Title: **Application of Buckling Restrained Braces in a 50-Story Building**

Authors: Jose A. Sy, Principal, SY2 + Associates, Inc.
Naveed Anwar, AIT-Consulting
Thaung Htut Aung, AIT-Consulting
Deepak Rayamajhi, AIT-Consulting

Subjects: Conservation/Restoration/Maintenance
Seismic
Structural Engineering

Keywords: Concrete
Seismic
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 Unpublished conference paper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 Unpublished

Application of Buckling Restrained Braces in a 50-Story Building
一座50层高建筑中屈曲约束支撑的应用


Jose A. Sy


Naveed Anwar


Thaung Htut Aung


Deepak Rayamajhi

Jose A. Sy

SY² + Associates, Inc.
Phillippines

email (电子邮箱): boysy@sysquared.com

Jose A. Sy has over 30 years of extensive experience in structural design engineering in a wide variety of projects, such as high-rise structures, commercial buildings, condominiums, hotels, call centers, banks and industrial facilities

Jose A. Sy在结构设计工程领域中具有超过30年的丰富经验，参与过多种工程项目，如高层结构，商业建筑，公寓，酒店，信息服务中心，银行和工业设施等。

Naveed Anwar, Thaung Htut Aung & Deepak Rayamajhi

AIT-Consulting
Thailand

email (电子邮箱): nanwar@ait.ac.th, aung.aitc@ait.ac.th

Naveed Anwar has over 25 years of extensive experience in the conception, planning, analysis, design, detailing and evaluation of multi-story buildings, bridges, water retaining structures, industrial buildings and special structures

Naveed Anwar具有超过25年的丰富工作经验，曾对多层建筑，桥梁，挡水结构，工业建筑和特殊结构的概念，规划，分析，设计，以及深化和评估

Thaung Htut Aung's field of expertise includes analysis and design of tall buildings, Structural Design Review, Structural Evaluation and Remedial Measure, Earthquake Engineering, and Performance-Based Design and Evaluation of Buildings.

Aung先生的专业领域包括高层建筑的分析与设计，结构设计审核，结构评估和补救措施，地震工程，以及建筑的绩效设计和评估。

Deepak Rayamajhi is currently an External Consultant for Performance-Based Design. His field of expertise includes Performance-Based Seismic Design of Tall Buildings, Structural Dynamics, Earthquake Engineering, Bridge Retrofitting, Micro hydropower design, analysis and design of structures.

Rayamajhi先生目前是绩效设计的外部顾问。他的专业领域包括高层建筑的抗震性能设计，结构动力学，地震工程，桥梁改造，微水力发电设计，分析和结构设计。

Abstract

The use of Buckling Restrained Braces (BRB) for enhancing the performance of tall buildings is gaining wider acceptance. This paper presents the first application of these devices in a major high-rise building in the Philippines, a 50-story residential reinforced concrete building with ductile core wall and BRB. The detailed modeling and design procedure of buckling restrained brace system is presented for the optimal design against the two distinct levels of earthquake ground motions; serviceable behavior for frequent earthquakes and very low probability of collapse under extremely rare earthquakes. The stiffness and strength of the system are adjusted to optimize the performance of the structural system under different levels of earthquakes. Response spectrum analysis is conducted for Design Basis Earthquake level and Service level, while nonlinear time history analysis is performed for the maximum possible earthquake.

Keywords: Buckling Restrained Braces, Performance Objectives, Non-Linear Time History

摘要

采用屈曲约束支撑（BRB）提高高层建筑性能已被广泛接受。本文介绍了在菲律宾首次应用这些结构装置的一栋主要高层建筑。对一栋50层高住宅建筑的钢筋混凝土结构中的延性核心筒墙和BRB系统进行了研究。为抵抗两个完全不同级别的地震地层运动优化设计，以及对在频繁地震中的可维修性和在极其罕遇的大地震情况下极低的倒塌可能性，提出了BRB系统的详细建模和设计过程；根据不同等级的地震，调整BRB系统的刚度和强度以优化结构体系性能。为设计基准地震（DBE）级别和可使用水平别进行反应谱分析，同时对最大可能发生地震进行非线性时程分析。

关键词：屈曲约束支撑，性能为目标，非线性时程

Introduction

Buckling restrained braces (BRBs) are widely used in seismic design and retrofitting of buildings, especially in the United States and Japan. The effective use of BRBs enhances the performance of the structural system under severe earthquakes (Dutta and Hamburger 2011).

BRBs have been used successfully in a number of projects in Japan and in the United States, including retrofitting of existing and new building construction to reduce the seismic induced responses (Ahmed 2011).

In this case study, a BRB system is utilized for the first time in the design of a 50-story tower, located in Makati City, Philippines. The case study building is 166.8-meter tall reinforced concrete residential building, standing on a one-level podium, with a tower plan area of 34.5 m x 26 m. Reinforced concrete bearing walls, gravity columns and post-tensioned (PT) flat slabs are used in the gravity load resisting system. The typical plan and elevation view are shown in Figure 1 and Figure 2, respectively. The typical story height of the building is 3.1 m.

The lateral load resisting system consists of a reinforced concrete bearing wall coupled with outrigger columns, connected by the BRBs (as

引言

屈曲约束支撑系统（BRBs）在建筑的抗震设计和结构改建中已被广泛采用，特别是在美国和日本。有效地采用BRB能够优化结构系统在强烈地震中的性能（杜塔和汉堡2011）。

BRB已成功被应用于日本和美国的多项工程之中，其中包括现有建筑结构改造和新建筑工程以降低由地震引起的反应（艾哈迈德·2011）。

在这个被研究的案例中，BRB系统第一次在这栋位于菲律宾马卡蒂市的50层高塔楼的设计中获得了应用。该项目是一栋166.8米高的钢筋混凝土结构的住宅建筑，位于一层高的裙楼之上，塔楼平面面积为34.5米×26米。在抗重力体系中采用钢筋混凝土承重墙，立柱和后张预应力（PT）平板。标准平面和立面图分别显示在图1和图2之中。标准建筑层高为3.1米。

抗侧力系统由钢筋混凝土承重墙与外伸支架柱所组成，沿弱轴方向（如图1所示）由BRB连接（如图3所示）。共使用16 个BRB，每个BRB在两层楼之间连接。8个BRB位于19层和23层之间，其余8个BRB位于43层和47层之间。BRB是由星震公司（Star Seismic Inc.）生产制造的。建筑有设在基础底板上的3层半地下停车库。塔楼主要包括住宅单元，露台和配套设施层。地面层包含零售和后勤空间。项目总面积约

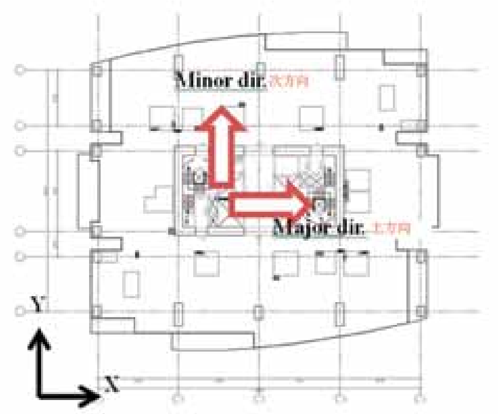

Figure 1. Typical floor plan of tower
图1. 塔楼标准楼层平面图

shown in Figure 3) along the weak axis direction (as shown in Figure 1). Sixteen BRBs are used, in which each BRB is connected in between two floors. Eight BRBs are located in between the 19th and 23rd floors and the remaining eight BRBs are located in between the 43rd and 47th floors. The BRBs are manufactured by Star Seismic Inc. The building has 3½-stories of below-grade parking, resting on the mat foundation. The tower consists mainly of residential units, and a terrace and amenity deck. The ground level contains retail and back of the house space. The total project area is approximately 79,000 square meters gross. This building was the first building to apply BRBs as a lateral load resisting system in the Philippines.

