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Title: Burj Dubai Stack Effect - Passive Stack Effect Mitigation Measures in the Design of the World's Tallest Building

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Burj Dubai stack effect

Passive stack effect mitigation measures taken in the design of the world's tallest building: Case Study of the Burj Dubai

Stack effect in buildings is the same as stack effect in chimneys. That is to say, in a chimney, stack effect is the draft produced by the difference between the temperature of the flue gas within the chimney and the outside air. The force of the draft is a function of both temperature difference and height of the flue. During periods of extreme weather, this effect becomes evident in buildings of even modest height, although the temperature differential is much less than in a chimney. Those of us that live in temperate and cold climates are familiar with the upward movement of air in wintertime. This is especially noticeable at the entrances to buildings, elevator shafts, stairwells, dumbwaiters, mail chutes and mechanical shafts. Stack effect also occurs in warm and tropical climates, especially in the summertime. We sometimes describe this phenomenon as "reverse" stack effect because the flow of air is downward. With "normal" stack effect, the air in the building has a buoyant force because it is warmer and less dense than the outside air. With reverse stack effect, the cooler more dense air is inside the building and wants to drop downward and flow out of the building at its' bottom. This latter case of "reverse" stack effect will be the most prevalent type encountered in the Burj Dubai.

Why is understanding stack effect important? Stack effect can impact the function, systems performance, equipment specification, energy use and operations of a building; especially a tall one. Although the physics that causes stack effect is known; its' impact on individual buildings and specific locations within those buildings can differ greatly. Environmental variables, such as the air temperature, atmospheric pressure, humidity, combined with the air tightness of the exterior wall and existence and height of vertical pathways for air transfer within the building will influence the magnitude of the effect. The magnitude of the effect can turn a mere annoyance into a larger problem affecting building operation and even safety. It is unpleasant to the

occupant to experience the sound and feel of air rushing up or down an elevator shaft or whistling through gaps in even closed doors. During certain times of the year, the rush of air when opening the entry doors into the lobby of a tall building not only makes it difficult to negotiate the entry, but think of the cost to the environment due to the loss of expensive conditioned (heated or cooled) air. Some tall buildings even have experienced problems with doors to exit stair shafts being forced open or held closed at certain times, due to stack effect. This problem can be serious if during an emergency the occupants trying to use those doors are elderly, very young or physically impaired. It is therefore important for the designer to understand this phenomenon so as to make provisions in the design to minimize, mitigate or accommodate this effect as well as to advise the Owner on issues that may arise in the on going operation of his building.

The purpose of this paper is to outline the challenges related to stack effect faced by the Burj Dubai design team and to describe the measures taken to mitigate them. The writer hastens to add that this process is still ongoing and will continue through construction and into the operational life of this super tall, unique structure.

Burj Dubai

The Burj Dubai (Tower of Dubai) will be the world's tallest structure when completed in 2009. The superstructure is currently under construction on a site in Dubai, UAE, formerly occupied by the military. At over 160 stories in height, it will be the centerpiece of a 3,700,000 m² (40,000,000 ft²) residential, office and retail development. The final height of the building is currently confidential, but when completed, this ultra-modern multi-use skyscraper will be in excess of 700 meters (2300 ft), significantly exceeding the height of the current record holder, the 509 meter (1670 ft) tall Taipei 101.



Fig 1. Burj Dubai under construction

The 280,000 m² (3,014,000 ft²) reinforced concrete Tower is primarily Residential but, it also contains a 5+ star Armani Hotel and Service Apartments, Corporate Office Suites and several floors at the top reserved for Communications and Broadcast equipment. The 180,000 m² (1,940,000 ft²) Podium is primarily utilized for Parking and Building Services, however, it also contains Hotel related Amenities such as the Ball Room, Restaurants and Retail. The client is Emaar Properties PJSC, the Project Manager is Turner International and the Main Contractor is Samsung.

Currently under construction, as of July 21, 2007, the Burj Dubai has surpassed the height of Taipei 101 (currently the tallest completed building in the world) and is scheduled to be topped out sometime in 2008. Refer to figure 1, showing the Tower under construction. Figure 2 is a rendered image of the Tower as it will look upon completion at the end of 2008. Furthermore, in order to understand the magnitude of the potential stack effect, refer to Figure 3 which graphically compares the height of Burj Dubai to the five next tallest buildings in the world.

