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MahaNakhon Tower and the Use of CTBUH Seismic Guidelines

Mahanakhon Tower与CTBUH抗震设计指导

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Dr. Kanokpat Chanvaivit graduated from Chulalongkorn University in Bangkok, Thailand with a degree in Structural Engineering. He is a senior structural design manager in the technical department at Bouygues - Thai Ltd. He is responsible for managing the design process, leading design teams, and controlling the criteria and design concepts for the design and construction of high-rise towers in Thailand, including MahaNakhon Tower (soon to be the highest tower in Thailand), Noble Ploenchit Towers, and South Point Pattaya.

Kanokpat Chanvaivit博士毕业于泰国曼谷朱拉隆功大学，主修结构工程，现任Bouygues - Thai有限公司技术部高级结构设计经理，负责监督设计过程、领导设计团队、管理泰国高层塔楼的设计和施工标准，并提出设计理念，曾负责的项目包括Mahanakhon Tower(即将成为泰国第一高塔)、Noble Ploenchit Tower以及South Point Pattaya。

Abstract

MahaNakhon Tower developed by PACE Development Corporation PLC is a 77-Story mixed-use development in Bangkok, Thailand. It will be Bangkok's tallest tower, standing at 314 meters. The main feature is its pixelation wrapping around the building which was the driving force behind the structural scheme that comprises of a central core with 12 mega columns that are inset from the façade. The vertical structure is linked together by three double-height outriggers. The structure was analysed using construction sequence FE models with bounded support conditions to determine the load distribution. Internal forces from the gravity construction sequence models are combined with internal forces from the Wished-in-Place lateral load FE models. This project incorporated CTBUH Recommendations for the Seismic Design of High-Rise Buildings (2008), Appendix B. This paper will primarily focus on the structural scheme, analysis and design, construction methodology; seismic forces from Thai local codes and CTBUH recommendations are also presented.

Keywords: MahaNakhon Tower, CTBUH Recommendations for the Seismic Design, High-Rise Buildings, Outrigger, Mega Columns, Construction Sequence, PACE Development Corporation PLC

摘要

Mahanakhon Tower坐落于泰国曼谷，楼高77层，为一项综合发展项目。2016年完工后，将成为曼谷第一高塔，达314米高。塔楼的最大特点在于围绕着整座塔楼的像素化效果，这项特点也成为结构方案背后的原动力。塔楼由中央核芯筒和12支巨柱所组成，巨柱嵌入外立面。竖向结构由三道双层高的伸臂桁架连接。结构在约束支撑的情况下，运用施工顺序有限元模型分析，以决定荷载分布。同时把施力顺序重力模型的内力与全方位综合有限元横向系统模型的内力相结合。项目考虑了世界高层都市建筑协会(CTBUH)的《高层建筑抗震设计导则(2008)》附件B。本文包括泰国本地抗震设计规范、国际抗震设计准则(IBC/ASCE7-05)和CTBUH建议的比较，并集中解说结构方案、分析与设计、施工方法，并论述CTBUH低地震风险地区的抗震设计导则。

关键词: Mahanakhon Tower、世界高层都市建筑协会抗震设计导则、高层建筑、伸臂桁架、巨柱、施工顺序、PACE 发展公司 PLC

Project Information

MahaNakhon Tower is a 77-Story (including a basement level), mixed-use development in Bangkok, Thailand located in the city's central business district. The total area of the development covers approximately 120,000 square meters and comprises 200 Ritz-Carlton-branded residential units, 159 Bangkok Edition hotel rooms (operated by The Ritz-Carlton Hotel Company), and retail areas. Bouygues - Thai Ltd. was selected as the main contractor for the design-and-build contract for all structural works by the Joint Venture between Pace Development Corporation PLC and Fishman Group (IBC). Once completed in 2015/16, it will be Bangkok's tallest tower, standing at 314 meters. MahaNakhon Tower was designed by world-class team of architects, and features an effect called 'pixelation' which creates an iconic form: a three-dimensional ribbon wrapping around the building's full

项目信息

Mahanakhon Tower坐落于泰国曼谷中心商业区，为一项综合发展项目，楼高77层(包括1层地下室)，总建筑面积约120,000平方米，包括200套丽思卡尔顿旗下的公寓房间、150套曼谷版酒店房间(由丽思卡尔顿酒店营运)，还有零售空间。Bouygues泰国有限公司和Pace发展公司以及Fishman集团(IBC)所组的企业联合体接获主承包商合约，负责本项目所有结构工程的设计和建造。Mahanakhon Tower预期于2015年底至2016年初完工，届时将成为曼谷第一高塔，达314米高。塔楼由德国建筑师Ole Scheeren (Buro Ole Scheeren)所设计，利用视觉错感打造具标志性的外观: 立体丝带围绕着整座塔楼，直到顶部。悬臂式长阳台和生活空间的表面层层重迭，形成数字化的像素效果(见图一)。

这项特点成为结构方案背后的原动力，塔楼由中央核芯筒和12支巨柱所组成，巨柱

height. The impression of digital pixelation comes from the stacked surfaces of the long cantilever terraces, or living spaces (see Figure 1).