In this paper, the overall procedure for the performance- based design of tall buildings is described. In the following section, the application of BRB is explained followed by seismic performance objective, design criteria, and acceptable limits for the project are described. Moreover, several modeling techniques are explained and final results are presented from nonlinear time history analysis.

Application of BRB

Conventional earthquake resistant structural systems depend on strength and ductility to control seismic responses. In this strategy, seismic energy is absorbed by the formation of plastic hinges in specifically designed regions, such as plastic hinges at the base of the wall and at the ends of the coupling beams. These regions should be able to deform into an inelastic range and sustain reversible cycles of plastic deformation without degrading strength and stiffness to a level which could harm the stability and integrity of the structure. However, the structure may suffer structural and non-structural damage to an extent that it may not be economically repairable (Ahmed 2011).

To avoid this, another strategy which incorporates energy dissipating devices in the structural system to reduce the inelastic energy dissipation demand on the framing system was developed. In this strategy, if the structural components may remain elastic during an earthquake, the structural and non-structural damage may be considerably reduced. BRBs are one of the promising options to use as the energy dissipating devices (Ahmed 2011).

BRBs are commonly made from encasing a core steel cross-shape or flat bar member into a steel tube casing and confined by infill concrete. The core and infill concrete are decoupled by the un-bonding material to prevent interaction between them. Accordingly, the axial load of the brace is transmitted by the steel core only, while the casing, through its flexural rigidity, provides the proper lateral support against flexural buckling of the core. The steel core member is designed to resist the

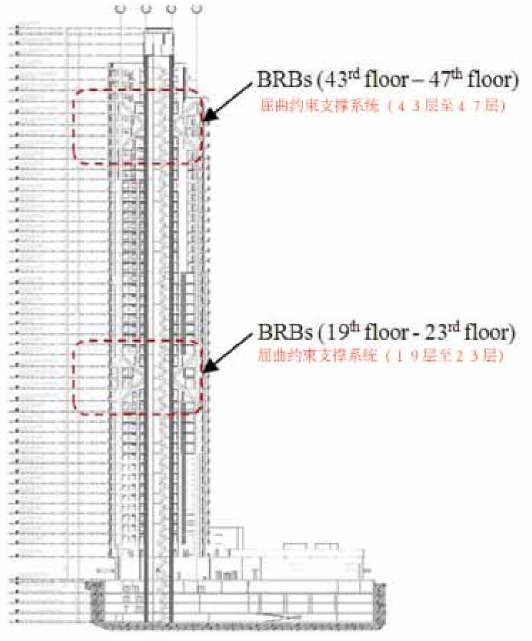

Figure 2. Sectional view
图2. 剖面图

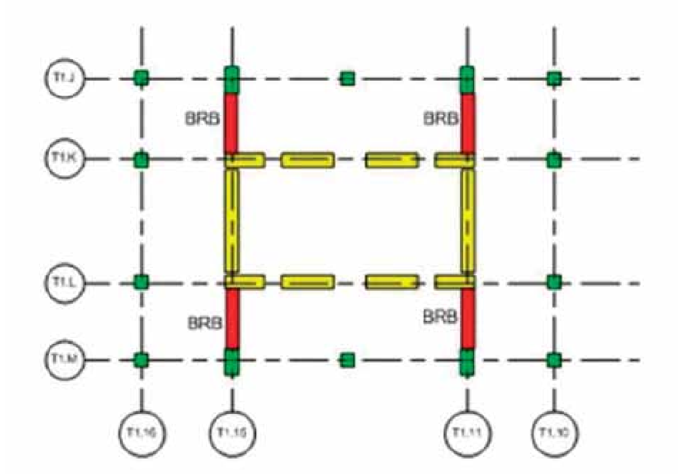

Figure 3. BRB Locations in plan
图3. BRB在平面中的位置

为79,000平方米。这是菲律宾第一栋采用以BRB作为抗侧力系统的建筑。

本文对高层结构性能化设计的全过程进行讨论。在以下部分中，接着对BRB的应用分别从抗震性能目标，设计标准，以及相关设计标准，和接受限度等方面逐一进行了分析说明。此外，还有一些建模技术的说明和对从非线性时程分析得出的最终结果的汇报。

BRB的应用

传统抗震结构体系依赖于强度和延性来控制地震反应。在这一策略中，地震能量被设在特定设计区域的塑性铰接构造所吸收，如在墙基和连梁两端的塑性铰接。这些区域应该能够变形至一个无弹性的范围，同时维持塑性变形的可逆循环而不降低强度和刚度以至于导致损害结构的稳定性和完整性的水平。然而，结构可能受到结构性和非结构性上的损害导致在经济效益上有无可修复的程度。（艾哈迈德·2011）。

为了避免这种情况，另一种策略为在结构体系中结合耗能装置以减少在框架体系中产生的非弹性耗能需求。在这个策略中，如在

axial forces with a full tensile or compressive yield capacity without the local or global flexural buckling failure. BRB in a frame structure typically consists of the BRB itself, a length of steel member that is stronger than the BRB and stiff end regions consisting of gusset plates and the beam-column joint region.

Seismic Performance Objectives

The specific seismic performance objectives are defined for the design of the case study building against three levels of earthquake hazards. These performance objectives are based on the Los Angeles Tall Buildings Structural Design Council (LATBSDC 2008) for the performance-based design of tall buildings (Fry et al. 2010)

Frequent/Service Level Earthquakes

(50% of the probability of meeting seismic performance levels in 30 years with 43-year return period): The structure should remain essentially elastic with minor damage to structural and non-structural elements, remaining serviceable after earthquakes.

Maximum Considered Earthquake Level

(2% probability of meeting seismic performance levels in 50 years with 2475-year return period): Substantial damage to the structure is allowed, potentially including significant degradation in the stiffness and strength of the lateral force resisting system. The building may be on the verge of partial or total collapse.

Additionally, in order to maintain the design of the building to the level of conventional design code, the design of the building is also considered for Design Basis Earthquake (DBE) Level (As defined by ASCE 7-05, Section 11.4): Moderate structural damage is allowed in which extensive repairs may be required. However, it should be noted that this level of design is omitted from LATBSDC (2008) guidelines.

Overall Design Procedure

Three phases are involved in the overall design procedure to meet the performance objectives: 1) Preliminary Design; 2) Service Level Evaluation; and 3) Collapse Prevention Level (MCE level) Evaluation.