The Design Team

The SOM design team in Chicago was fully interdisciplinary. SOM services included architectural, structural, building services and interior fit-out design and ran from concept design stage in the form of a limited competition through full construction documents. An important aspect of the SOM team was that individual members had experience on the design and operation of several of the top ten tallest buildings ever built. Those structures included Sears Tower and John Hancock Center in Chicago and Jin Mao in Shanghai. Because of this experience, as the design phase commenced, RWDI, a specialist consultant in wind engineering, located in Guelph Ontario, was added to the team. Their expertise included an ability to provide a computational basis for the stack effect forces.

The Physics Behind Stack Effect

As previously stated, the magnitude of stack effect, and its' potential impact, will vary with the temperature difference between inside and outside, the height of the building or shaft

and the location within the building or shaft. Excepting the effect of wind, for a given location in the building, the stack effect force will vary with the temperature differential, therefore, it follows that one can generalize that stack effect will vary with the season of the year and time of day. Knowledge of the absolute and relative magnitude of the seasonal and diurnal temperatures permitted the analysis to be undertaken.

Assuming external air pressure and barometric pressure are constant over the height, the pressure difference that results from either normal or reverse stack effect is expressed using the following equation:

$$\Delta P = K_s \left(\frac{1}{T_o} - \frac{1}{T_i} \right) h$$

where: ΔP = pressure difference, in H₂O (Pa)

T = absolute temperature of outside air, °R (K)

T_i = absolute temperature of air inside shaft, °R (K)

h = distance above neutral plane, ft (m)

K_s = coefficient, 7.64 (3460)

The neutral plane is the elevation where the hydrostatic pressure inside the shaft is equal to the pressure outside the shaft.

To give one an idea of the potential magnitude of stack effect in a super tall building, we can make the following assumptions:

Internal Temperature:	+21° C
External Temperature:	+46° C
Height of Shaft	700 meters

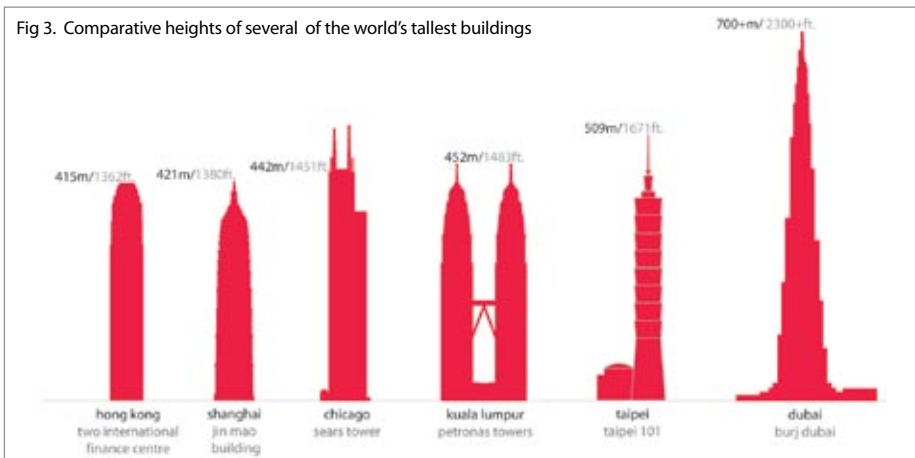
The resulting magnitude of the pressure differential at the top and bottom of the shaft, discounting wind effects and the effect of the HVAC system, would be +320 Pa and -320 Pa respectively. For those more familiar with imperial measure, that would be a pressure difference of over 6 psf from the neutral plane at the midpoint of the shaft or about 13 psf between the top and the bottom.

As the design reached maturity in late 2005, RWDI completed their analysis and released their final report. That report became the basis by which the "active" and "passive" mitigation measures were developed and implemented on the project. ↗



Fig 2. Rendering of Burj Dubai.

Fig 3. Comparative heights of several of the world's tallest buildings



“Active” mitigation measures

The “active” measures refer to actions taken in the mechanical system design specification to permit two strategies to mitigate stack effect. Firstly, the sensing of air pressure differentials that indicate an elevated level of pressure will instigate the automatic relief of excess air from appropriate locations in the tower. Secondly, air flow monitoring stations will measure supply and exhaust air flow to maintain a neutral to slightly positive air balance inside the Tower. Details of these “active” measures will be the subject of a separate paper.

“Passive” mitigation measures

The “passive” measures refer to the measures taken in the fundamental design and disposition of programmatic elements of the Tower as well as specific measures specified for the architectural elements of exterior wall, and builders work. The approach taken by the architectural design team in the overall and detail design of the project could be characterized as follows:

- 1) Augmentation
- 2) Isolation
- 3) Segmentation

Augmentation refers to elements of the work that have been augmented or improved in certain ways. Examples include improvements to the air tightness and robustness of doors and partitions or the specification of improved performance to the exterior curtain wall.