This feature was the driving force behind the structural scheme that consists of a central core with 12 mega columns that are inset away from the façade. Bouygues - Thai Ltd. has been working with ARUP (Australia) as the design advisor; Warnes, as the Thai local structural consultants; Hok Lok Siew Design Co., Ltd as the local architects, and the technical department from Bouygues Batiment International (Paris). The structural design is being reviewed by Robert Bird Ltd (Australia).

Analysis and Design

Structural System and Construction Methodology

The primary vertical structure includes the central-rectangular reinforced concrete core, 12 mega columns and three sets of outriggers. Due to the pixilation of the floor plate the columns are inset relatively close to core so that the floor plate has to cantilever significantly. A typical floor footprint dimension is approximately 39 meters by 39 meters, whilst the outside dimensions of the central core wall at ground is approximately 23 meters by 23 meters and tapers incrementally at discrete intervals up the building. Thus, the habitable floor area of the slab outside the plan area of the central core on each side of the building is approximately eight meters.

Three mega columns are located on each side of the tower approximately 5.4 meters away from the core wall surface which is almost in the middle of the floor slab area. This results in the 12 mega columns having a tributary area that is almost half of the total footprint area. This means that approximately half of the slab gravity load is supported by the 12 mega columns while the other half is supported by the center core walls (see Figure 2).

As is standard practice for a high-rise tower, the ratio of the central core to the total height of the building is 1:14, sufficient for a lateral load resisting system and serviceability without outriggers. Although MahaNakhon Tower has a ratio of 1:13.6, the outriggers are still required for several reasons. Firstly, all of the mega columns are shifted horizontally toward the center core from L19 to L20 for architectural purposes to increase the cantilever edge spans for the pixilation effect. This means that the outriggers on L19 to L20 are analogous to transfer structure that supports the misaligned mega columns. This is achieved by raking the columns between L19 to L20 and resolving the rake in the column by the floor plates and the infill outrigger walls (see Figure 3).

Similarly, the outrigger walls on L51 to L52 are required as transfer deep beams to support the addition of a row of columns above. Secondly, the outriggers are required to distribute the load from the columns to the core that in turn reduces the differential axial shortening between the core walls and mega columns. Without the outriggers connecting the columns to the core the distribution of the slab gravity load in the core walls to the mega columns would be approximately 50%-50% whilst the cross-sectional area of the mega columns is significantly smaller than the area of the core walls. Therefore, the axial stresses are significantly unbalanced between the two structural elements. With the inclusion of the outrigger walls connecting the vertical structure the load distributes favourably to 70%-30%. Finally, the outriggers improve the lateral stiffness of the tower by linking the center core walls with the surrounding mega columns to create a framing mechanism that minimise the fundamental period of the tower, the dynamic part of the wind loads, and lateral drifts and accelerations.

Figure 1. MahaNakhon Tower (Source: image courtesy of PACE Development PLC)
图一：Mahanakhon Tower（图片提供：PACE 发展公司PLC)

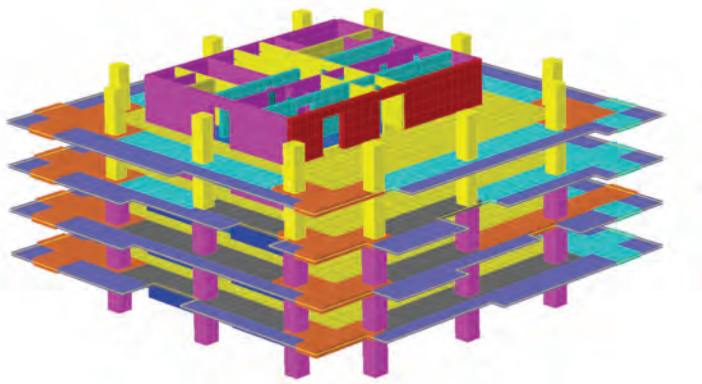

Figure 2. Typical floor 3D Finite Element Model (Source: Bouygues-Thai)
图二：标准层三维有限元模型 (来源：Bouygues-Thai)

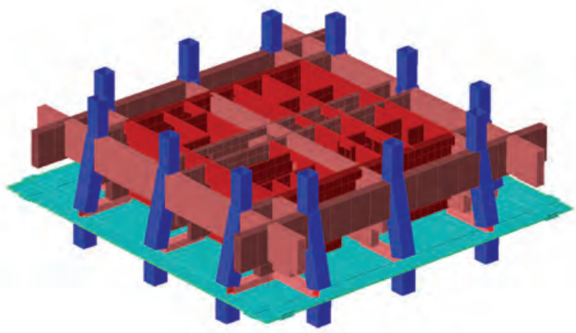

Figure 3. Outrigger Structures 3D Finite Element Model (Source: Bouygues-Thai)
图三：伸臂桁架悬结构三维有限元模型 (来源：Bouygues-Thai)