Preliminary Design

In this phase, elastic response spectrum analysis and design are performed in accordance with the code-based design approach by using appropriate load factors and strength reduction factors against the gravity loads, wind load and seismic load. Appropriate initial sizes of BRBs are used in the analysis. Site specific response spectrum for DBE level is used for the preliminary design phase. Structural components to remain elastic are designed by applying the appropriate amplification factors.

Service Level Evaluation

Primary response characteristics such as story drift, coupling beam and shear wall demand to capacity ratios are checked against the demands resulting from the response spectrum analysis using site specific service level response spectrum with 43-year return period (50% of probability of meeting seismic performance levels in 30 years). The required capacities of BRBs are determined so they remain elastic under the service level earthquakes.

Collapse Prevention Level Evaluation

Design verification is performed by nonlinear response history analysis (NLRHA) against the MCE level earthquakes with 2475-year return period (2% of probability of meeting seismic performance levels in 50 years). Seven pairs of site specific ground motions are used to conduct

地震时结构构件可能保持弹塑性，结构性和非结构性的损坏可能性会大大减少。BRB作为耗能装置是一个很有发展前途的选择。（艾哈迈德・2011）

BRB系统通常是以钢套管外包十字形核心钢或扁钢件并以混凝土内填制成。核心钢和内填混凝土以无粘结材料分离，以防止它们之间的相互作用。因此，支撑的轴向荷载只由钢核心传送，而套管，通过其抗弯刚度，提供适当横向支撑以防止核心的屈曲。设计的核心钢构件以完全拉压承载能力承受轴向荷载而不造成局部或全部的屈曲屈服。BRB在框架结构中通常包括BRB钢构件本身，钢构件的一段比BRB刚度更强，固定端区域由角撑板和梁柱节点区域组成。

抗震性能目标

具体抗震性能目标是针对抵抗三个级别地震的范例建筑设计所定义的。这些性能目标是基于洛杉矶高层建筑结构设计理事会（LATBSDC2008）对高层建筑的性能设计的规定。（Fry等2010）

频繁/可使用程度地震

（30年内有50%机率可遇到与该抗震性能相符的震级，重现周期为43年）：结构应保持本质上的弹塑性，其结构性和非结构性构件带有轻微损坏，在地震之后可继续使用。

最大考虑地震级别

（50年内有2%机率可遇到与该抗震性能相符的震级，重现周期为2475年）：实质性结构损害是允许的，潜在地包括抗侧力体系的刚度和强度明显的劣化。建筑可能达到部分或全部倒塌的临界状态。

此外，为了保持建筑设计达到常规设计规范的水平，建筑设计也考虑设计基准地震（DBE）级别（ASCE7-05，第11.4章节的定义）：可能需要大幅度修复的中等结构损害是容许的。然而，应当指出的是，这一设计级别已从LATBSDC准则（2008）中被删除。

整体设计过程

整体设计过程涉及三个阶段以符合性能目标：1）初步设计;2）可使用程度评估;3）防止倒塌程度（MCE水平）评估。

初步设计

在这个阶段，以规范为基础的设计方法进行弹性反应谱法分析和设计，使用适当荷载系数和承受重力荷载，风荷载和地震荷载的强度折减系数。分析中使用BRB的适当初始尺寸。初步设计阶段使用设计基准地震（DBE）级别的现场具体反应谱法。采用适当的放大系数设计结构构件以保持弹性。

可使用程度评估

对主要响应特性中诸如楼层位移，连梁和剪力墙需求与承载力之比与采用现场特定可使用水平，重现周期为43年（30年内有50%机率可遇到与该抗震性能相符的震级）的反应谱法分析所得的需求结果进行检查对比。BRB所需的承载力得以确定使它们在可使用水平地震荷载作用下仍保持弹性。

防止倒塌程度评估

通过非线性反应时程分析（NLRHA）与重现周期为2475年的最大考虑地震（MCE）级别地震（50年内有2%机率可遇到与该抗震性能相符的震级）比较进行设计验证。用七对场地特定地层运动形式来进行非线性响应时程分析。以七个地层运动形式方法得出平均需求并用于MCE级别中的设计评估。按需要调整初步设计以符合验收准则。

检查连梁，核心筒墙弯曲响应和BRB的预期非线性响应。而在检查非线性响应时程分析时，核心筒墙剪力，隔板，地下层墙，基础和柱以保持本质上的弹塑性。

the nonlinear response history analysis. Average of demands from a seven ground motions approach is used for design evaluation at MCE level. The preliminary design is modified as required in order to meet the acceptance criteria.

Coupling beams, core wall flexural response and BRBs are checked in anticipation of a nonlinear response while core wall shear, diaphragms, basement walls, foundations and columns are checked to remain essentially elastic during the nonlinear response history analysis.

Seismic Performance Criteria

Service Level

The expected responses of building components to fulfill the performance objective at Service level earthquake are shown in the Table 1.

Maximum Considered Earthquake Level

The expected responses of building components to fulfill the performance objective at MCE level earthquake are shown in Table 2.

Finite Element Modeling

A complete three-dimensional finite element model is created, which includes the tower and the whole podium. For the evaluation of nonlinear response of the building under MCE level earthquakes, the flexural response of core wall, slender coupling beams and slab outrigger beam; the shear response of deep coupling beams and the axial load response of BRBs are modeled with nonlinear force-deformation behavior. The modeling and analysis of building for evaluation and design at Service Level earthquake and DBE level are carried out in ETABS 9.5 computational platform. An elastic model is created with the specified material properties and appropriate stiffness modifiers for the structural components. For the MCE level performance evaluation, a nonlinear three-dimensional model is created in PERFORM-3D (Version 4.0.4) computational platform.

Analysis Tools

The modeling and analysis of a building for evaluation and design at Service Level earthquake and DBE level are carried out in ETABS 9.5 computational platform. An elastic model is created with the specified material properties and appropriate stiffness modifiers for the structural components. For the MCE level performance evaluation, nonlinear three-dimensional model is created in PERFORM-3D (Version 4.0.4) computational platform.

Nonlinear Modeling of Buckling Restrained Braces

PERFORM-3D-"BRB compound component" is used to model the BRBs. The BRB compound component has three parts: 1) BRB basic component, which incorporates the nonlinear behavior (inelastic deformation) of BRBs; 2) Elastic bar basic component, which corresponds to the BRB steel outside the main inelastic zone; and 3) Stiff end zone, with a specified length and a cross sectional area that is a multiple of the elastic bar area. The end zone accounts for the gusset plates at both ends of the member. The backbone curves used for the modeling of BRB is shown in Figure 4.

The coefficients Ry, ω and β are estimated based on the properties of the BRBs provided by Star Seismic Inc. The initial stiffness (Ko) of the BRB is estimated based on cross sectional properties and material properties by A_sE/L (where A_s cross sectional area of steel, E is Young's Modulus of Elasticity of steel, and L is the effective length of the brace in inelastic behavior i.e. approximately 70% of the pin to pin BRB length).

