (APM), the world’s tallest air traffic control tower, and over 60km of baggage handling belts.

The owner, the General Authority of Civil Aviation of Saudi Arabia (GACA), originally let the project with a design team led by French airport designer Aéroports de Paris Ingénierie. At the end of the schematic design stage, however, GACA instituted a design–build bid and issued these schematic design drawings as tender documents.

The construction-winning company, Saudi Binladin Group (SBG), hired Arup to carry out the structural design for the main PTB and several ancillary buildings, including the air traffic control tower, as the project’s structural engineer. For all the remaining design work, Atkins was appointed as lead design consultant.

Figure 1. Original rendering of the project.

2. Design Management

To best handle the project, the PTB was divided into eight zones:

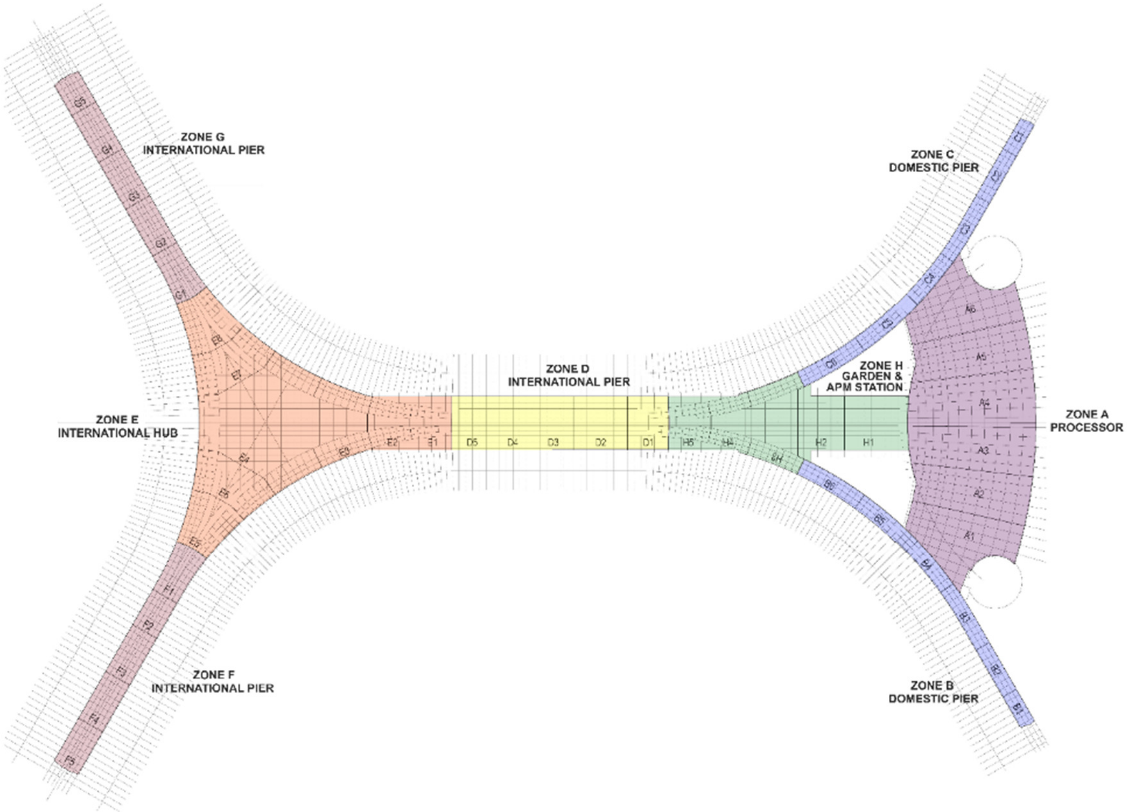

Figure 2. Plan of Pasenger Terminal Building (PTB) showing its zones.

The scale, diversity, and aggressive design schedule meant that no single Arup office could undertake all the work within the timeframe, so it was decided to divide the work between the New York/New Jersey, Boston, Chicago, San Francisco, Toronto, Madrid, Belgrade and Dubai offices.

3. Reinforced Concrete Podium Structures

The structural system comprised RC shear walls laterally, with all but the Processor Hall using cast in situ beams on the column lines with two-way spanning slabs. Due to the large column spans in the Processor Hall (typically 13m x 18m), a one-way ribbed system was used instead, to control defections and reduce concrete volume.

Because of the existing high water table and the possibility of future food levels >2m above the highest water table, as determined by the geotechnical engineer, the PTB basement was designed as a jointless subgrade structure. With a 1.4km long subgrade and nearly 2km length of suspended ground level slab and mat slab, the basement was prone to significant thermal, creep, and shrinkage stresses.