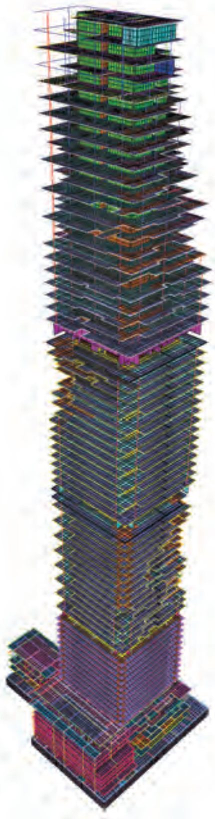

Figure 4. MahaNakhon Tower 3D Finite Element Model (Source: Bouygues-Thai)
图四：Mahanakhon Tower三维有限元模型 (来源：Bouygues-Thai)

The horizontal structural system for the typical hotel floors (L8-L18) consists of reinforced concrete slabs that are 200 millimeters thick for the internal span while the cantilever span has a thickness of 220 millimeters. The slabs are supported by post-tensioned band beams that transfer the loads to the 12 mega columns. The eight meter-edge cantilever spans require the band beam size to be 1,600 millimeters wide and 600 millimeters thick.

For the higher residential zone (L21-L68), the mega columns are shifted towards the center core for architectural purposes to increase the cantilever edge spans for the pixilation effect. This meant that the slab was required to be thick at 250 millimeters. The band beams are also wider – from 2,500 millimeters to 3,000 millimeters – depending on the areas, while the band beam thickness was maintained at 600 millimeters to accommodate building service pipes and ducts.

The whole tower is supported by a relatively deep reinforced concrete mat foundation with a total volume of 21,400 cubic meters of concrete. The thickness of the mat foundation varies from 8.75 meters under the tower area, down to 4.50 meters at the perimeter. The 129 reinforced concrete barrette piles, measuring 1.20 meters by three meters, are used to support the mat foundation with the pile tip at -65.00 meters down to the second sand layer.

Figure 4 shows the whole tower 3-dimensional finite element model including the mat foundation on the flexible supports (see Figure 4).

Construction Sequence of FE Gravity System Models
Results from preliminary analysis showed that it is necessary to connect the mega columns to the core by the outrigger walls. The outrigger walls stabilise the kink in the mega columns during construction, reduce the tie force required to resolve the kink at L19 and reduce the differential axial shortening between the core walls and the mega

嵌入远离外立面的位置。Bouygues泰国有限公司与澳洲设计顾问ARUP、泰国本地结构工程顾问Warnes、本地建筑师Hok Lok Siew设计有限公司和巴黎Bouygues Batiment 国际公司技术部携手合作，并将结构设计交由澳洲Robert Bird 有限公司做独立第三方审查。

分析与设计

结构体系及施工方法
主要结构体系以中央矩形钢筋混凝土核芯筒为主，周围附有12支巨柱以及三道伸臂桁架。由于楼板边像素效果关系，巨柱要比较接近核心筒，从而使楼板的悬挑长度比较大。Mahanakhon Tower标准楼面约为39米乘39米，而中央核芯筒的外围大小约为23米乘23米，并沿高度不规则地逐步向内收缩。因此，最上居住楼层的楼板边距离塔楼中央核心筒芯墙外侧每边约为8米。

塔楼每侧均建有3支巨柱，离中央核芯筒表面约5.4米，位置近乎楼板区的中央。这样使得12支巨柱的负载面积占总占地面积近一半，表示楼板的重力荷载的一半由12支巨柱支撑，另一半由中央核芯筒承托 (见图二)。

根据高层塔楼的标准做法，中央核心筒边长与大楼总高度的比例为1:14，足以在没有伸臂桁架的情况下，支持抗侧力体系和保持服务能力。虽然Mahanakhon Tower中央核心筒边长与大楼总高度的比例为1:13.6，但仍然需要伸臂桁架，原因如下: 首先，19到20层的所有巨柱水平移向中央核心筒位置，以增加楼板悬挑长度，达到像素化建筑效果。这就表示19到20层的伸臂桁架与支撑错位巨柱的转换结构相似。为了实现这种结构，19层与20层之间倾斜的柱子与用来分解作用力的楼板和加密伸臂悬架墙起到了主要作用。(见图三)。

同一道理，51 到 52层的伸臂桁架用作转换深梁以支持上部新增的一排柱子。其次，由于需要用伸臂桁架把巨柱的荷载传递到核芯筒，以便减小巨柱和核芯筒之间的沉降差异。如果没有伸臂桁架连接巨柱和核心筒，由于巨柱和核心筒负担的楼面重力荷载比列接近 1:1，但巨柱的横截面积远较中央核心筒面积小，导致两个结构构件的轴向应力严重不平衡，因此需要伸臂桁架以重新分配楼面重力荷载，减少核芯筒和巨柱之间的沉降差异。最后，通过连接中央核芯筒与四周巨柱伸臂桁架提高了塔楼的侧向刚度，以构建框架结构，减低塔楼的基本周期、风力荷载的动力影响性质，以及侧向位移和加速度。