Item 项目	Value 值
Story drift 层间位移	0.5%
Coupling beams (conventional shear reinforcement) 连梁（传统剪力加固）	Shear strength to remain essentially elastic 抗剪强度保持本质上弹性
Core wall flexure 核心筒墙弯曲	Remain essentially elastic 保持本质上的弹性
Core wall shear 核心墙剪力	Remain essentially elastic 保持本质上的弹性
BRBs 屈曲约束支撑系统	Remain elastic 保持弹性

Table 1. Performance Criteria for Service Level Earthquake
表1. 可使用水平地震的性能标准

Item 项目	Acceptable Value 可接受值
Story drift 层间位移	3%
Coupling beam rotation (diagonal shear reinforcement) 连梁旋转（对角线剪力加固）	0.06 radian rotation limit 0.06 弧度的旋转极限
Coupling beam rotation (conventional longitudinal reinforcement) 连梁旋转（传统的纵向加固）	0.025 radian rotation limit 0.025弧度的旋转极限
Core wall reinforcement axial strain 核心筒墙钢筋轴向应变	Rebar strain = 0.05 in tension and 0.02 in compression 钢筋应变= 0.05受拉及0.02受压
Core wall concrete axial strain 核心筒墙混凝土轴向应变	Concrete Compression Strain = 0.004 + 0.1 ρ(fy / f'c) 混凝土压缩应变=0.004 + 0.1 ρ(fy / f'c)
Core wall shear and basement walls 核心筒墙剪力和地下层墙	Average shear demand times 1.3 平均剪力需求x1.3

Table 2. Performance Criteria for MCE Level Earthquake
表2. MCE级别地震的性能准则

抗震性能标准

可使用程度

以满足可使用程度地震性能目标的建筑构件预期反应，如表1所示 。

最大考虑地震级别

以满足MCE级别地震性能目标的建筑构件预期反应，如表2所示。

有限元模型

建立一个完整的三维有限元模型，其中包括塔楼和整个裙房。为验证建筑在MCE级别地震荷载作用下的非线性响应，核心筒墙，细长连梁和楼板外伸支架梁的弯曲响应;深连梁的剪力响应和BRB轴向荷载的响应，以非线性承载变形特性进行建模。采用ETABS中9.5计算平台评估与设计在可使用水平和DBE级别地震荷载作用下的建模和建筑分析。为带指定材料特性和适当刚度修正的结构构件建立一个弹性模型。为MCE级别的性能评估，在PERFORM-3D（4.0.4版）的计算平台中建立非线性三维模型。

分析工具

采用ETABS中9.5计算平台评估与设计在可使用水平和DBE级别地震荷载作用下的建模和建筑分析。为带指定材料特性和适当刚度修正的结构构件建立一个弹性模型。为MCE级别的性能评估，在PERFORM-3D（4.0.4版）的计算平台中建立非线性三维模型。

BRB的非线性模型

PERFORM-3D-“BRB复合构件”用于制作BRB模型。BRB复合构件有三个组成部分：1）BRB基本构件，其中结合BRB非线性特征（非

Nonlinear Modeling of Ductile Core Wall

Orakcal and Wallace (2006) presented several modeling techniques for ductile reinforced concrete wall. Fiber modeling is used to study the nonlinear flexural behavior of the core wall. For the given wall cross-section, quantity of longitudinal reinforcement, and transverse reinforcement, the modeling of wall involves: 1) dividing the wall cross-section into concrete (unconfined and confined) fibers and reinforcement fibers; 2) selection of appropriate constitutive models for concrete and steel; and 3) providing appropriate boundary conditions (Orakcal and Wallace 2006, Wallace 2007).

The PERFORM-3D shear wall element is used to model the nonlinear behavior of core wall. Two parallel fiber sections are used to model the shear wall section. The first fiber section consists of only uniformly distributed steel and the second fiber section consists of both concrete and boundary zone steel reinforcement. For the uniformly distributed steel, auto-size fiber elements are used, whereas for a latter one, fixed size fiber elements are used. The height of fiber element is modeled as floor height at every floor level except at podium level, where wall is separated into 5 elements along the longitudinal axis of the tower. Shear behavior in the wall is modeled with elastic material properties.

Nonlinear Modeling of Coupling Beams

In this building, two types of coupling beams are present. First one is a deep beam with a span to depth ratio of 1.9 (span/depth < 4), and second one is a slender beam with a span to depth ratio of 4.3 (span/depth > 4). Since deep beams are dominated by shear behavior, they are modeled as shear deformation controlled behavior while the slender beams are modeled as flexural deformation controlled behavior.

The modeling of coupling beams were carried out by procedure described in Wallace (2007) and Wallace et al. (2009).The deep coupling beam is modeled with an elastic frame section with a nonlinear shear hinge located at the mid span of the element. The capacity of the shear hinge is calculated based on the diagonal reinforcements. The elastic stiffness of the deep beams is reduced to 0.16EIg. The effective stiffness calculation is based on the dimension and required ductility (Wallace et al. 2009). The ultimate capacity is taken as the 1.33 times of the yielding capacity.

The slender coupling beam is modeled with two moment hinges, located at the ends of the beam. The capacity of the moment-curvature hinges are calculated based on the longitudinal reinforcements provided in the beams. The deformation capacities are used in accordance with ASCE 41-06 for flexural coupling beams. The elastic stiffness of the slender beams is reduced to 0.5EIg (ASCE 41-06).

Nonlinear Modeling of Slab Outrigger Beams

In the tower portion, the floor is modeled as rigid floor diaphragm. The slab is not modeled as an area element in the tower. However, equivalent "slab outrigger beams" are used in the model in order to determine the nonlinear response of post-tensioned slab, interaction with core wall and columns. Slab outrigger beams are modeled with nonlinear hinges at both ends of the beam (as shown in Figure 5). Moment-curvature type hinges are used to model nonlinearity in the slab-beam. The moment capacity of the slab beam is calculated based on the reinforcement in the slab. The nonlinear properties of the moment hinges were matched to the study of Klemencic et al. (2006). The post-tensioning effect is considered in the calculation of the flexural yielding capacity of the slab. However, the performance of the moment hinges is not specifically reviewed.

At the podium and basements level, the slabs are modeled without a

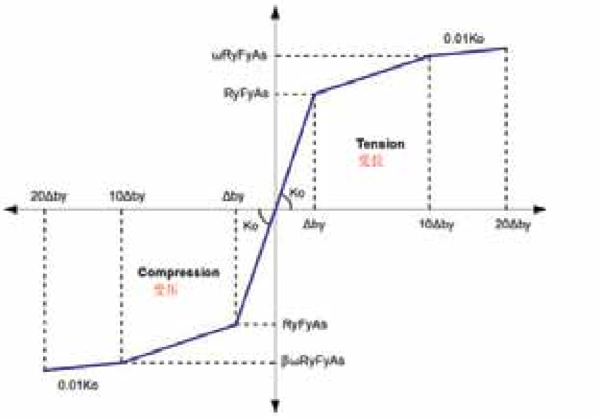

Figure 4. Assumed Backbone Curve for Buckling-Restrained Braces
图4. 为BRB所假设的骨架曲线

弹性变形）;2）弹塑性杆基本构件，相当于BRB钢构件外的主要无弹性区;3）固定端区，具有指定的长度和一个乘倍于弹性钢条面积的横截面面积。构件两端计入角撑板的构成末端区。BRB模型用的骨架曲线如图4所示。

