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

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Subjects: Architectural/Design
Building Case Study
Urban Design

Keywords: Construction
Design Process
Structure

Publication Date: 2012

Original Publication: CTBUH 2012 9th World Congress, Shanghai

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 Unpublished conference paper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 Unpublished

The Design and Construction of the Palais Royale, Mumbai, India

印度孟买Palais Royale大厦的设计与施工

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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

摘要

本论文介绍了位于印度孟买市中心的Palais Royale住宅大厦的设计和建造。竣工后，该大厦将成为印度最高的建筑。大厦的立面图如图1所示。Palais Royale住宅大厦是一个带有中央中庭的八边形建筑。介于建筑上部为住宅公寓，下部为停车空间，所以柱子的竖向安置并未完全相接。由于柱子要承载巨大负荷,因此在竖直构建上使用了高强度的水泥。一个工地试验室的建立保证了项目建设质量。大厦的混凝土工程进展预期在2013年封顶。本文以不同方面深入讨论这座竣工时将成为印度最高大厦的设计和建造。

关键词：最高的住宅大厦、印度、厚度最大的转换梁

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.

引言

Palais Royale(发音为: pa-lai ro-yaal),是建筑的法语名字,意思为皇家宫殿。这座享有声望的高层住宅大厦位于孟买，开发商为Shree Ram城市基础设施有限公司。

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.

地理位置

该项目位于孟买南部Worli Naka区的中心地段。大厦的建筑高度由地平面算起为310米，但是从地基最低端到大厦最顶尖，结构高度为325米。大厦八边形底座的尺寸是84米x86米。最小宽高度比为4.0， 使大厦在横向荷载下具有内在的稳定性。大厦总施工面积超过300万平方英尺，共有88个楼板。

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

结构体系

总体来讲，该建筑在筏板地基上采用钢筋混凝土结构。

公寓楼面

对于典型的公寓楼面，在印度一般的做法是在阳台、厨房、卫生间等处"降板"。这为开发传统的平板混凝土结构造成了不小的困难。图2展示了一个公寓楼面，其

Figure 1. Elevation of Palais Royale, Mumbai.
图1. 孟买Palais Royale大厦立面

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

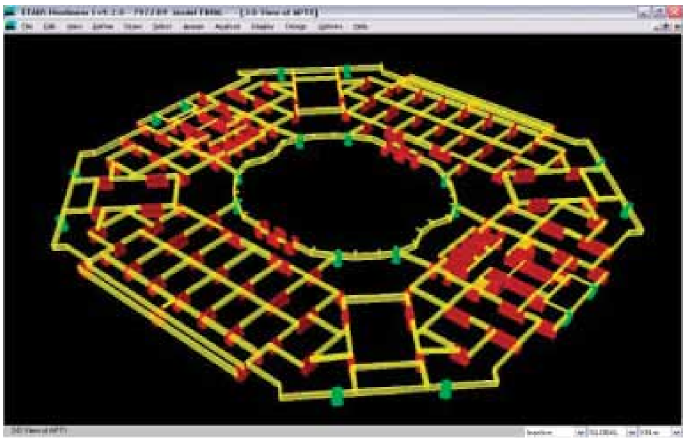

Figure 2. Typical Apartment Level Framing Plan.
图2. 典型公寓层构架平面

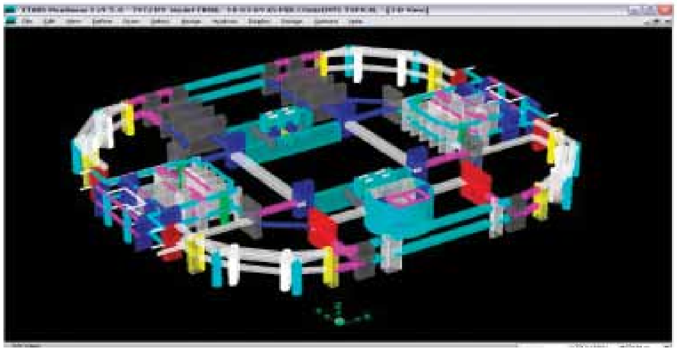

Figure 3. Typical Amenity Level Framing Plan.
图3. 典型服务设施层的构架平面

中梁板结构被应用。图3展现了便利设施层。图4展现了转化大梁层。介于建筑上部为住宅公寓，下部为停车空间，所以柱子的竖向安置并未完全相接。住宅平面共有244根柱子，停车平面共有88根柱子。因此厚度高达9米、宽度在12米至15米间的转化大梁被安置在间隙层中用于确保在两个不同领域的柱子分布的有效性。应Brahmasthan地区要求在大厦中央安置的中庭体现了支持外围的结构优势。