Left unchecked, these could seriously jeopardise the facility's watertightness, and so the mat was cast with late pour strips at 60m spacing. These extended through the mat foundation below grade, up through the basement retaining walls, and through the ground level slab. The strips remained uncast until whichever was later: 90 days after placing the adjacent mat foundation and basement walls, or 45 days after placing the suspended ground level slabs.

With the nearby Red Sea's severe environmental conditions in mind, the concrete design strictly adhered to ACI (American Concrete Institute) guidelines [1] to ensure enhanced durability.

3.1. Concourse Piers podium

Design of the superstructure began with the Concourse Piers (Zones B, C, D, F and G). These had the benefit of a highly repetitive building geometry but correspondingly challenging unique wall layouts between the movement joints which, at 54m, 72m and 90m spacings, created a total of 27 independent segments within the Concourse Piers and 46 in all throughout the PTB

The design criteria assumed a range of ±30℃ for the roof and non-insulated spaces, ±20℃ for insulated spaces not on grade, and ±15℃ for foundations and basement walls in direct contact with the ground. This could severely impact the concrete shear wall design, so more advanced analysis was needed to show these demands to be overly conservative, and never actually experienced by the structure. In this regard, rigid base conditions at the bottom of the shear walls were replaced with a fully modelled mat foundation to accurately represent its actual stiffness. Also, frictional soil stiffness was modelled as horizontal soil springs along the mat surface, with vertical soil springs introduced to more accurately represent the rotational restraint at the base of the core walls and linear shear walls. Additionally, reduced flexural and axial inertias were used, to account for the loss stiffness induced by cracking.

3.2. International Hub podium

For the International Hub (Zone E) podium design RC shear walls supply lateral resistance, and the floor framing is typically two-way fat slabs between beams on the column lines. Seven of its segments resembled those of the Concourse Piers, but the central eighth segment was more complex, due to its interaction with the central dish of the roof above. This roof imposed a lateral thrust onto the level 2 concrete slab from a series of sloped A-frame columns. The imposed forces resolve through the centre of the ring, counteracting those from the opposite A-frame.

These opposing forces required at the Hub centre a jointless segment with a maximum width of 225m east–west.

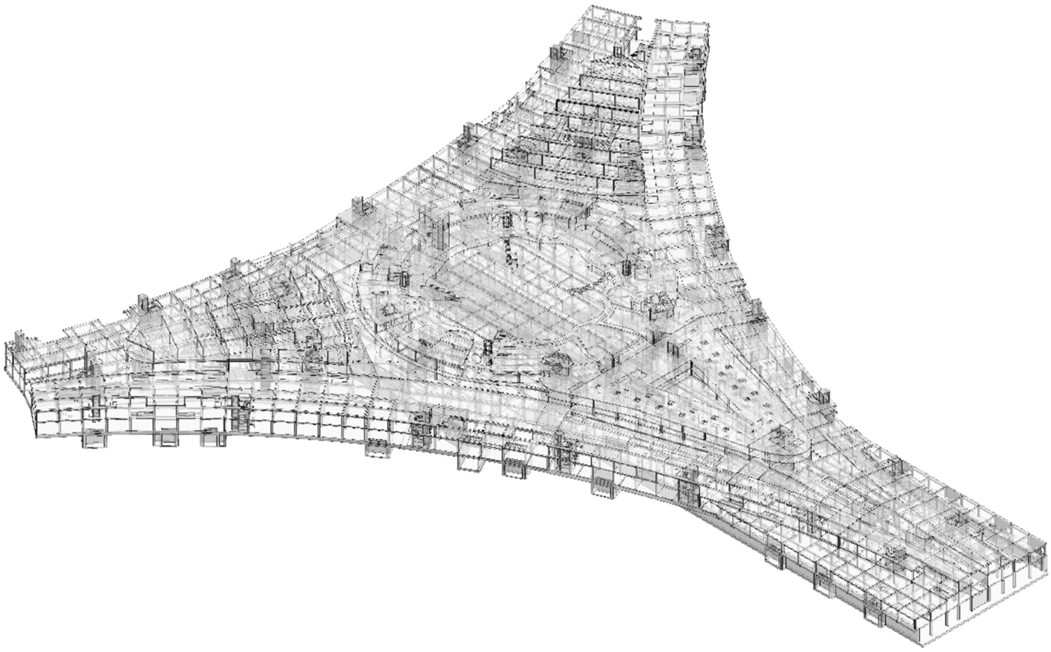

Figure 3. Reinforced concrete structure for the International Hub (PTB Zone E).