Ry，ω和β系数值是根据星震公司（Star Seismic Inc.）所提供的BRB特性资料估计的。BRB的初始刚度（Ko）的估计是基于A_sE/L的横截面属性和材料性质（A_s为钢的横截面积，E是钢的杨氏钢弹性模量，L是BRB在无弹性行为中的有效长度，如约70%的销钉至销钉BRB长度）。

延性核心筒墙的非线性模型

Orakcal和Wallace（2006）提出了延性钢筋混凝土墙的几个建模技术。纤维模型是用来研究核心筒墙的非线性抗弯性能。对于给定的墙体横截面，纵向，横向钢筋的数量，墙体模型包括：1）墙横截面分成为混凝土（无约束和约束）纤维和钢筋纤维;2）为混凝土和钢材选择适当的本构模型，以及3）提供适当的边界条件（Orakcal和Wallace2006年，Wallace2007年）。

PERFORM-3D剪力墙元素用于模拟核心筒墙的非线性特性。两个平行的纤维截面被用来模拟剪力墙断面。第一个纤维截面仅有均匀分布的钢材，第二个纤维截面同时由混凝土和边缘区钢筋组成。关于均匀分布的钢材，使用自定尺寸的纤维元素，而后者使用固定尺寸的纤维元素。纤维元素的高度模拟除裙房层以外的每一层楼层高度，同时沿塔楼纵轴方向的墙被分隔成5个单元。墙内剪力反应由具有弹性属性的材料模拟。

连梁的非线性模型

在此栋建筑中，存在两种类型的连梁。第一种是跨高比为1.9（跨度/高度<4）的深梁， 第二种是跨高比为4.3（跨度/高度>4）的细长梁。由于深梁主要受剪力作用，它们被模拟为受剪力变形控制，同时细长梁被模拟为受弯曲变形的控制。

根据Wallace（2007年）和Wallace等人（2009年）描述的步骤建立连梁模型。以弹性框架部分并在该元素的中跨设非线性剪力铰链模拟深连梁。剪力铰链的承载力计算是以对角加固为基础。深梁弹性刚度被降低至0.16EIg。有效刚度计算是基于尺寸和所需的延性（Wallace等，2009年）。极限承载力是屈服承载力的1.33倍。

细长连梁被模拟为梁端设两个弯矩铰链。根据提供给梁内纵向钢筋计算弯矩曲度铰链的承载力。所采用的变形能力是按照ASCE41-06的弯曲连梁。细长梁的弹性刚度被降低至0.5EIg（ASCE41-06）。

平板外伸支架梁的非线性模型

在塔楼部分，楼板被模拟成应刚性楼层隔板。楼板不被模拟成塔楼的面积元素。然而，在模型中采用类似的“平板外伸支架梁”以确定后张预应力楼板，与核心筒墙和柱之间相互作用的非线性

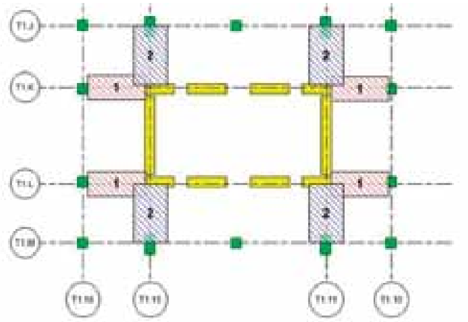

Figure 5. Slab Outrigger Beams in Plan
图5. 平板外伸支架梁平面

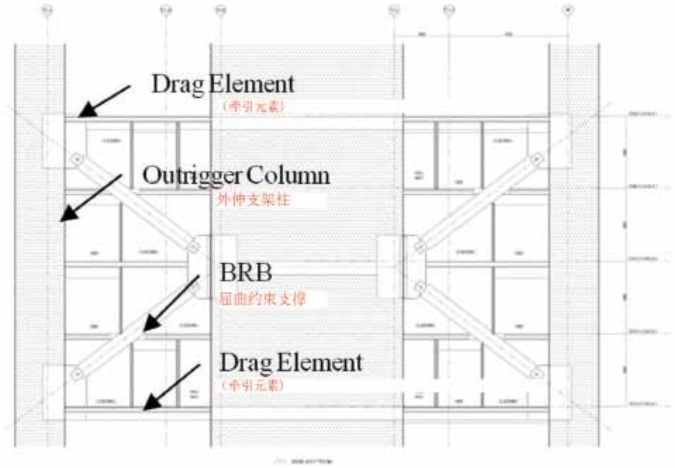

Figure 6. Buckling Restrained Brace System
图6. 屈曲约束支撑系统

rigid floor diaphragm. Slabs in the podium and basement are modeled using linear shell elements. The elastic flexural stiffness of the slabs and equivalent slab-beams are reduced to $0.5EI_g$.

Modeling of Foundation

To simulate the soil-structure interaction effects, retaining walls in the basement were also modeled with an elastic linear shell element and surrounding soil was modeled with nonlinear springs. The properties (force and deformation) of nonlinear springs are estimated from the geotechnical soil report provided by a geotechnical consultant. Though the lateral resistance of soil was considered, the damping of the soil on the sides of the basement wall was neglected in the study. In terms of boundary conditions, the base of the core wall was modeled as a pin connection (i.e. without rotational restriction), the bases of the columns are modeled as fixed and soil springs are fixed along their main axis. The modeled was subject to the seven sets of ground motions at the base of the mat foundation and average response was computed. The ground motions are used from Geotechnical earthquake engineering site specific study report available for this project.

Detailed Design of a BRB System

Design of Buckling Restrained Braces

The typical BRBs system used in the building is shown in Figure 6. Initial sizing of the BRB was carried out based on the wind and seismic loading, with the worse condition from seismic loading for DBE level earthquake. After nonlinear analysis for a MCE level earthquake, the size of the BRBs was adjusted for the optimal performance and to control the story drift. The stiffness of the BRB was adjusted by varying the cross–sectional area and effective length of the steel core. The stiffness was adjusted in such a way that the stiffness of the BRB at the floor is higher than the story stiffness in that floor. Relatively stiff bracing attracts higher seismic demand on the BRB caused to early yielding than reinforced concrete core wall. Moreover, yielding of a BRB serves as energy dissipation and provides the higher ductility to core wall system as well.

Detailed Connection Design

Detailed connection design of the BRB system is carried out in accordance with AISC 360-05 and ACI 318-08. Gusset plate connection with BRBs is designed to satisfy the dimensional requirements for the pin-connected members in accordance with AISC 360-05, Section D5. Pin hole in the gusset plate is located midway between the edges of the member in the direction normal to the applied force. The width of the plate at the pin hole is provided which is not less than 2beff + d and the minimum extension, a, beyond the bearing end of the pin hole, parallel to the axis of the member, is not less than 1.33 x beff.