酒店标准楼层(第8到18层)的巨柱范围内由200毫米厚的钢筋混凝土楼板构成，而悬臂范围则用220毫米厚的钢筋混凝土楼板。楼板由后张预应力扁梁所支撑，并将荷载传递到周边的12支巨柱。边缘部分8米的悬臂范围需要使用1600毫米宽和600毫米高的扁梁支撑。

至于较高层的住宅区(第21到68层)，巨柱移向中央靠近核心筒位置，以增加悬臂边缘面积，达到像素化建筑效果，故此所需的钢筋混凝土楼板厚250 毫米。另外，扁梁也较阔，宽度由2,500毫米到3,000毫米不等，视平面积而定，惟扁梁的高度须保持在600毫米，以保证机电管道空间。

整座塔楼由相对较厚的钢筋混凝土筏板基础所支撑，混凝土总量为21,400立方米，筏板基础厚度从塔楼中心区的8.75米，减少到边

columns. Hence, the construction sequence of the MahaNakhon superstructures was planned as follows: core walls and mega columns are cast by slip form to the first MEP transfer floors (L19-L20). Floor plates were then casted by the special forms several levels lower than the mega columns until the first MEP transfer floor (L19). Then the outrigger and belt walls (L19-L20) were casted by traditional forms. The same procedure is repeated for the second and third MEP transfer floors (L35-L36 and L51-L52), then continue up to the roof (L77).

It can be noted from the above sequences that selfweight and parts of the superimposed dead loads, such as the façade and partition load in the floor plates, were always directly distributed to the supporting mega columns before outrigger walls casting. Therefore, the finite element modelling for these load cases should reflect the actual load path in the mega columns, center core walls and outrigger walls. To achieve this, the construction sequence finite element gravity system models were chosen rather than those that are traditional, complete and instantaneously built for all the structural elements to be analysed in one go, also known as "Wished-in-Place" models.

The mega column loads in the Wished-in-Place models may be less than the actual load path because some of the mega column loads will be re-routed back to the center core by the hanging effect due to the relatively high stiffness of the outrigger walls. This behaviour leads to a less conservative mega column design load and also a less conservative mega column punching load on the raft foundation. On the other hand, the net downward forces in the outrigger will be higher than actual behaviour. This makes the net upward force in the outrigger less conservative while the net downward force will be non-economical and overestimated. These construction sequence FE models are also important for creep effect prediction in mega columns and core walls as it is required in the long-term analysis for pre-setting strategy.

In addition, MahaNakhon Tower was also modelled on the bound support conditions concept, i.e. fixed supports and long-term spring supports were used to account for the uncertainty of column load distribution. This is because the vertical structure is sensitive to the foundation stiffness due to its indeterminacy.

Wished-in-Place FE Lateral System Models

Lateral loads such as wind and seismic loads can be classified as short-term loads. They come and go after the full tower is completely constructed. Hence, the Wished-in-Place FE lateral system models were chosen for these types of loads, including live load cases. The center core wall works together with the perimeter mega columns through the outrigger system as a lateral load resisting frame. Coupling beams are assigned to be cracked under ultimate wind or seismic loads. The concept of bounded support conditions using fixed or short-term spring supports is still applied to these Wished-in-Place models. Internal forces from the gravity construction sequence models were combined with internal forces from the Wished-in-Place lateral load FE models for the design of each element. Please refer to Table 1 below for the model details and naming system. (see Table 1).

CTBUH Seismic Design Guidelines

CTBUH recommends for the seismic design of high-rise buildings that a non-linear response history analysis is necessary to determine the structural performance of high-rise buildings in the range of a moderate-to-high seismic hazard. However, in regions with low seismic hazards, a multi-mode response spectrum analysis is adequate to

缘位置的4.50米。129支钢筋混凝土方形桩，大小为1.20米乘3米，用作支持筏基，桩尖位于-65.00米处的第二层砂土层。

图四显示整座塔楼的三维有限元模型，包括弹柔性支撑的筏板基础(见图四)。

关于施工顺序的有限元重力系统模型

初步分析结果显示需要伸臂桁架将巨柱和中央核心筒结构相连接。施工时，伸臂桁架能够稳定巨柱的扭转，减少19楼控制扭转所需的连接力，同时减少核芯筒和巨柱之间的沉降差异。有鉴于此，Mahanakhon Tower上部结构的施工顺序如下：核芯筒和巨柱由滑动模板浇置到第一个机电转换层(第19到20层)，然后用特别模板将楼板浇置到巨柱低几层的位置，直到第一个机电转换层(第19层)为止，伸臂桁架墙和带墙(第19到20层)则用传统模板施工。第二和第三个机电转换层(第35到36层和第51到52层)重复相同顺序，直到完成顶层(第77层)。