As well as the design challenges related to the landing of the A-frame roof columns, this central segment had to be redesigned to accommodate new retail, restaurant and plant areas not in the original concept. The area was especially critical for co-ordination as it is at the intersection of three grid systems: the central north–south spine Piers, the east and west International Piers (intersecting at 120˚ angles with the north–south) including curved transition grid lines, and the radial grid of the dining and shopping areas.

The transfer solutions at this intersection of grid systems thus needed to be redesigned and coordinated very rapidly, most of this happening while the foundations were being built. The construction/design overlap needed considerable engineering judgment on contingencies for loading allowances.

3.3. Processor podium

The Processor (Zone A) podium design is a modified version of that for the Concourse Piers and International Hub, but its large column spacing justified a one-way ribbed system in lieu of the much heavier two-way fat slab system in the original Aeroports de Paris Ingénierie schematic design. The system has 400mm wide x 0.8m deep ribs at 1.8m centers supported on 2.0m wide x 0.8m deep beams on the column lines.

The Processor’s lateral system also required special consideration because of the size of the floor plates and the jointing of the roof, the stability of which relies on pairs of quadripod trees to engage the flexural stiffness as a portal frame, so that each of the three roof segments spans east–west across podium movement joints.

3.4. Garden and APM Station

In the Garden and APM station (Zone H), a different solution at ground level was needed to accommodate the juxtaposition of the radial column grid from the curved Concourses above with the rectilinear column grid in the basement below; a thick transfer slab was used to handle the resulting two-way transfers.

The southernmost is the largest unjointed segment in the entire PTB, some 290m x 110m, with the lateral system carefully positioned and oriented to avoid locked-in stresses due to thermal loads.

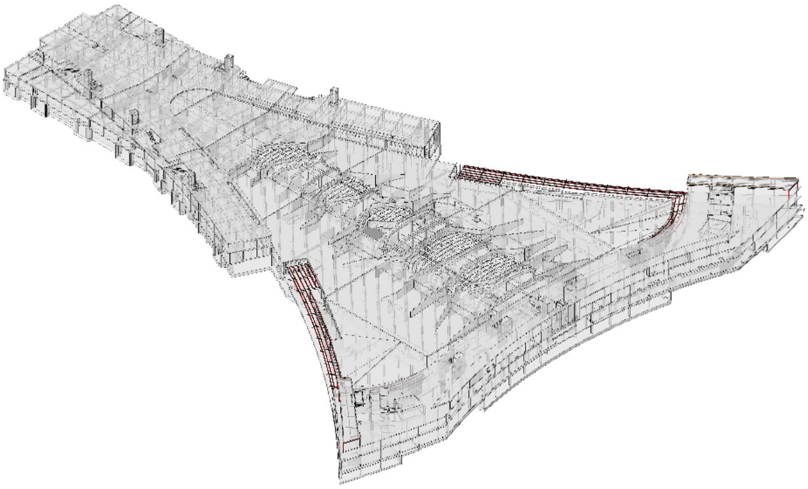

Figure 4. Reinforced concrete structure for the garden and APM station (PTB Zone H).

The garden and APM station feature the only portion of the roof that includes concrete. A green roof garden above level 1 supports heavy plantings and tall trees in addition to topping build-ups up to 4m above the slab.

The APM station is partly embedded in the garden with arched concrete beams and slabs creating the vaulted space for the tracks and station. The arched roof and walls are penetrated by irregular glazed skylights that introduce daylight and give views of the garden to waiting pedestrians.

4. The Structural Steel Roofs

The International Hub and Processor roofs have a combined plan area of over 90 000m^2; both are constructed as integrated systems of conventional steelwork and customised space frame systems, whereas the Concourse Pier roofs are framed with conventional structural steel beams, girders, and planer trusses.