Isolation refers to designing additional layers or barriers to the passage of air due to stack effect. Examples include the provision of vestibules, air locks and revolving doors between areas of differential pressure

Segmentation is similar to Isolation except that it takes a normally continuous element and breaks it down into shorter segments thereby reducing the variable of height in the stack effect equation. Examples include the separation of stair shafts at Area of Refuge floors.

With the above in mind, each one of the following elements were reviewed and designed utilizing one or a combination of the approaches outlined in order to mitigate the impact of stack effect on the project.

1) Exterior Wall Design Criteria

- a) Air infiltration minimum design performance criteria for fixed and operable components of the exterior wall are established in the technical specifications. The level of performance is based on internationally recognized standards for high performance custom designed curtain walls.
- b) Prototype testing is outlined in technical specification in order to verify the performance of the curtain wall system.
- c) Field quality control testing as outlined in technical specification in order to verify the performance of the actual curtain wall constructed on the building.
- d) The wind loads as documented on the construction documents include a factor for both positive and negative internal pressures due to stack effect.

2) Terrace Doors

- a) Air infiltration design criteria for operable components of the exterior wall are established in the technical specifications. The doors will be fully gasketed and provided with an automatic door bottom or gasketed threshold at the door bottom.

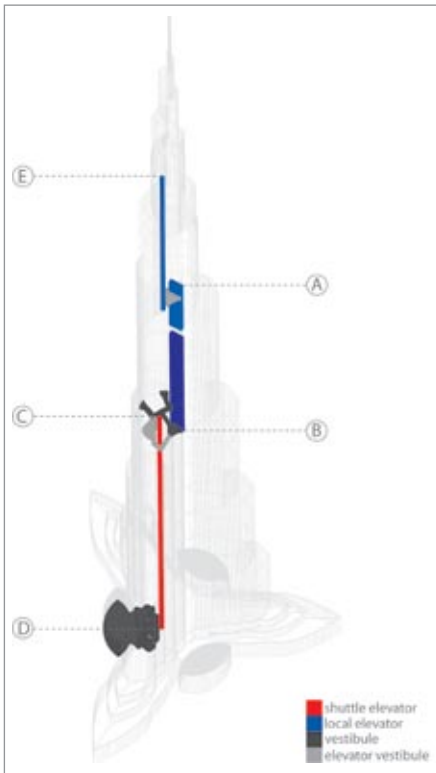


Fig 4. Diagrammatically shows the air travel paths that are potentially active due to stack effect in a super tall building such as Burj Dubai. Based on the above equation and discounting the effect of wind and HVAC systems, the magnitude of stack effect can be calculated if one knows the potential air travel paths. For example, the positive and negative magnitudes of stack effect at points A and B, connected by the local elevator shaft is less than that at points C and D connected by the high rise shuttle elevator shaft. Furthermore, the greatest potential magnitude would be the differential between points D and E if one considers the possible interconnection of shafts over the entire height of the building.

- b) Motor operated openers are specified on the terrace doors in order to control door operation and prevent the possibility of the door either being prevented from opening or swing open wildly due to stack effect or wind.
- c) A nuisance alarm is interlinked with both the terrace door and the unit entry door so that both doors are not open at the same time.
- d) Sonimometers, with wind direction and speed sensors, are placed at each terrace door to alert the occupants of high wind conditions.

3) Unit Entry Doors

- a) Enhanced fire rating (45 minutes) to the solid core timber doors and frames thereby providing a minimum level of robustness and maximum permitted gaps between door and frame.
- b) Door ironmongery includes gasket "smoke" seals and a concealed automatic door bottom. The specification for the automatic door bottom calls for a model that permits adjustment to the amount of closure of the gap between the door and threshold. It is important as part of the commissioning that the adjustment of these items is coordinated with the mechanical system performance requirements with respect to stack effect while maintaining a gap for a small amount of make-up air into the residence.
- c) The units are separated from the corridor by 1 hour fire rated construction. At the openings in the structural concrete shear walls, the partitions are to be constructed to face of structural wall and from floor to underside of structural slab, above. All gaps, penetrations and interfaces are to be sealed utilizing materials appropriate to maintain the air tightness, fire rating and acoustical requirements.

4) Corridor "Hex" Doors

- a) Glass doors with operable glass sidelights on the typical above grade occupied floors provide an additional barrier between the exterior wall and the vertical transportation and building services shafts located within the core. Refer to Figure 5.
- b) The glass sidelights are normally held closed, however, they are interlinked with the fire alarm system. In the case of a fire, the sidelights automatically open 90 degrees to permit the passage of smoke from the corridor into the core, where the smoke control extract riser is located, for exhaust by the mechanical system.