根据以上顺序，自重和附加恒载，例如外立面幕墙和楼面间隔墙荷载会在伸臂桁架完成前直接传递在支撑的巨柱上。因此，这些荷载的有限元模型须反映巨柱、中央核芯筒和伸臂桁架中的实际加载路径，为此，选择施工顺序有限元重力系统模型较为合适，而不是采用传统的所有结构构件完全瞬间模型，即称为"全方位综合模型"来进行分析。

由于伸臂桁架刚度较高，部份巨柱荷载会重新回流到中央核芯筒，造成"全方位综合模型"中的巨柱荷载可能少于实际加载路径中的荷载，继而使得巨柱本身的设计荷载偏小以及巨柱在筏板基础上的冲切荷载也偏小，另一方面，使得伸臂桁架的总体向上荷载偏小，而总体向下荷载则变得超出预期很不经济。这些施工顺序有限元模型对于预设策略的长期分析，预测巨柱和中央核芯筒的徐变效应十分重要。

此外，Mahanakhon Tower的模型也是基于约束支撑概念，即运用固定支撑和长期弹簧支撑来考虑巨柱荷载分布的不确定性，这是由于其竖向结构的不确定型号对基础刚度较敏感。

	Flexible foundation		Rigid foundation	
Construction sequence FE gravity system models 关于施工顺序的有限元重力系统模型	Model naming "CS" 以"CS"命名的模型 (C-construction sequence, S-spring support) (C代表施工顺序，S代表弹簧支撑) Long term spring supports 长期弹簧支撑 Stage 1: Raft foundation only 第一阶段: 筏板基础 Stage 2: Raft to L19 第二阶段: 筏板到第19层 Stage 3: Raft to L35 第三阶段: 筏板到第35层 Stage 4: Raft to L51 第四阶段: 筏板到第51层 Stage 5: Raft to Roof 第五阶段: 筏板到楼顶		Model naming "CF" 以"CF"命名的模型 (C-construction sequence, F-Fixed support) (C代表施工顺序，F代表固定支撑) Fixed supports 固定支撑 Stage 1: Fixed support to L19 第一阶段: 固定基础到第19层 Stage 2: Fixed support to L35 第二阶段: 固定基础到第35层 Stage 3: Fixed support to L51 第三阶段: 固定基础到第51层 Stage 4: Fixed support to Roof 第四阶段: 固定基础到楼顶	
Wish-in-Place FE lateral system models 全方位综合有限元侧向系统模型	Model naming "US 475" 以"US475"命名的模型 (U-ultimate lateral forces, S-spring support, short term) (U代表侧向受力极限，S代表短期弹簧支撑)	Model naming "US 2475" 以"US2475"命名的模型 (U-ultimate lateral forces, S-spring support, short term) (U代表侧向受力极限，S代表短期弹簧支撑)	Model naming "UF 475" 以"UF475"命名的模型 (U-ultimate lateral forces, F-fixed support) (U代表侧向受力极限，F代表固定支撑)	Model naming "UF 2475" 以"UF2475"命名的模型 (U-ultimate lateral forces, F-fixed support) (U代表侧向受力极限，F代表固定支撑)

Table 1. Model Details and Naming System (Source: Bouygues-Thai)
表一：模型详情和命名系统(来源：Bouygues-Thai)

Parameters 参数	Thai local seismic code/ IBC, ASCE 7-05 泰国抗震设计规范/国际抗震规范	CTBUH Seismic Design Guidelines, Appendix B CTBUH导则与泰国抗震设计规范对比
Analysis method 分析方法	Modal analysis 模型分析	
Response spectrum 反应谱	Site Specific Hazard Assestment 场地地震危险评价	
Seismic return period 地震回归期	475 Years	2475 Years
Damping ratio 阻尼系数	5%	2%
Response modification factor, R 抗震力反应调整系数R	4	1
Seismic Mass 地震载荷计算	DL+SDL+0.25LL 静载荷+地震静载荷+0.25×活载荷	
Demand to Capacity ratio 需求能力比	1	2
Phi(Ø, Strength reduction factor) 强度折减系数Ø	0.7 to 0.9	1

Table 2. Seismic Parameter Comparison (Source: Bouygues-Thai)
表二：抗震设计参数比较 (来源：Bouygues-Thai)