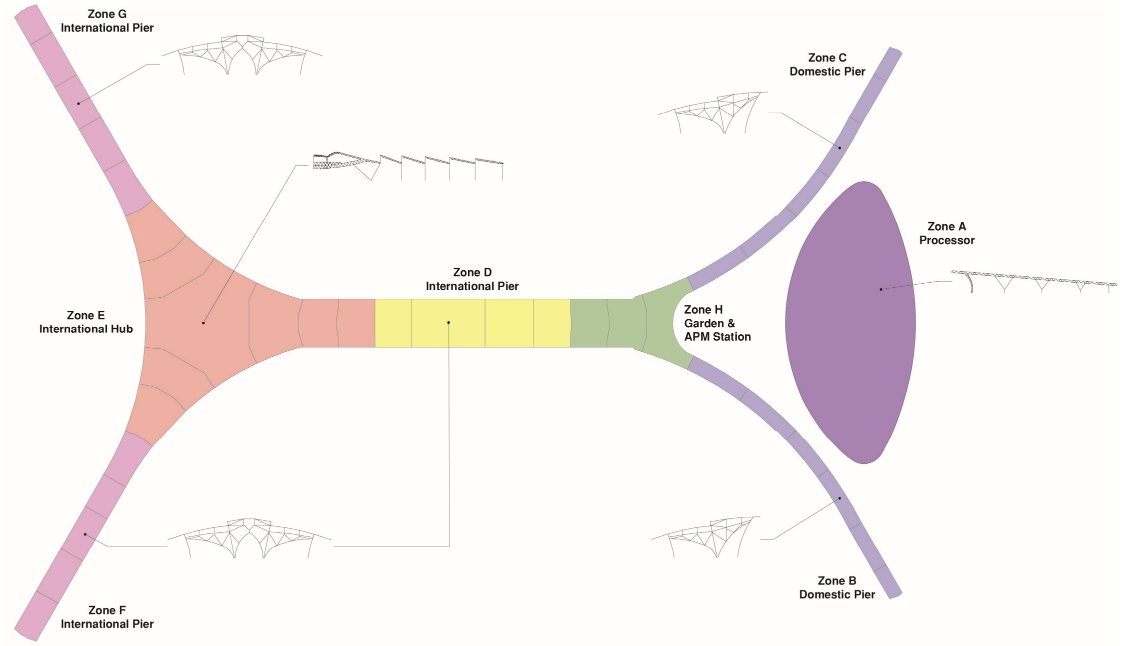

Figure 5. Various roof profiles for the Processor, Hub and Concourses.

4.1. The space frame design

Geometry scripting tools were developed using Grasshopper and manual Rhino methods to design the process of establishing base geometries for the best modular arrangement. The team created script routines to automate the iterative analysis and design procedure. Each design pass required no fewer than four iterations of element dimensioning and re-analysis, as both the loads and stiffness (and thus internal force distribution) changed significantly whenever even a small percentage of the elements changed size.

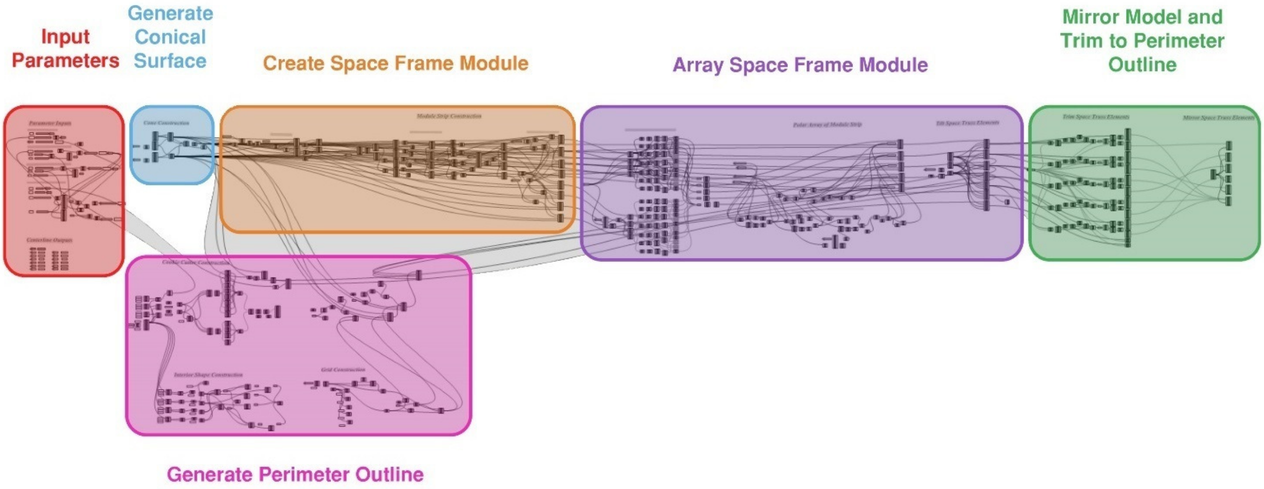

Figure 6. Processor roof geometry generator.

After understanding and dimensioning a series of typical connections, the behaviour of the node connections were modelled in LS-DYNA to better understand and quantify the relationship between fixity, stiffness, bending capacity, and axial capacity.

