Title: The Design and Construction of the Palais Royale, Mumbai

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Abstract

This paper describes the design and construction of the Palais Royale Residential Tower in downtown Mumbai, India (the tower is 325 m. tall from the bottom of the raft to the top of the roof cap). When completed it will be the tallest building in India. An elevation of the building is shown in Fig. 1. The building is an octagonal shape with a central atrium. Since there is residential occupancy above and parking below, the column placement does not match vertically. As the columns carry heavy loads, high strength concrete was used in the vertical elements. Quality control was achieved by setting up an on-site testing laboratory. The tower concrete work is expected to be topped out by 2013. The article will describe in more detail the various aspects of the design and construction of this the tallest tower in India when completed.

Keywords: Tallest Residential, India, Deepest Transfer Girders

Introduction

Palais Royale (pronounced as pa-lai ro-yaal) is a French name which means a Royal Palace. This prestigious high-rise residential building in Mumbai is being developed by Shree Ram Urban Infrastructure Limited.

Location

Situated in the heart of south Mumbai, Worli Naka, the building with a height of 310 m above the ground level has a total structural height of 325m from the bottom of the foundation to the top of the elevation cap. The base dimensions of the octagonal building are 84m by 86m. The height to least width ratio is less than 4.0 which has inherent stability under lateral loads. The construction area of the building is over three million sq.ft. with 88 slabs.

Structural Systems

The overall building is a reinforced concrete structure on a raft foundation.

Apartment Floors

For the typical apartment floors, Indian practice is to "sink" the slabs in such areas as balconies, kitchens, toilets, etc. This provides...
considerable difficulty in developing a conventional flat plate concrete structure. Figure 2 shows an Apartment level floor. A beam and slab system was used. Figure 3 shows an Amenity Level floor and Figure 4 the Transfer girder level. Since there is residential occupancy above and parking below, the column placement does not match vertically. The residential floor has 244 columns and the parking levels have 88 columns. Hence up to 9m deep by 1200mm to 1500 mm wide transfer girders were placed in an interstitial level to enable efficient column locations in each occupancy. Presence of an atrium in the centre as a Brahmasthan requirement has provided the structural advantage of the supports being on the periphery.

**Parking And Amenity Levels**

The structural system below transfer girder level is comprised predominantly of a Post-Tensioned Flat Slab except in the Brahmasthan where the 25m by 22m rectangular area is framed by strong, post-tensioned beams. The amenity areas carry huge loads, the average intensity of the superimposed loads (SDL + LL) being as high as 35kN/sq.m at the swimming pool level. The parking levels are designed for the possibility of double stacked parking.

**Soil Profile**

Soil consultants estimated a safe bearing pressure of 220 T/sq.m with settlement less than 25 mm. Modulus of subgrade reaction of 8800 T/m3 was recommended for the design of raft foundations. Cross-hole velocity test yielded average values of Poisson's Ratio, Young's Modulus

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**Figure 1. Elevation of Palais Royale, Mumbai.**

图1. 孟买Palais Royale大厦立面

**Figure 2. Typical Apartment Level Framing Plan.**

图2. 典型公寓层构架平面

**Figure 3. Typical Amenity Level Framing Plan.**

图3. 典型服务设施层的构架平面

**Figure 4. Transfer Girder Framing Plan.**

图4. 转化大梁构架平面
and Shear Modulus as 0.32, 5200MPa and 200 MPa respectively showing excellent characteristics of the rock profile. Due to presence of weak soil for the upper 8 to 9m, a soil retention system was erected in the form of contiguous concrete infilled tubular steel piles, held to the bedrock with inclined pre-stressed rock anchors.

Foundations
The core walls around the left shaft are a key stabilizing element. The balance of the lateral stiffness is provided by rigid frames in both directions. The building foundation is a 3.5m thick raft. Since there was a maximum limit of 400m3 daily supply of ready-mix concrete in the beginning of the project, numerous vertical and horizontal construction joints were required in the construction of the raft. This imposed some design challenges. The raft is founded on rock with an allowable bearing capacity of 220t/m2.