Structural element 结构构件	Intermediate detailing requirements for elements with a demand to capacity ratio greater than 1 and less than 2 对于构件需求能力比在1到2之间的采用中等节点大样要求
Beams, columns and coupling beams 梁、柱和连梁	Detail in accordance with clause 21.3 of ACI318-99 as an intermediate moment frame. 中等抗弯框架采用与国际抗震规范ACI318-99条款21.3一致的节点大样要求
Outriggers 伸臂桁架	Limit the demand to capacity ratio to less than 1 to ensure an elastic response. 需求能力比限制在1以下以保证在弹性限度内
Base of Core wall 核心筒基础	If the concrete compressive strain is more 0.3% then use special shear wall detailing (i.e. boundary elements). This is only required at the base of the wall (minimum one Story). 如果混凝土压缩应变大于0.3%则采用特殊剪力墙大样 (如: 边缘构件) 只适用于与核心筒墙的基础部分 (至少一层高)
	If the concrete compressive strain is less than or equal to 0.3% then use ordinary shear wall detailing. 如果混凝土压缩应变小于等于0.3%则采用一般剪力墙大样

Table 3. The approach for the intermediate detailing of the different element types adopted for MahaNakhon Tower (Source: Bouygues-Thai)
表三：MahaNakhon Tower不同结构构件的中间大样 (来源：Bouygues-Thai)

assess the structural performance following the guidelines in Appendix B and load combinations from Thai local seismic codes which are in line with international seismic codes (IBC/ASCE7-05). The main parameters are summarised in Table 2.

The structure was first analysed and designed conforming to Thai local code which requires 475 year seismic event, 5% damping ratio with the response modification factor (R) equals to 4.0. After member sizes and reinforcements are determined, CTBUH seismic guidelines were applied to check the structural performance.

CTBUH recommends the seismic hazard to be based on the mean 2475 year spectrum demand in which the damping ratio is no greater than 2.0%. Moreover, CTBUH also states that the performance of the structure is satisfied if the ratio of strength demand-to-capacity for load combinations involving 2475 year earthquake effect is less than 2.0 for all deformation-and-force-controlled actions with expected strength capacity for deformation controlled actions and with specified capacity for force controlled actions.

When implementing CTBUH Appendix B, it was found that Step 6 required further clarification as there aren't specific intermediate detailing requirements for all structural element types. It was noted that ordinary shear walls have reasonable ductility so it was proposed that special detailing would only be required at the base of the wall where the plastic hinge would form if compression governed. The table below summarises the approach for the intermediate detailing of the different element types adopted for MahaNakhon Tower (see Table 3).

Due to the limited time frame for the design and built process, a non-linear time history analysis was impractical. Though the actual comparison of the performance assessment from this approach cannot be achieved, forces from these two approaches are presented here as a rough comparison. In order to compare the design forces, a factor of ½ is multiplied to the forces from CTBUH approach due to the fact that the allowable demand to capacity ratio is 2.0, while a factor of 1/Phi is multiplied to the forces from Thai local code.

Figure 5 shows the story shear of the whole building under Thai local seismic code and the CTBUH seismic design guidelines on different support conditions. VX and VY denote the seismic base shear in X

全方位综合有限元侧向系统模型

侧荷载如风荷载和地震荷载分类为短期荷载。整幢大厦完全建成后，这些荷载将会不断变化。故此，全方位综合有限元侧向系统模型会用于考虑这类荷载，包括活荷载。巨柱和中央核心筒结构通过伸臂桁架相连接共同形成侧向抵抗框架，在风荷载和地震荷载作用下耦合梁被设定成可开裂。运用固定或短期弹簧支撑的约束支撑概念仍适用于这类综合模型。把从重力施工顺序模型得到的内力和从"全方位综合有限元侧向系统模型"得到的内力相组合，来进行各种构件的设计。表一所示为模型详情和命名系统 (见表一)。

世界高层都市建筑学会抗震设计指导

世界高层都市建筑学会(CTBUH)对高层建筑抗震设计有一系列指引，在评估位于中至高地震风险地区的高层建筑结构表现时，必须使用非线性地震响应时程分析。不过，在低地震风险地区，多模态反应谱分析已足够用来评估结构表现，只要结构符合CTBUH抗震设计导则附件B和泰国抗震设计规范的荷载组合，两者与国际抗震规则(IBC/ASCE7-05)相符。主要参数列于表二 (见表二)。

本项目首先按照泰国抗震设计规范则在475年回归期地震作用下进行分析和设计，考虑5%的阻尼系数和响应修正系数R =4，据此，在构件尺寸和配筋确定后，再按照世界高层都市建筑学会抗震设计指引检查结构性能。

世界高层建筑与都市人居学会抗震设计指导建议的抗震设计反应谱的重现期为2,475年，建议的阻尼系数小于2% (表示结构比较有弹性和少裂痕) 。相对ASCE7-05，调整结果的抗震力高1.25倍。CTBUH不允许减低钢筋混凝土剪力墙结构的抗震力反应调整系数R，而泰国本地容许反应调整系数为4.0，因而形成较高的抗震力——CTBUH提出的抗震力是泰国的四倍。此外，按照世界高层建筑与都市人居学会 (CTBUH) 的要求，在与2,457年重现期相关的地震荷载组合下，只要所有结构单元其强度对需求能力比小于2.0，结构的性能即可达到目标，等同变形和力同时控制情况下。通常变形控制情况下具有期望的强度能力，力控制情况下具有特定的强度能力。