停车楼层和便利设施楼层

转化大梁层面之下的结构体系由占主导地位的后张预应力平板组成（在Brahmasthan，25米x22米的矩形区域由坚韧的后张预应力衡量框架支撑）。便利设施楼层承担着巨大的负荷，叠加负荷(SDL + LL)的平均强度在泳池层高达35kN/sq.m。停车层被设计作为双层停车场。

土层剖面

土壤专家评估出了220吨/平方米的安全承压和小于25毫米的安置。8800吨/立方米的地基反应系数被推荐用在筏板地基的设计中。由井间速度测试得出了泊松比、弹性模量、剪切模量的平均值，分别为：0.32、5200兆帕、200兆帕，结果显示出岩石剖面的优良特性。由于在上层8米到9米间存在的松软土壤，一个由注入混凝土的众多钢管柱组成的土壤保持系统被倾斜的预应力岩锚固定在基岩上。

地基

围绕左侧立井的核心墙体是一个重要的稳定化要素。刚架在两个方向上为侧向刚度提供了平衡。建筑的地基是一个厚3.5米的筏板。由于在项目初期阶段，预拌混凝土的每日最大供应限量为400立方米，所以在筏板建设中需要建有大量的横向及竖向的连接。这产生了一些设计上挑战。在基石上的筏板的容许承载力为220吨/平方米。

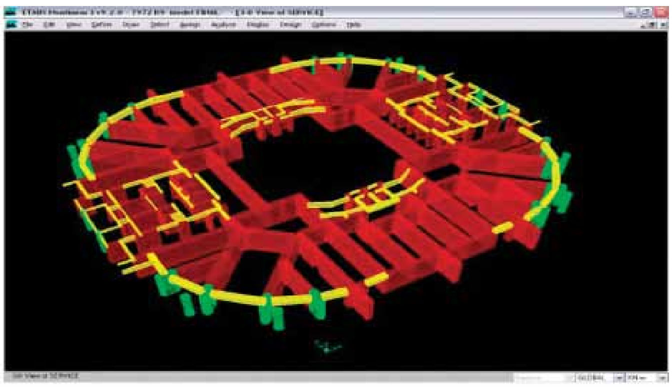

Figure 4. Transfer Girder Framing Plan.
图4. 转化大梁构架平面

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)
  – Los Angeles Tall Buildings Structural Design Council guidelines for 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)

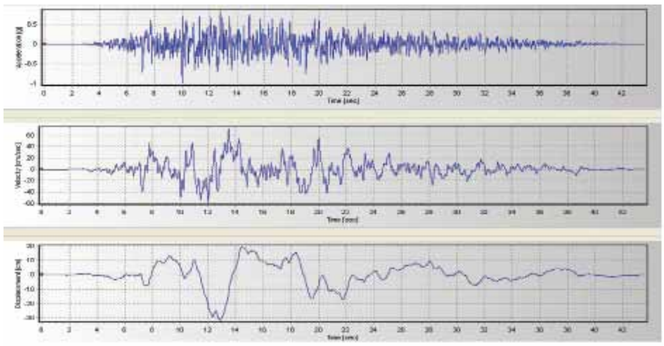

Figure 5. Site-Specific Time History Scaled To Unity.
图5. 基地时程分析

结构分析

风洞试验

由RWDI负责的风洞试验显示出在十年的逆程周期中，各种模拟风况下最大加速度总计为7.2 milli-g，而出自ISO标准10137:2007的数值为14 milli-g（由一至五年的逆程周期标准推算出十年的逆程周期）。