Structural Analysis

Wind Tunnel Tests
Wind tunnel tests by RWDI showed that for a ten year return period the Total Peak Acceleration in simulated wind conditions was 7.2 milli-g against the ISO criteria 10137:2007 of 14 milli-g (extrapolated from the criteria for 1 to 5 year return period to 10 year return period).

Site Specific Seismic Studies
For the first time in India, site-specific seismic studies were conducted for a residential building, with the help of IIT Roorkee. The spectrum was assigned in the ETABS model as an additional load case (see Figure 5). The basic seismic design corresponds to Earthquake Zone 3 by the Indian code.

Computer Model
A combination of shell diaphragm and membrane diaphragm was chosen to simulate framing conditions of the structure, in order to optimize the run time and the computer memory. The flat slabs at the parking and amenity levels have been treated as shell elements contributing to the lateral stiffness. Figure 6 shows the three-dimensional ETABS model.

At the residential levels, the lateral resistance is derived from the beam/column frame action. Hence, the diaphragm is modeled as a membrane. Cracked section properties were assigned in accordance with the code recommendations. The foundation raft was analyzed using SAFE, using the reactions obtained from the ETABS Analysis.

Analysis Results
The maximum lateral deflection at the top level of the building is only 300 mm. Hence the general performance of the building is well-controlled. The massive proportions and the enormous stiffness of the building are evident from the modal frequencies found to be 0.1206 Hz for Mode 1 in Y direction, 0.1349 Hz for Mode 2 primarily in X direction and Mode 3 showing 0.1515 Hz primarily in Z direction as torsion. Fortunately, significant differential elastic shortening of columns and shear walls due to vertical loads was not observed.

Salient Aspects of Seismic and Wind Design:
- Extensive reference to international guidelines:
  - CTBUH guidelines for seismic design of tall buildings (2008)
  - Pacific Earthquake Engineering Research Centre – seismic performance objectives for tall buildings (2008)
- Generation of site specific response spectra and time-histories (undertaken for the first time for a civil application in India)
Analysis Of Transfer Girders
The transfer girders were analyzed by Solid Finite Element Method (see Figure 7). Both individual girder models and integrated layout model involving all girders and the three floor levels within the girder depth were assembled in STAAD-Pro. The stress patterns clearly indicated that the girders acted in conformity with strut-tie model corresponding to deep beam action (see Figure 8). In-depth research was carried out to design the girders, which are probably the largest transfer girders being constructed in the world. The transfer girders have been provided with horizontal and vertical post tensioning to achieve monolithic behavior and deflection control (see Figure 9). The post-tensioning is carried out stagewise to avoid excessive upward deflections in early stages of construction.

Concrete Information
M:80 concrete for columns and shear walls and M:60 concrete have been used for slabs and beams. With the help of an elite team of concrete experts, concrete manufacturers, admixture vendors, contractor’s engineers and batching plant operators, innumerable trial mixes were tested for various performance criteria. Eventually, M:80 SCC was finalized with free water cement ratio of 0.225 and free water binder ratio of 0.23. With 450 kg cement content and 168 kg/cu.m fly ash, the target strength was 90 N/sq.mm. Micro silica content was tried starting from 0% and was varied up to 10% to examine the performance. The design was finalized with 5% i.e. 23 kg/cu.m micro-silica content. Minor adjustments are carried out for aggregate quality variation and moisture content on a routine basis.

Façade
The façade for Palais Royale will primarily consist of glass and a maintenance-free material known as “Corian” manufactured by Du Pont. Glass will be used to envelop the service cores on east and west sides and Corian will be used on the remainder of the building surface. It is desired that the façade should need minimum maintenance in the future, hence these materials. Du Pont has guaranteed that this material will sustain the vagaries of Mumbai climate and the onslaught of pollution.