当运用世界高层都市建筑学会抗震设计指引附件B时，由于没有各种结构构件特定的中间大样要求，第六步需要进一步澄清。由

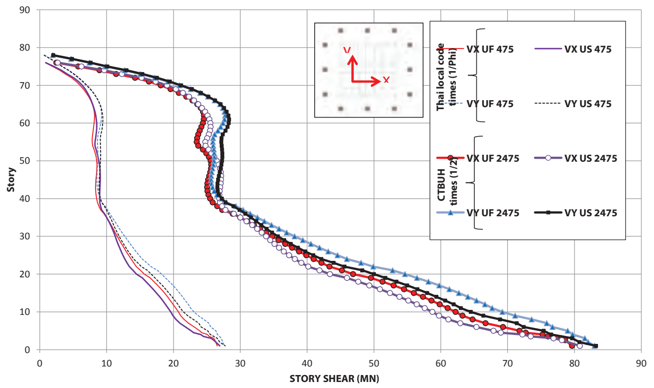

Figure 5. Seismic Story Shear (Source: Bouygues-Thai)
图五：地震荷载作用下层间剪力 (来源：Bouygues-Thai)

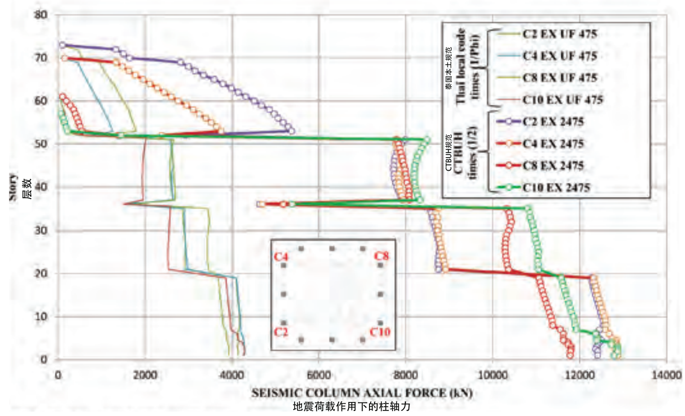

Figure 7. Seismic Column Axial Forces (Source: Bouygues-Thai)
图七：地震荷载作用下柱轴力 (来源：Bouygues-Thai)

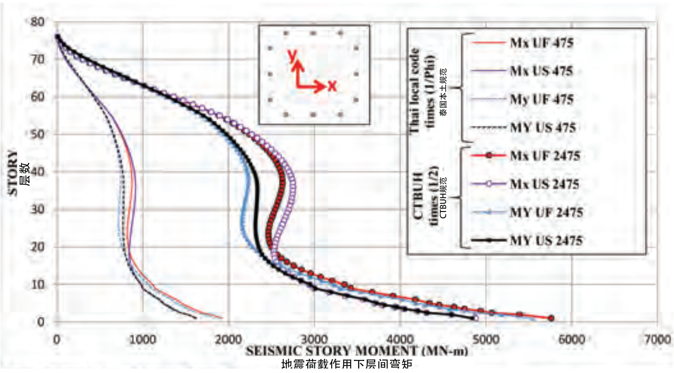

Figure 6. Seismic Story Moment (Source: Bouygues-Thai)
图六：地震荷载作用下层间剪力 (来源：Bouygues-Thai)

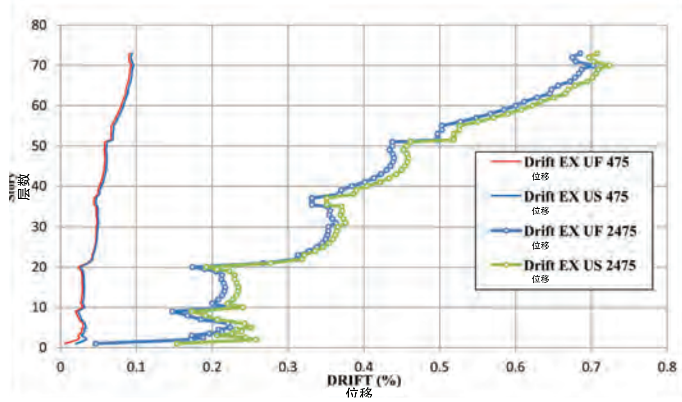

Figure 8. Seismic Story Drift (Source: Bouygues-Thai)
图八：地震荷载作用下层间位移 (来源：Bouygues-Thai)

and Y directions, respectively. The naming system of the models was explained in Table 1. Maximum base shears in both X and Y directions are almost identical for the same seismic return period. The fixed support condition has slightly higher base shears than the spring support condition. What is particularly interesting is that the base shears following CTBUH seismic guidelines are approximately three times higher than the Thai local seismic code (see Figure 5).

Figure 6 shows a story moment for both approaches. As expected, the story moments are also approximately three times higher in the case of CTBUH for both support conditions (see Figure 6).