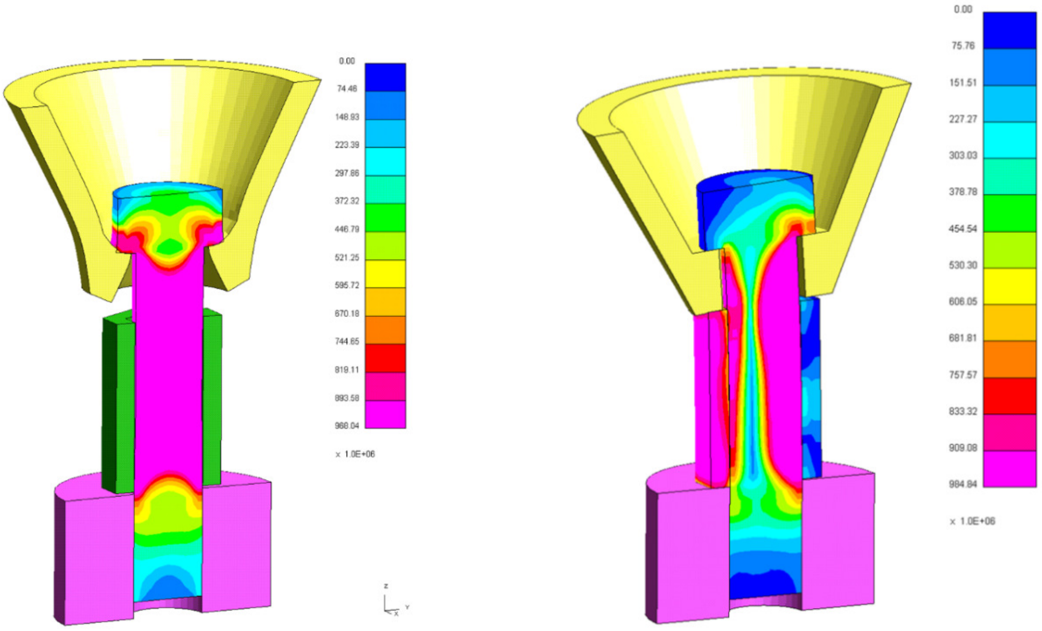

Figure 7. Non linear analysis images of the stresses within the bolt under two expected loading conditions a) direct tension loading parallel to the axis of the bolt; b) rotational loading, effectively putting the bolt into bending.

4.2. International Hub roof design

This “starfish” of unlikely proportions measures 300m tip-to-tip. Its central rotunda, which became known as the “lens”, is 120m across, with the starfish legs dubbed the “gills” due to their scalloped shape.