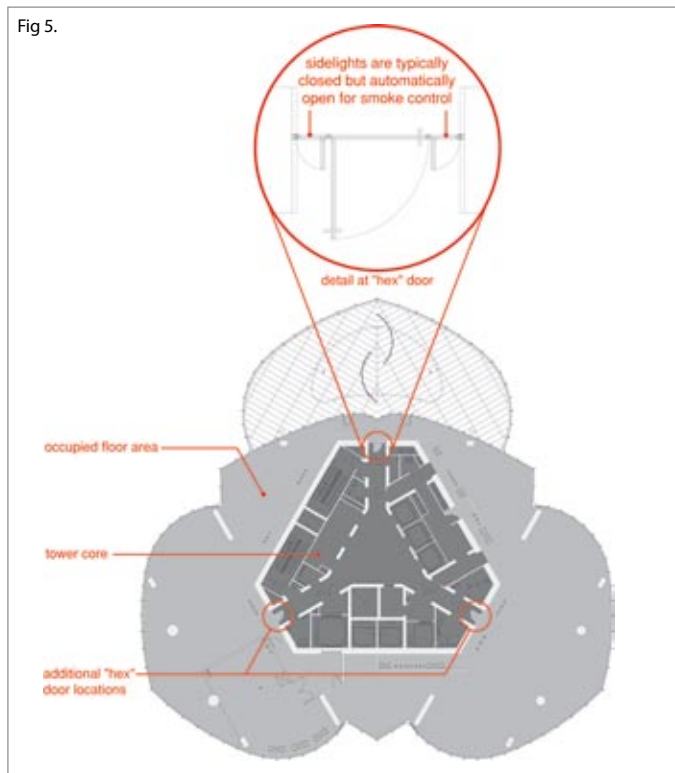
5) General Measures Related to Elevators, Elevator Equipment and Shafts

- a) In lieu of venting each elevator shaft to the exterior, a sprinkler head is provided at the top of each shaft as permitted by Code and agreed with the local authorities.
- b) For special provisions applied to the elevators with the tallest continuous shafts. Provisions include the addition of special gap seals at the doors, enhanced door closers and operators, lapping type leading edges to the doors and measures to reduce the size and extent of slab penetrations at the top of the hoistway.
- c) From an operational standpoint, the period of time that each elevator door remains open (timed interval) can be adjusted seasonally so as to minimize the period of time during times of the year that experience greater stack effect.

6) Vestibules and Shafts to the Service Elevators with the Tallest Continuous Runs

- a) The shaft to elevator BS1/F, at over 500 meters, is the tallest continuous shaft in the building. Furthermore, at level 138 it connects through a vestibule to the shaft to elevator BS3/F which continues upward for more than 100 meters.
- b) The enclosures of each shaft are separated from the rest of the building by 2 hour fire rated construction. Where not structural concrete, the partitions are to be constructed to the face of structural wall and from floor to underside of structural slab, above. All gaps, penetrations and interfaces are to be sealed utilizing materials appropriate to maintain the air tightness, fire rating and acoustical requirements.
- c) The elevator doors opening directly into these shafts, at the top third and bottom third of their height, are provided with gaskets in addition to special gap seals, in order to reduce the amount of infiltration and noise due to stack effect. ↗

- d) Vestibules are provided on all floors separating the entrance to each of these elevator shafts from the rest of the building. The vestibule enclosure is rated at 2 hours and is to be constructed as noted above. The flush hollow metal doors and frames to these vestibules are fire rated 1.5 hours and are provided with jamb and sill gasketing.
- e) The doors into the pits and machine rooms of these elevators are noted on the contract documents to be "Improved for Stack Effect". "Smoke seal" type gaskets are provided at the head and jambs and an automatic door bottom or gasketed threshold at the door bottom.
- f) Due to the assumed frequency of use to and from the Loading Dock into the main service elevators, an "airlock" type vestibule has been provided at Concourse Level. In addition to air tight construction, the two sets of doors are interlocked so that they both are not be open at the same time.



7) Vestibules and Shafts to the Double Deck Observatory/Corporate Suite Shuttle Elevators

- a) The shafts to elevators OB1 and 2, at over 450 meters, are the second tallest continuous shafts in the building. Having said that, these elevators are high speed shuttles, with only four top and four bottom door openings at stops.
- b) The elevator doors opening directly into the shafts are provided with special gap seals, in order to reduce the amount of infiltration.
- c) The shaft enclosure is completely within the core and constructed of reinforced concrete for its' entire height.
- d) Vestibules with revolving doors are provided at the Concourse Level (Corporate Suite) and Ground Level (Observatory) Lobbies. Although not fire rated, the construction is detailed to be as air tight as possible. The pressure due to stack effect was also considered in establishing the design load criteria to the vestibule walls.