基地抗震研究

在印度理工大学（IIT ）Roorkee的帮助下，一些专门针对地基的抗震研究运用在了此住宅大厦中，这是印度历史上的第一次。作为附加负载案例，频谱被设定在ETABS模型中（见图5）。基本抗震设计对应印度规范设定的三号地震区。

计算机模型

壳状地下连续墙和膜状地下连续墙组合被选用模仿结构的框架状态，并使运行时间和电脑存储量得到最大化。停车层和便利设施楼层的平板楼面被当做为横向刚度服务的外壳元素。图6展现了三维ETABS模型。

在住宅层横向阻力源自于横梁/柱子框架的作用。因此地下连续墙在模型中被建为表层。开裂断面特征依照规范建议而被要求。地基筏板由SAFE分析，使用来自ETABS分析中得到的反应力。

结果分析

高层建筑顶端的最大横向位移仅为300毫米。可见，建筑物的整体性能是受到良好控制的。显而易见的是，建筑大型的面积和巨大的刚度来自莫代尔频率：Y方向上模式1为0.1206赫兹， X方向主要为模式2并显示0.1349赫兹，在Z方向以扭矩的形式主要为模式3并显示0.1515赫兹。幸运的是，由于柱子和剪力墙竖向上的负荷而产生显著差异的弹性压缩并未发现。

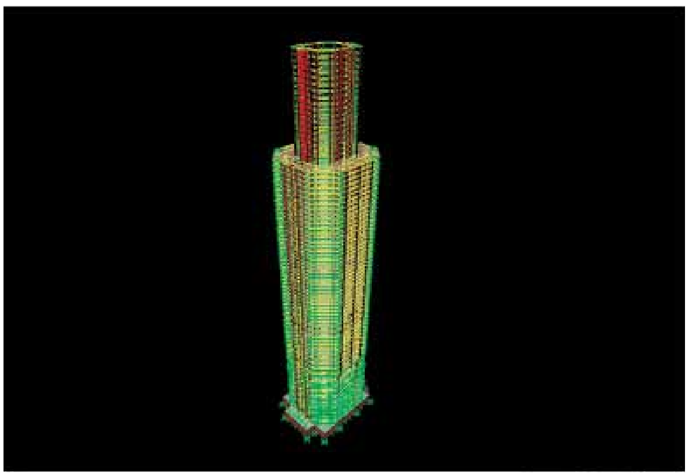

Figure 6. ETABS Model.
图6. ETABS模型

- Palais Royale being treated as a Special Structure as defined by IS-1893 (2002)
- Minimum design base shear scaled to 1 % of the seismic weight.
- Intrinsic damping for seismic & wind design = 1%
- Structural elements modeled using cracked section properties.
- Importance factor of 1.5 used
- Seismic deflections under DBE controlled to H/750
- Wind accelerations under 10 year return period wind pegged at 10 milli-g

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.