Eco-Friendly Measures
The project is pre-certified for Platinum rating by the IGBC in the LEED ratings. The main features are: fly ash is extensively used in the high-strength concrete for the structure; all construction waste is being recycled to the fullest possible extent; rain water falling on the entire complex will be harvested and used for gardening and flushing requirements; all waste water both grey and black will be treated to potable standards and reused for gardening and flushing requirements; all kitchen waste will be processed to produce manure for internal and external use; and use of recyclable materials like stainless steel in the finishing works is proposed.
Energy Conservation

The building has features like deep overhangs and shades which naturally reduce need for energy which otherwise would be needed for cooling. Use of energy efficient triple glazed windows will reduce heat gain. The roof will be coated with reflective paint to reduce heat gain. Structural cooling by circulating cold water in the peripheral slabs to reduce temperature is used which will further reduce the air conditioning load. All lighting is designed with energy efficient fixtures. Sensors will be put in place to monitor occupancy of common areas and lighting will be controlled according to the occupancy levels. Use of natural ventilation in the atrium is induced by strategically providing openings at service and refuge levels.

Alternate Energy Sources

A solar hot water system is used for providing hot water in bathrooms. A wind-solar off-grid power plant will be used to power the outdoor lighting mainly to be used at night. The generated power will be stored in a power stack of tubular gel cell bank. An estimated 64000 KWH of power will be generated per annum which will obtain a reduction of about 400 tons of carbon pollutants.

Security Measures

In the present scenario, the security plan is based on an effective deterrent, early detection and swift response to security threats. Lotan Consultants from Israel are the security consultants. Besides the conventional systems of the barriers, photo recording of visitors, vehicles and other checks, an emphasis will be placed on discreet behavioral pattern observation which can detect possible security violators at the fringe and well in advance.

Smoke Detection & Studies In Atrium

Fire scenarios are unpredictable. An effective smoke extraction system helps the occupants sustain a fire even better. Computational Fluid Dynamic techniques provide an opportunity to obtain an assurance of effective smoke removal at an early stage of building design. With high-power computers, a virtual hot smoke testing of the building design is carried out. Diagrams showing studies for Palais Royale were carried out by Zeus Numerix.

Construction

Construction Methodology

M:80 concrete, use of self-compacting concrete, using surface retarders, introduction of retarded concrete to avoid cold joints, column cages, compulsory use of couplers for rebar splicing, Automatic Climbing System for Walls and cores etc. are some of the

cracks control (图9)。后张预应力有阶段性的进行以避免建设早期过度的向上弯曲。

混凝土信息

建筑柱子和剪力墙采用M:80混凝土，平板和横梁采用的是M:60混凝土。在由混凝土专家、制造商、外加剂供应商、承包单位的工程师和搅拌机操作员组成的精英团队的帮助下，不计其数的适配被测试于不同的性能指标。最终，M:80 SCC最终被定义0.225的自由水灰比和0.23的自由水胶比，450kg的水泥用量配以168kg/cu. m的飞尘使目标强度达到90 N/sq.mm。0%变化至10%的极小的硅含量被应用于测试性能。最终设计定以5%(也就是23 kg/cu.m)的微硅含量。另有为少数调整用于骨料质量变化和含水量。

外墙

Palais Royale的外墙主要由玻璃和一种由Du Pont公司制造、名为“Corian”的免维护材料组成。玻璃将用在服务核心筒的东侧和西侧墙面，而建筑其他墙面则使用Corian材料。这些材料的运用使建筑外墙被期待着在未来的使用中维护次数达到最少。Du Pont公司也保证Corian材料将在孟买多变的天气状况和污染环境中得以维持。

生态友好的措施

该项目被LEED评估等级中的IGBC预鉴定为白金级别。而主要的特点有：回收的粉煤灰在高强度的混凝土结构中大量使用；所有的施工废弃物都将尽可能地彻底回收；落在整座建筑上的雨水将会被收集并用于园艺和冲刷方面；包括中水和黑水在内的废水会被处理达到可利用标准并被用于园艺和冲刷方面；所有厨房都会被处理为可以用于内部和外部的肥料；利用像不锈钢一样的回收材料作为整体工程也被考虑在内。