反应。平板外伸支架梁被模拟成梁两端带非线性铰链（如图5所示）。采用弯矩曲率型铰链以模拟板梁的非线性。根据楼板内钢筋计算楼板梁的抗弯性。弯矩铰链的非线性特性与Klemencic等人（2006年）的研究相符。后张效应被考虑在楼板屈曲能力的计算中。然而，对弯矩铰链的性能不作特别审查。

在裙房及地下层，楼板被模拟成不带刚性的楼层隔板。采用线性壳元素模拟裙房和地下层的楼板。楼板和等效平板梁的弯曲弹性刚度被降低至$0.5EI_g$。

基础的建模

为模拟土壤结构相互作用的影响，采用线性弹性壳单元模型模拟地下层挡土墙与和非线性弹簧模型模拟周围的土壤。根据岩土顾问提供的岩土报告来估计非线性弹簧特性（受力与变形）。虽然土壤的抗侧力被考虑到，但地下层墙侧的土壤阻尼在研究中被忽略。在边界条件方面，以销连接模拟核心筒墙基（即无旋转限制），柱基被模拟为固定的，土壤弹簧沿其主轴固定。模型接受在底板基础部位的七套地层运动和平均响应会被计算。从岩土地震工程现场具体的研究报告中得出的地层运动可用于此项目。

BRB系统的详细设计

BRB的设计

典型BRB系统在建筑中使用如图6所示。BRB的初始尺寸是依据风荷载和地震荷载所确定，并参考了DBE级别地震中地震荷载的最差状况。在做MCE级别的地震的非线性分析之后，调整BRB的尺寸以优化其性能并控制层间位移。对截面积和有效钢芯长度进行更改来调整BRB刚度。这样调整之后，楼板的BRB刚度要高于该层的楼层刚度。在BRB上相当的刚性支撑吸引更高地震能量从而造成比钢筋混凝土核心筒墙更早的屈服。此外，以BRB的屈服用作耗能并对核心筒系统提供更高的延性。

连接细节设计

BRB系统的详细连接设计是按照AISC 360-05与ACI318-08实行的。BRB与角撑板的连接设计是根据AISC 360-05， D5章节中满足对销钉连接构件尺寸要求。角撑板内销钉孔位于与外加力正交方向的构件边缘之间的中间部位。所提供于销钉孔处的板宽不小于2beff+d和最小的延伸，a ，超过销钉孔的轴承端与构件轴平行，是不小于1.33 xbeff。其中，beff= 2T= 16mm，但不超过从孔边缘至部件边缘的实际距离，有关距离的量度方向与外加力正交（d是销钉直径（mm），t为板块厚度（mm）。

在角撑板设计方面，对角撑板分别建模，并应用BRB系统的最大设计屈服力。进行线性分析，将角撑板内应力与该板块预计屈服应力检查比较。以该板临界屈曲强度为基础检查角撑板在受压荷

Where, beff = 2t = 16, mm but not more than the actual distance from the edge of the hole to the edge of the part measured in the direction normal to the applied force (d is pin diameter (mm) and t is thickness of the plate (mm).

In gusset plate design, gusset plates are modeled separately and the maximum design yield force of BRB is applied. Linear analysis is conducted and the stresses in the gusset plate are checked against the expected yield stress of the plate. The buckling of the gusset plate under the compressive loading is also checked based on the critical buckling strength of the plate.

Steel studs that restrain the gusset plate embedded in the concrete are designed against the shear demand in accordance with ACI 318-08. Steel strength of the studs, concrete breakout strength and concrete pry out strength are checked to ensure the net force from the studs is transferred to the concrete.

Furthermore, the load path of net vertical force from the gusset plate to the steel column (embedded in the reinforced concrete outrigger column) and then from the steel column into the concrete column is checked based on the capacity of each element. The axial capacity of the drag element is also checked to transfer the horizontal component of the force from the BRB.

Analysis Results

Model Analysis

The natural periods of the building are 5.75 s and 4.86 s in principal directions with 0.40 and 0.42 modal participating mass ratios. The first three mode shapes of the building are shown in Figure 7. The first and second mode are dominated in lateral deformation in Y and X, respectively, and the third mode is in torsional deformation.

Base Shear

The base shear is compared between DBE level response spectrum analysis and the average MCE level nonlinear response history analysis in Table 3. The base shear is calculated above the podium level and considers the tower portion only. The seismic weight of the tower above the podium level is 616,900 kN. The design base shear (shear calculated above the podium) is approximately 3.5% and 3.8% in each principal direction, which is higher than the minimum limit of 3%, set by the LATBSDC-2008 guidelines. Furthermore, the dynamic base shear calculated from the average seven time histories is approximately two times higher than the design base shear, which is typical in high rise buildings.

Story Shear and Story Moment

Story shears and story moment distributions are plotted along the height of the building and shown in Figure 8 and Figure 9, respectively. The story shear at the basement level is generally decreased in most of the time histories except where the story shear has increased. This may happen due to the irregular distributions of basement walls and supports i.e, soil springs at the back of the basement walls. Furthermore, abrupt change in shear demand at the mid-height of the tower in y-direction is due to the BRBs. BRB cause reduction in seismic shear demand; however, little effects in story moment demand.

Story Drift

In the preliminary investigation, the story drifts are checked at MCE level without using BRBs. Then, the BRBs are applied in the model and the story drifts are rechecked. One advantage is that the BRB system reduces the story drift of the building in the principal minor direction. The maximum story drifts envelope for both principal directions are less than 3%, which is an acceptable limit against MCE level

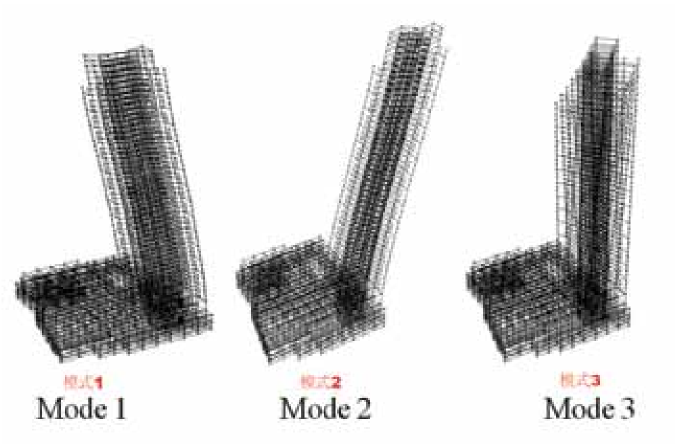

Figure 7. Mode Shapes
图7. 模式形状

载下的屈曲。

钢螺栓用来固定预埋在混凝土内的角撑板是按照ACI318-08抗剪需求设计。检查螺栓的钢强度，混凝土突破强度及混凝土撬出强度以确保净荷载从螺栓上转移至混凝土。

此外，根据每个构件的承载力检查从角撑板至钢柱（预埋在钢筋混凝土外伸支架柱中）然后从钢柱至混凝土柱的净竖向受力荷载途径。牵引单元的轴向承载力在BRB系统的水平方向分布的内力转换也被检查。

分析结果

模式分析

建筑的自然周期在主方向上为5.75秒和4.86秒并带有0.40和0.42振型质量参与系数。前三种模式形状如图7所示。第一和第二种模式分别是以在Y和X的侧向变形为主，第三种模式是扭曲变形中。