Figure 7 illustrates the seismic load cases column axial force distribution. Clearly, the column forces C2, C4, C8 and C10. (named in Figure 7) are three times higher in the case of CTBUH than in the Thai local code as well (see Figure 7).

Figure 8 demonstrates the inter-story drifts that are all well under the 1.5% limit, as specified in Thai local seismic code and IBC/ASCE 7-05. Please note that there is no such limit in CTBUH seismic design guidelines (see Figure 8).

Since the load combinations involving seismic forces are not often the major cases that govern section design, the results show that the seismic strength demand to capacity ratio of all elements are less than 1.0. Therefore, earthquake-related construction details are not required. Hence, designing with a better performance level target with CTBUH recommendations instead of local Thai seismic code enhances the improvement of overall behaviour of the tower under seismic conditions by strengthening key seismic resisting elements with few design amendment.

于通常剪力墙具有合理的延性，所以它提出只有压缩力为支配情况下剪力墙底部形成塑性较时才需要特别大样。下表所示为MahaNakhon Tower的各种结构构件所采用的中间大样汇总。(参见表三)

由于设计和施工时间紧迫，不可能进行非线性时程分析。尽管无法进行非线性时程分析从而进行性能评估的真正比较，从两种情况得到的内力值汇总在此以便进行大致比较。为比较设计内力，用系数½乘以按照世界高层都市建筑学会抗震设计指引建议得到的内力，因为允许需求强度比为2，而泰国规范是乘以系数Ø。

以Mahanakhon Tower为例，由于泰国本地规范和CTBUH导则的支撑需求不同，图五显示全幢大楼的抗震层剪力。VX和VY分别表示X和Y方向基底剪力。表一已解释模型的命名系统。X和Y方向的最大基底剪力在相同的地震重现期差不多完全相同。固定支撑情况下的基底剪力比弹簧支撑稍高。值得留意的是，根据CTBUH抗震指引产生的基底剪力比泰国本地规范高约3倍 (见图五)。

图六为两种抗震设计规范的层间弯矩。与估计一样，在两种支撑情况下，CTBUH的层间弯矩为泰国本地规范的3倍 (见图六)。

图七为地震荷载作用下的柱轴力分布。很明显，CTBUH指引下，C2、C4、C8和C10(见图七)的柱轴力比泰国本地规范得出的高约3倍 (见图七)。

图八显示抗震层间位移均低于泰国本地抗震规则和IBC/ASCE7-05限制的1.5%，CTBUH导则并未订明此限制 (见图八)。

由于和地震荷载组合情况不是控制截面设计的主要组合，结果显示对大部分构件而言，抗震强度需求对抵抗能力的比值均小于1.0。因此，不需要抗震节点大样。同时，通过修改加固主要的抗震

Conclusion

1. MahaNakhon Tower was designed taking into consideration the actual construction sequences using bounded support conditions: fixed supports and long-term/short-term spring supports to ensure that the structural main elements such as mega columns, outriggers, core walls and raft foundation can resist the possible load distribution.
2. CTBUH seismic design guidelines require stronger response spectrum accelerations and more elastic properties in the structural elements in terms of a lower damping ratio without any response modification factor. However, CTBUH allows the demand-to-capacity ratio to be as high as 2.0 without any capacity reduction phi, Ø.
3. Since the seismic loads govern only in some portions of the building, then the higher demands from CTBUH can be taken cared to ensure the structural performance. This CTBUH approach is economically appropriate for the high-end luxury tower like MahaNakhon
4. Appendix B of the CTBUH seismic guidelines mostly gives recommendations on strength issues and detailing requirements which are more about ductility; especially when the demand to capacity ratio is greater than 1.0. No deformation/drift limit is specified.

构件的设计，即可保证本项目可达到世界高层都市建筑学会抗震设计指引建议的好过泰国规范所定的性能目标。

总结

1. Mahanakhon Tower的设计考虑到运用约束支撑的实际施工顺序。固定支撑和长期/短期弹簧支撑确保主要结构单元(包括巨柱、伸臂桁架、中央核心筒和筏基)能够抵御实际可能的荷载分布。
2. 世界高层都市建筑学会抗震设计导则要求较强的反应谱加速和更为有弹性的结构构件，阻尼比较低，且没有任何反应调整系数。但CTBUH允许需求能力比可达2.0，且没有任何强度折减系数Ø。Mahanakhon Tower建有钢筋混凝土剪力墙，整体地震荷载会较泰国本地规范的高约7.5倍，确保优质结构表现。
3. 由于地震荷载只在本大楼某些位置其控制作用，那么按照世界高层都市建筑学会更高的要求可以保证结构性能，这种做法对于像Mahanakhon Tower这样的高端豪华大厦而言是一种经济合适的。
4. 世界高层都市建筑学会抗震设计导则附件B主要指出有关强度以及大样的建议，更注重延性，特别是需求能力比大于1.0的情况。并未订明变形和位移限制。

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