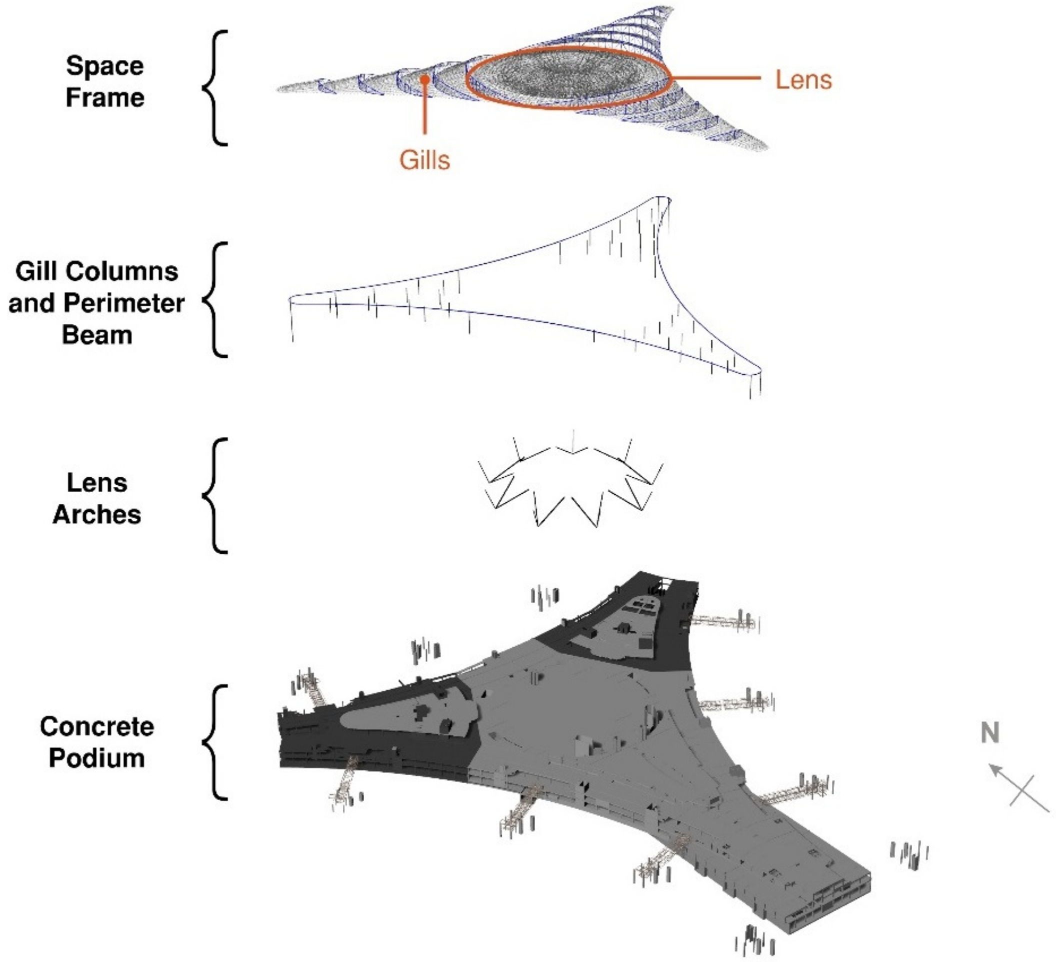

Figure 8. Components of the International Hub roof “lens” and “gills”.

The roof is a single unjointed structure, built from a close integration of light filigree space frame components and contrasting large-diameter curved steel tubes. Both systems resist gravity and lateral loads, with the space frame restraining the long, large tubes and the tubes defining the free edges of the space frame. The tubes likewise provide traditional touch-points for the adjoining façades.

Stability is provided by nine great arches arranged around the lens that lean in towards the center. These reach directly into the space frame itself, with each leg touching 13 space frame elements through a single 350mm diameter spherical connection node.

4.3. Processor roof design

The Processor’s 66 300m^2 space frame roof is supported by vertical columns along the north, east, and west façades; by curved “banana” trusses along the southern façade; and by the series of interior quadripod trees.

The Processor’s podium structure is divided into six segments by fve north–south oriented movement joints, while the roof’s three segments have two movement joints. Occasional pin-ended vertical steel struts within the depth of the roof along the joints serve as shear links between adjoining roof segments, preventing vertical slip along the joints while enabling the roof segments to translate laterally relative to each other.

This misalignment of the podium and roof movement joints necessitated much analysis of all permutations of relative podium and roof displacements, to quantify the internal force effects developing from differential movements between the two systems.

The Processor space frame is 2.5m deep, with top and bottom layers of circular hollow sections arranged on a plan grid of about 3m x 3m. Circular hollow sections likewise connect the top and bottom layers of the space frame to complete the system.