基底剪力

表3对基底剪力通过DBE级别响应频谱分析和与平均MCE级别非线性反应时程分析进行了比较。底部剪力计算在裙房层以上，并仅考虑塔楼部分。裙房层以上的塔楼抗震重量为616900kN。设计基底剪力（裙房以上的计算剪力）在每一个主方向约为3.5%和3.8%，这超过LATBSDC2008年准则规定的3%最低限额。此外，从平均7次时程计算的动态基底剪力比设计基底剪力大约高出两倍，这是高层建筑特有的。

楼层剪力和楼层弯矩

沿建筑物高度绘制楼层剪力和楼层弯矩分布，分别在图8和图9中显示。大部分时程中地下层的楼层剪力普遍降低。发生这种情况是由于地下层墙与支撑的受力不均所导致,比如地下层墙后的土壤压力。此外，由于BRB，塔楼中高度部分的y向剪力需求

Load Cases 负载情况	Base Shear 基底剪力	% of Seismic Weight % 抗震重量
DBE (major dir.) DBE （主方向）	21,012	3.56
DBE (minor dir.) DBE （次方向）	22,691	3.84
MCE (major dir.) MCE （主方向）	47,892	7.76
MCE (minor dir.) MCE （次方向）	46,462	7.53

Table 3. Base Shear Comparison
表3. 基底剪力比较

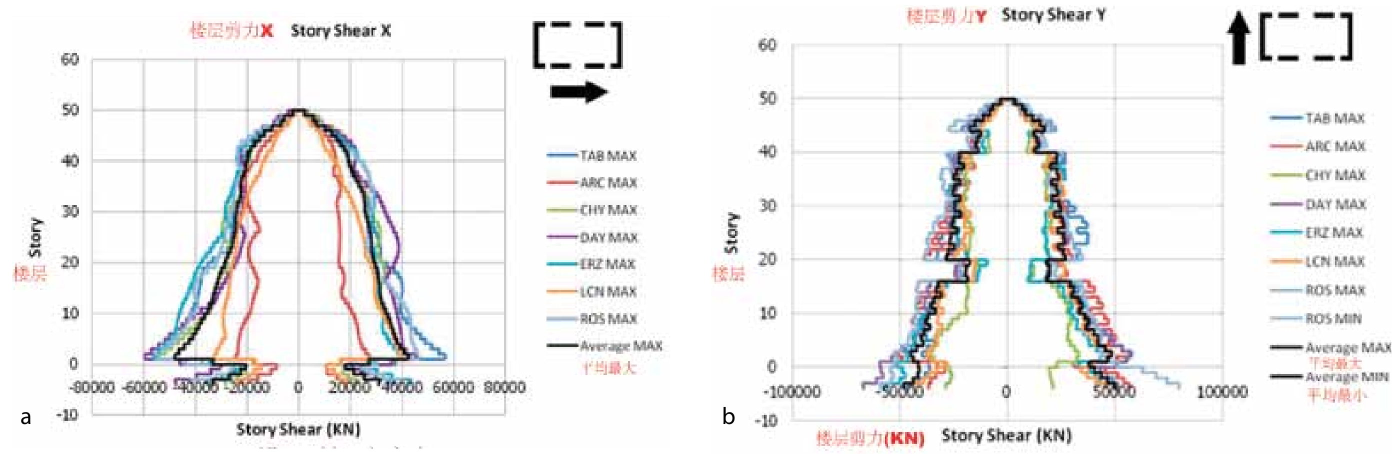

Figure 8. Plot of Story Shear : (a) in X; (b) in Y
图8. 楼层剪力（a）在X向；（b）在Y向的测绘

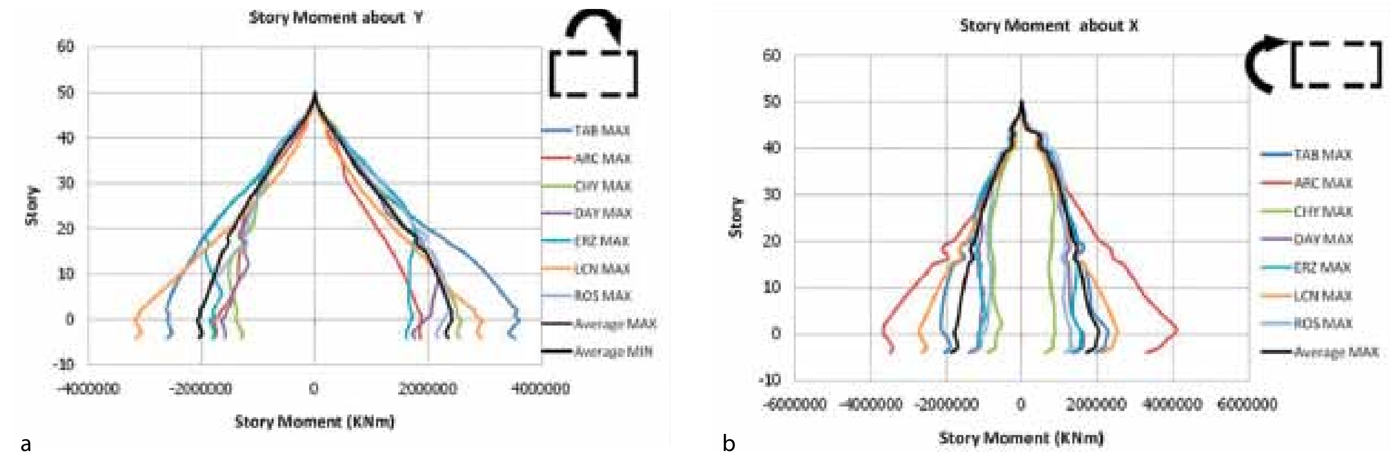

Figure 9. Plot of Story Moment (a) about Y; (b) about X
图9. 楼层弯矩（a）在Y向；（b）在X向的测绘

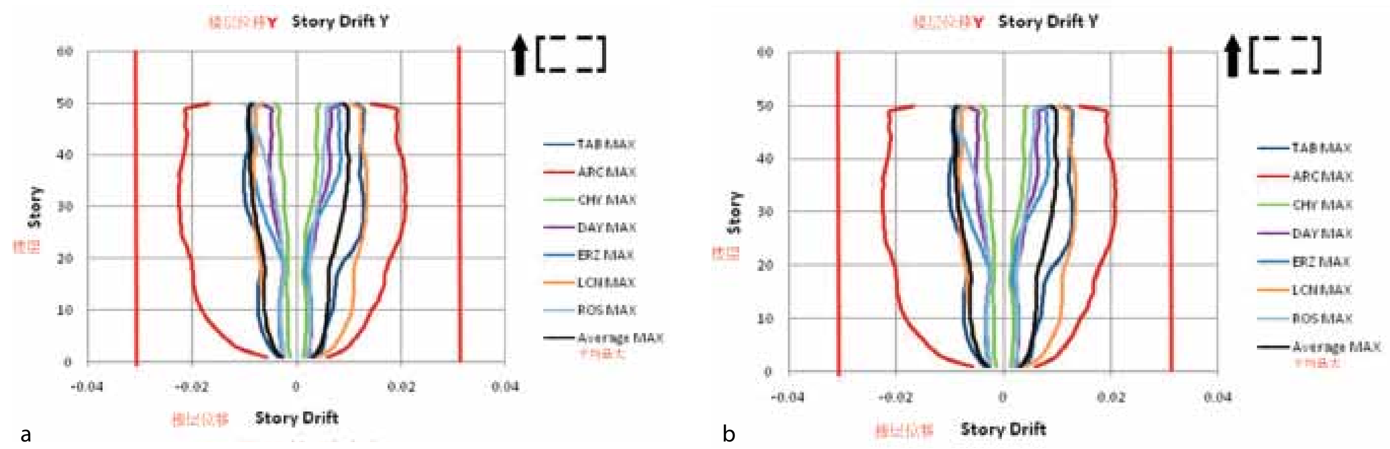

Figure 10. Plots of Story Drift: (a) along X; (b) along Y)
图10. 层间位移绘制：（a）沿X向；（b）沿Y向

earthquakes as shown in Figure 10.