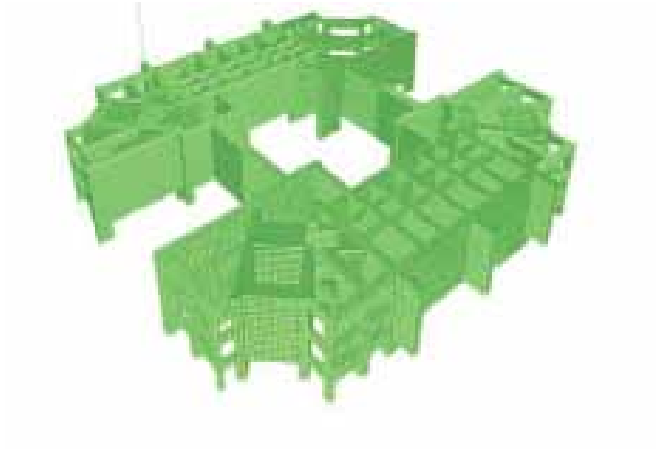

Figure 7. Solid Finite Element Model In STAAD.
图7. STAAD有限元模型

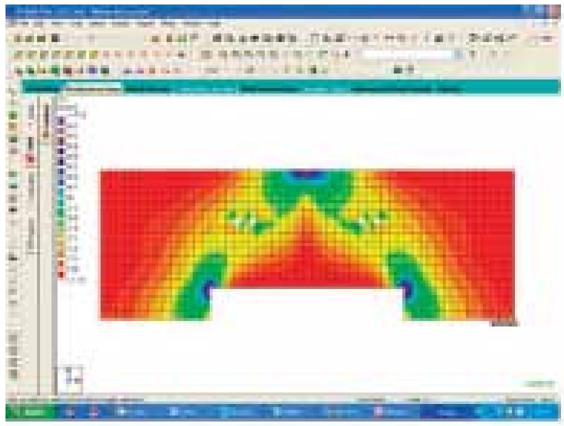

Figure 8. Strut-Tie Action : Stess Pattern.
图8. 拉压杆模型：应力分布型式

地震和风力设计的突出方面：

- 广泛借鉴国际指导方针：
  - CTBUH高层建筑抗震设计指南（2008）
  - 洛杉矶高层建筑结构设计学会高层建筑指南（2008）
  - 太平洋地震工程研究中心——高层建筑抗震性能目标（2008）
- 基地特殊反应和时程的应用（首次出现在印度民用建筑中）
- Palais Royale被当成是由IS-1893 (2002)定义的特殊结构
- 最小的设计基地剪力达到地震重量的1%
- 地震及风力设计中的内在阻尼=1%
- 结构元素模型采用开裂断面特征
- 采用了1.5倍的重要因素
- 在DBE下的地震偏移被控制至H/750
- 十年逆程周期中风力加速度记为10 milli-g

对转化大梁的分析

转化大梁的分析由有限元法完成（见图7）。单独的大梁模型和整体布局模型都涉及了所有大梁和在大梁厚度内的三个楼层，并在STAAD-Pro中被装配。应力分布型式清楚地表明了大梁与拉压杆模型在深梁作用下的表现一致（见图8）。为设计大梁而采取了深入调研。而这很可能是世界上正在建设的最大的转化大梁。这些转化大梁在横向和纵向上通过后张预应力来获得单片行为和

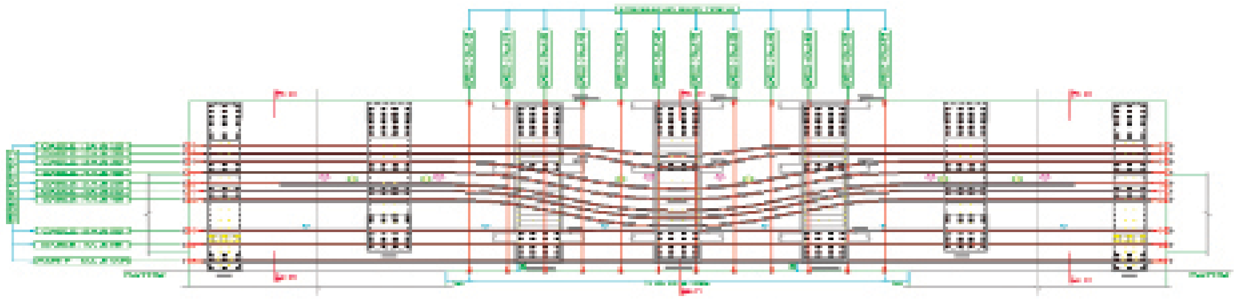

Figure 9. Post-Tensioning Of Transfer Girders
图9. 转化大梁的后张预应力

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 annumm 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

挠度控制（见图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，而建筑其他墙面将使用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修次数达到最少。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被尽可能地彻底回收；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在园艺和冲刷方面；所有厨余都会被处理为可以用在内部和外部的肥料；利用像不锈钢一样的回收材料作为整饰工程也被考虑在内。

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。使用高效能量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、自给自足的发电机将主要用于夜间户外的照明系统。被收集的能源将会被储存在一个管状能源栈中。据估计，每年产生的6.4万千瓦时的能量将会减少大约400吨的碳污染。

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。