能源节约

建筑中较长的悬挑和遮阳板合理地减少了能源的使用从而降低了对冷气的需求。使用高效的三层玻璃减少了热量吸收。而屋顶也会因为被覆盖的反光涂料而减少对热量的摄入。

由冷水环绕在外围楼板的结构冷却方式降低了整体结构体系的温度，从而减少空调的负荷。所有的照明采用了节能灯具。感应器将会被放置在居民共同使用的公共区域，并会根据空间使用级别来控制灯光。在服务层和避难层安置开口实现了中庭的自然通风。

可替代的能源资源

太阳能热水供给系统将提供用于浴室的热水。一个利用风能、自给自足的发电机会主要使用于居民区的照明系统。被收集的能源将会被储存在一个蓄积能源系统中。据估计，每年产生的6.4万千瓦时的电量将会减少大约400吨的碳污染。

图9. 转化大梁的后张预应力
salient aspects of the construction method suggested by Sterling. The Owner selected the Meva system of shuttering and a placement boom to expedite construction. Most of the concrete was pumped. Two site batching plants supply most of the concrete.

Mock Ups
A practice of setting up true scale mock-ups to study the veracity of the systems was adopted on this project. For example, two mock foundation blocks were cast with 3.5 m depth with reinforcing bars as per the actual design requirement, and were cast, cured and monitored for formwork system, feasibility of using SCC, temperature variation, thermocouple working, segregation characteristics, characteristic strength curve and Evalue. These mock-ups were tested two months in advance before commencing the actual foundation concreting. Similarly, the bottom chord of 2 m depth of the overall 9 m deep transfer girder with all the rebars and other embedments was cast, which proved to be enormously helpful in understanding the complexities of rebar placement and in adopting suitable methodology prior to actual work at the 76 m level.

Quality Control
The Owner and the Design team set up a rigorous quality control regime. The project structural design was Peer Reviewed. Separate studies were conducted for unusual loads. A site laboratory was set up, augmented by testing by external testing laboratories.

安全措施
目前的安全计划是建立在有效地制止、早期监查和对安全威胁的反应的基础上的。以色列的Lotan咨询公司是项目的安全顾问。出传统的屏障、来访者录像记录、车辆和其他事项的监查系统外，可以在边缘并提前探测出潜在安全隐患的特别行为模式观察系统将被着重使用。

烟雾探测及中庭研究
火灾是难以预测的，而一个有效的烟雾探测系统可以帮助居住者更好的处理火灾。计算流体动力学技术在建筑设计的早期阶段提供了一个有效去除烟雾的保证。借助着高功率的计算机，建筑设计的热烟测试被实施，图解展示了由Zeus Numerix施行的对项目的研究。

建造
建造方法
一些由Sterling公司建议的重要的建造方法有：M:80混凝土、自密实混凝土的应用，使用表面层缓凝剂并引入缓凝混凝土来避免冷缝，以及column cages，钢筋拼接必须使用的钩架，用于高墙和核心筒建设的自动爬升系统等等。项目业主为提升建设速度从而选用了Meva模板系统以及placement boom。混凝土大多为泵送混凝土。基地上的两台混凝土混合机供给了绝大部分的混凝土。

实物模型
该项目采用实际比例的实物模型用来研究系统的准确性。例如，两个 按照设计要求，深度3.5米的两个地基模型被配以钢筋浇注、固化并被监测，用以检验模板系统。使用SCC的可行性、温度变动、地热偶的工作状态、隔离特性、特征强度曲线以及Evalue。这些实物模型在大厦地基混凝土动工前两个月被检测。

质量保证
项目的业主和设计团队设立了一个严格的质量保证管理体制。其结构设计已经通过同行审查。对于不寻常的负荷也已安排了数个分别的研究。一个工地试验室被建立，用以增加外部测试试验室的测试。