- e) Vestibules with either revolving doors or double sets of doors are provided at the Level 123 (Corporate Suite Sky Lobby) and Level 124 (Observatory).
- f) The doors into the pits and machine rooms of these elevators are noted on the contract documents to be "Improved for Stack Effect". "Smoke seal" type gaskets are provided at the head and jambs and an automatic door bottom or gasketed threshold at the door bottom.

8) Laundry and Linen Chutes

- a) In lieu of venting each chute to the exterior, a sprinkler head is provided at the top of each shaft as permitted by Code and agreed with the local authorities.
- b) The doors opening directly into the chutes are fire rated and electronically interlocked with each other to prevent two being open at the same time.

- c) The chute enclosures are completely within the core and of reinforced concrete and/or gypsum shaftwall construction their entire height.
- d) Space around each chute within the shaft enclosure is to be sealed off every five floors with sheet metal.
- e) Each chute is located within the core in a Trash or Housekeeping room separated from the rest of the floor by a fire rated, self closing door.

9 Perimeter Fire Stopping and Exterior Wall Interface

- a) The gap between the inside face of the exterior wall and edge of slab will be completely sealed with an approved fire containment system.

b) The details of the exterior wall, as developed by the contractor, should be reviewed so as to identify and mitigate continuous vertical cavities where air could bypass the perimeter fire stopping system. Specific attention should be paid to sealing the slab edge at the column to shadowbox condition where the gypsum board column finish encloses a void that will be continuous up the building. It is suggested that the contractor adopt a special inspection program to assure that construction quality is maintained at this and other critical locations that are repeated throughout the tower.

10) Exit Stair Enclosure, Offsets and Areas of Refuge

- a) The stairs are purposely offset at floors containing Areas of Refuge, so as to interrupt the passage of air due to stack effect. The overall objective is to modify the impact of stack effect by treating each stair segment as if it is a shorter, stand alone shaft.
- b) The enclosures of each stair shaft and each Area of Refuge are separated from the rest of the building by 2 hour fire rated construction. Where not structural concrete, the enclosing partitions are to be constructed to the face of structural wall and from floor to underside of structural slab, above. All gaps, penetrations and interfaces are to be sealed utilizing materials appropriate to maintain air tightness, fire rating and acoustical requirements.
- c) In general, at least two fire rated, self closing doors separate the segments of each of the stairs.

11) BMU Equipment Rooms:

- a) The blockwork walls to the BMU equipment rooms, when the equipment is in operation and exterior doors are open, becomes the Towers' exterior enclosure. These walls, louver assemblies and doors must be constructed to the air tightness and environmental criteria of an exterior wall.
- b) All openings, joints and junctions in the blockwork walls should be fully sealed. Blank-off panels in the louvered portion of these walls are to be imperforate and ductwork and plenum connections fully sealed.

c) The doors and frames into the BMU equipment rooms are flush, hollow metal and will be fully gasketed and provided with an automatic door bottom or gasketed threshold at the door bottom.

12) Fire stopping and stack effect mitigation in shafts within residential units:

- a) In shafts with piping only, the fire stop assembly and seal is located at slab penetration. All penetrations in the partition to be acoustically sealed but do not need to be fire stopped as the fire separation is maintained at the slab.
- b) In shafts with ductwork only, fire dampers are provided where the duct penetrates the fire rated partition. Mineral fiber and sealant are provided to seal the gap around duct penetrations in the slab every 5 floors (max.) to mitigate stack effect.
- c) Openings in the floor slab within shafts containing duct risers, where not occupied by a duct (i.e. above the termination points of rising ducts or below the termination points of falling ducts) will be sealed off. The overall objective to modify the impact of stack effect by treating each group of residential floors served by the riser shaft as if they are a shorter, stand alone stack.

Conclusion

Stack effect in buildings is a natural phenomenon and cannot be avoided. It can however, be modified by design if its' nature is understood. Changes in building design and construction can modify the distribution of pressures and air flow due to stack effect. Because of the extreme nature of the potential problem on Burj Dubai, the design team addressed these issues at an early stage of planning. Furthermore, it is expected that additional knowledge about the behavior of stack effect and efficacy of mitigation measures will be gained as the project proceeds through construction, commissioning and operation.

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