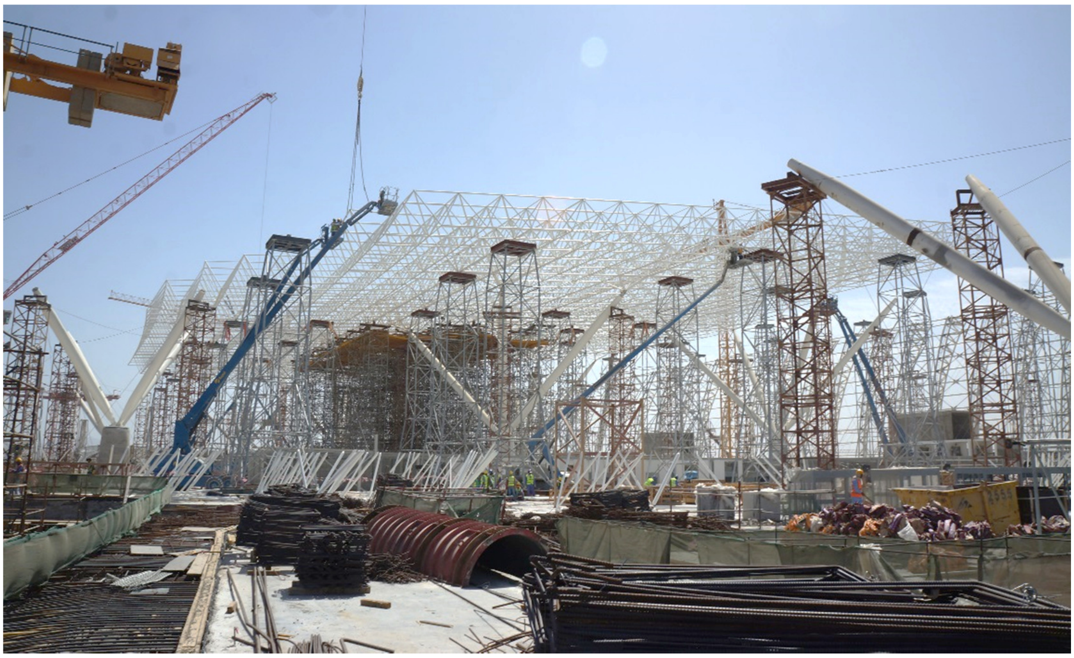

Figure 9. Processor, construction of the space frame.

4.4. Concourse Pier Roof Design

The seven Concourse Piers cover more than 130 000m^2, with their roofs extending for a total of 3.2km. This vast expanse required an economical and repetitive structural system capable of simplifying the construction process.

The original structural design employed a bi-directional truss system with transverse primary trusses and longitudinal secondary trusses. These trusses contained many pieces, which would have complicated erection and impeded building service runs. It was proposed a revised scheme that simplified the system considerably. Trusses were used within the natural depth created by the clerestory only, and made to span 18m between interior supports or “cranes”, with all secondary members changed to rolled beam sections.

Each crane structure has at least two locations where three curving, tubular columns meet. In the original design, these came together at non-coincident workpoints, but due to architectural space constraints, were modified to converge to single coincident workpoints.

The original connection could have been easily fabricated from three separate pieces, cut, and then shop-welded, but as it proved impossible for the fabricator to maintain the required high level of architectural finish once the three pipes were made to converge, it was decided to cast these particular connections which required also non-linear modelling and analysis.

The more conventional framing of the Pier roofs used an automated optimisation routine to maximise structural design efficiency.

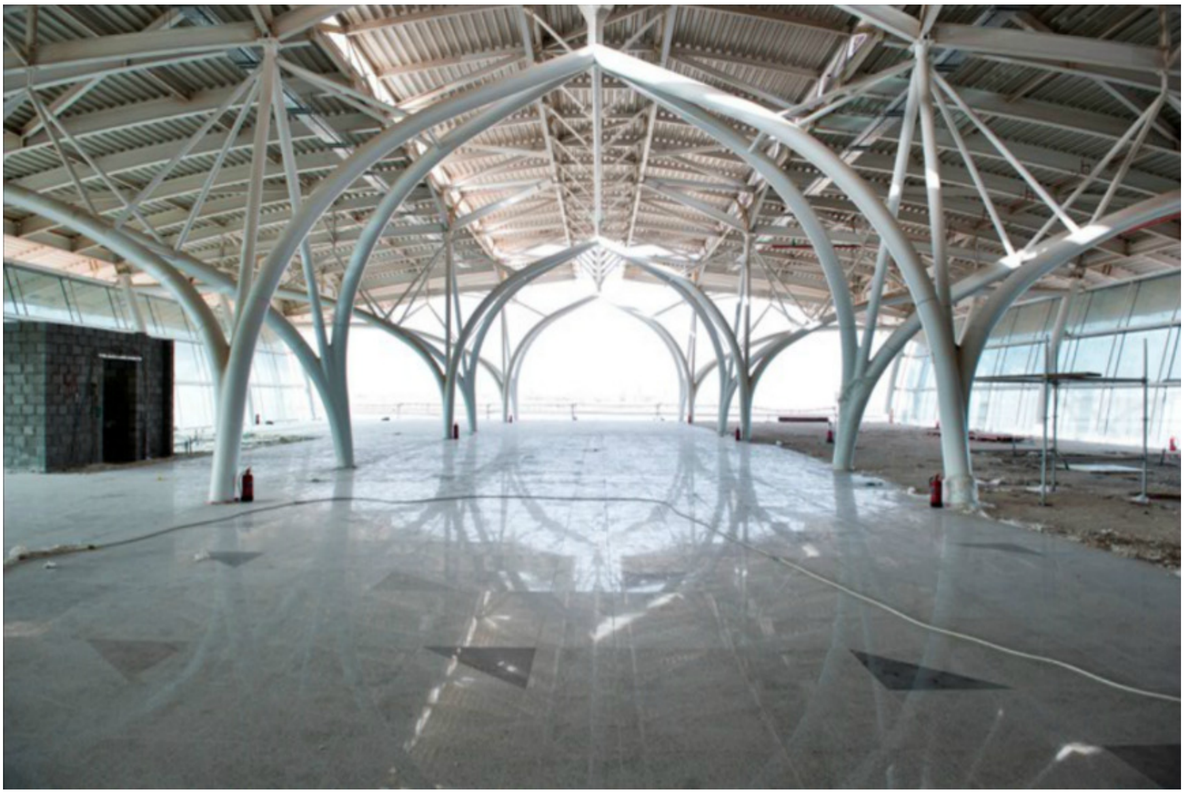

Figure 10. Cranes structures in position.