Ductility of Buckling Restrained Braces

In order to evaluate the response of BRBs and performance levels, the ductility of buckling restrained braces is checked against the acceptable limit. Firstly, the strain for each BRB is extracted from the analysis and the average ductility demand is calculated. It is found that all BRBs have average ductility demand less than 9, which is the maximum allowable ductility demand for primary braces components mentioned in ASCE 41-06.

Axial Strain in Core Wall

The flexural capacity of a shear wall is evaluated in terms of the yielding

突变。BRB造成对抗震剪力需求的降低，对楼层弯矩要求影响不大。

层间位移

在初步分析中，检查在MCE级别中不使用BRB系统的层间位移情况。然后，在模型中设BRB，并对层间位移复查。BRB系统的一个优势是减少在主次方向建筑的层间位移。两个主方向上最大的层间位移小于3%，如图10所示，这是抗MCE级别地震的一个可接受极限。

BRB的延性

为评估BRB系统的反应和性能水平，BRB系统的延性与可接受的限度相核对。首先，从分析提取每个BRB的应变和计算平均的延性

of vertical steel and crushing of concrete materials. The strain in steel extreme fibers and concrete fibers are checked against the acceptable strain limits. The compression strain of MCE analysis is increased by two times and compared with the acceptable limit. Furthermore, the comparison of before and after the application of BRBs shows that the moment and shear demands are reduced in the core wall after the application of buckling restrained braces, especially in the principal minor direction. From the results, all the strains are within the acceptable limit.

Effectiveness of BRB system

Since the buckling restrained braces are yielded significantly at MCE level earthquakes, the design base shear is reduced compared to the building without a BRB system. Especially, moment and shear in the core wall is reduced remarkably due to the utilization of BRB system. Furthermore, the storey drifts in the principal minor direction are improved after the application of BRB system.

Conclusion

The buckling restrained bracing system is used for the first time in the primary lateral force system of the high-rise building in Philippines. The design and application of buckling restrained braces are initiated into local structural engineering practice. The buckling restrained braces combined with ductile core wall systems lead to a better performance for tall buildings for reducing base shear and controlling deformation.

Acknowledgements

The authors would like to thank Magnusson Klemencic Associates for their peer review, as well as their guidance in design of BRB system for the case study project. Furthermore, the authors acknowledge Star Seismic Inc. for the provided information about buckling restrained braces. Lastly, the authors extend sincere thanks to Ayala Land, Inc., the Client of the case study project.

需求。据发现，所有BRB有小于9的平均延性需求，这是ASCE41-06中所提及的主要支撑构件的最大允许延性需求。

核心筒墙的轴向应变

剪力墙的受弯承载力是依据垂直钢的屈服和混凝土材料的破碎来评估的。钢材极端纤维与混凝土纤维应变与可接受的应变极限核对。MCE分析的压缩应变增加了2倍，并与可接受极限相比。此外，BRB的应用前后的对比表明，弯矩和剪力的需求在核心墙后采用BRB后被降低，特别是在主要子方向上。从结果来看，所有应变是在可接受的极限范围之内。

BRB系统有效率

由于BRB在MCE级别地震中屈服显著，与没有BRB系统的建筑相比，设计基底剪力被降低。特别是核心筒墙内的剪力和弯矩由于使用BRB系统而被明显降低。此外，采用BRB系统后，在主要轴方向的层间位移得到改善。

结论

BRB系统是首次被采用于菲律宾高层建筑的主要抗侧力系统。BRB系统的设计和应用正式加入到当地结构工

程实践中。与延性核心墙系统相结合的BRB以降低基底剪力和控制变形而达到更佳高层建筑性能。

致谢

作者感谢同行评审Magnusson Klemencic Associates (MKA)，以及他们为案例研究项目对BRB系统所作的设计指导。此外，作者感谢星震股份有限公司（Star Seismic Inc.）提供有关的BRB资料。最后，作者对案例研究项目业主-Ayala Land, Inc.表示衷心感谢。

References（参考书目）:

ACI 318-08. (2008). **Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary (ACI 318R-08)**. American Concrete Institute: Farmington Hills, MI.

Ahmed, M. (2011), **Optimal Reduction Inelastic Seismic Demand in High-rise RC Core Wall Buildings Using Energy Dissipating Devices**. Dissertation, Structural Engineering Field of Study, Asian Institute of Technology.

American Society of Civil Engineers (2005). **Minimum Design Loads for Building and Other Structures (ASCE 7-05)**. American Society of Civil Engineers.

American Society of Civil Engineers (2006). **Seismic Rehabilitation of Existing Buildings (ASCE 41-06)**. American Society of Civil Engineers.

Computers and Structures, Inc. (2006). **Perform 3D, Nonlinear Analysis and Performance Assessment for 3D Structures User Guide**, Version 4. Computers and Structures, Inc., Berkeley, CA.

Dutta, A. and Hamburger, R.O. (2011). Case Study of a 40-Storey Buckling-Restrained Braced Frame Building Located in Los Angeles. **The Structural Design of Tall and Special Buildings**, Wiley InterScience. 19, 77–93.

Fry, J.A, Hooper, J.D., and Klemencic, R. (2010). Core Wall Case Study Design For Pacific Earthquake Engineering Research/California Seismic Safety Commission. **The Structural Design of Tall and Special Buildings**, Wiley InterScience. 19, 61-75.

Klemencic R, Fry JA, Hurtado G, Moehle J.(2006). Performance of Post-Tensioned Slab-Core Wall Connections. **PTI Journal** 4(2): 7–23. Los Angeles Tall Buildings Structural Design Council. (2008), An Alternative Procedure for Seismic Analysis and Design of Tall Buildings Located Los Angeles Region. Los Angeles Tall Buildings Structural Design Council.

Orakcal K, Wallace JW. (2006). Flexural Modeling of Reinforced Concrete Walls – Model Calibration. **ACI Structural Journal** 103(2): 196–206.

Wallace, J. W.(2007). Modeling Issues for Tall Reinforced Concrete Core Wall Buildings, **The Structural Design of Tall and Special Buildings**, Wiley InterScience, 16, 615-632.

Wallace, J., Naish, D., Fry, J.A., and Klemencic, R. (2009). Presentation, **PEER Annual Meeting**, Tall Buildings Initiative Session. October 15-16, San Francisco, CA.