5. The air traffic control tower

The tender documents specified a 130m tall air traffic control tower but GACA, keen for the tower to be the world's tallest, mandated that the roof height be extended to 136m from grade. The tower is a 119m RC shaft supporting an 18m high, two-storey cab and "parasol" roof structure.

The tower is founded on a 2.95m deep x 20m wide octagonal RC mat supported on 43 RC piles, each 1.2m in diameter. The central vertical RC shaft that serves as the tower's spine has a constant inside diameter of 10.55m, but its wall thickness steps four times up its height in segments that are 1.0m, 0.75m, 500mm, and 350mm thick.

Arup's wind engineering experts assessed the tall, slender tower's dynamic behaviour, and concluded that it would be inappropriate to rely on code-specified wind loads because the tower's shape given the height-width ratio of nearly 12:1, which would result in significant cross-wind excitation. Clearly a wind tunnel test would be needed to model the structure's actual response. However, in order to progress the design ahead of finalised wind pressure data, the Arup specialists derived an accurate approximation of these effects, enabling the design team to develop appropriate superstructure and foundation systems quickly and early, which was critical to meet the design schedule.

The wind tunnel investigation also confirmed that a tuned mass damper would be needed to augment the tower's inherent level of damping, to moderate the building's response to wind pressure and control induced accelerations. A damper was not included in the tender documents, but the predicted accelerations greatly exceeded the occupancy comfort standards established in ISO 101374 [2] unless tower damping was increased to a minimum of 4%. The design issue then became where to locate the device.

While the optimum location would be as high as possible, there was little space in the cab or shaft to accommodate it, but the team realised that the varying gap between the outer façade and internal concrete shaft formed an excellent space to suspend an annular inertial damper.

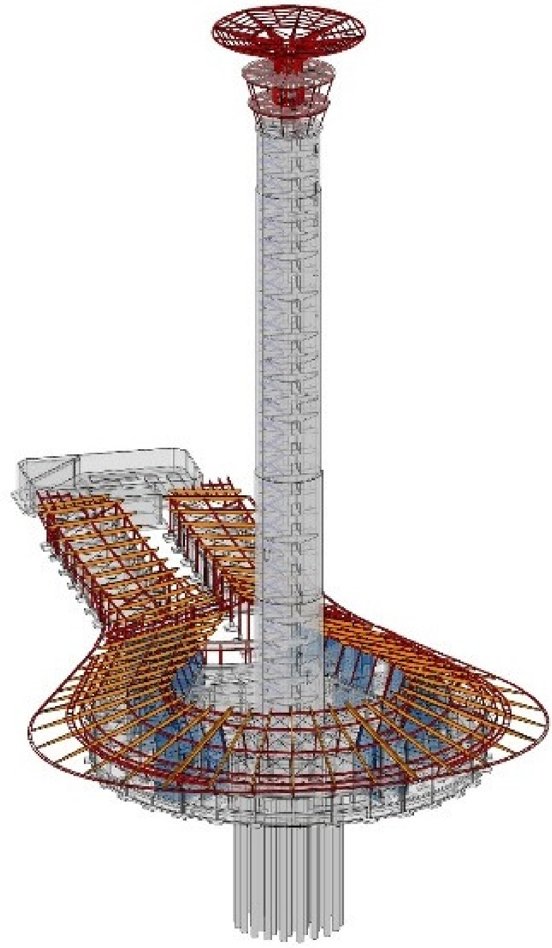

Figure 11. The air traffic control tower, base building, and technical block.

Acknowledgments

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References

[1] AMERICAN CONCRETE INSTITUTE. 350-06. Code requirements for environmental engineering concrete structures. ACI, 2006.

[2] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. ISO 10137:2007. Bases for design of structures – Serviceability of buildings and walkways against vibrations. ISO, 2007.

[3] M. Clark, J. Collins, P. Garcia, P. McCafferty, C. McMillan, D. Scott, T. Tavolaro, J. Tubbs, P. Tillson, C. Zdawczyk. King Abdulaziz International Airport: the structural design and fire engineering for Package 421. The Arup Journal 2014 Issue 2.