EFFECT OF USING PERFORMANCE-BASED APPROACH FOR SEISMIC DESIGN OF TALL BUILDING DIAPHRAGMS

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ABSTRACT

This paper presents how performance-based design (PBD) approaches can help to improve the structural performance and cost effectiveness in design of floor diaphragms of tall buildings under earthquakes. In contrast to the prescriptive design approaches, performance-based design provides a systematic methodology for assessing the performance capability of overall building system and its components. The performance-based design explicitly evaluates the response of the building under the potential seismic hazard, considering the probable site-specific seismic demands as well as the uncertainties in the post-yielding response and behaviour of the building under seismic events. Case study of 57-story reinforced concrete residential building with 4 basement levels is presented. The building was designed for Design Basis Earthquake (DBE) level in accordance with traditional code-based design procedures at the preliminary design stage. After preliminary design, the performance of the building was checked explicitly at Service Level Earthquake (SLE) (43-year return period) and Maximum Considered Earthquake (MCE) level (2475-year return period), using linear and nonlinear response history procedures. Diaphragm design forces at podium level and tower levels were explicitly checked at site-specific MCE level event rather than application of code-specified modification factors to estimate the forces and deformation under code-specified earthquake level. Cost effectiveness of the design was evaluated by comparison of the indicative quantities and parameters between the code-based design and the modified design based on PBD.

KEYWORDS

Performance-based design, diaphragm, tall building, earthquake.

INTRODUCTION

Performance-based design is a state-of-the-art design approach for the seismic-resistant design, which has been widely used, for seismic evaluation of existing buildings and seismic design of number of new tall buildings. The conventional seismic design codes consider the reduction in design seismic force which implies the structural inelastic behaviour through the application of seismic response modification factor, R, in the simplified elastic analysis methods. While allowing inelastic deformation in the deformation-controlled members detailed for ductility, force-controlled members that are designed to remain elastic would experience the significant higher seismic force demand than reduced design forces by seismic response modification factor. To account for this effect, structural overstrength factor, Ω_0, is multiplied to the design seismic forces to predict the maximum forces in members that are to remain elastic, especially in design of diaphragms. The intent of those factors is to simplify the structural design process by application of elastic analysis procedures. Those procedures do not consider the structural performance of component level, the ground motion characteristics and redistribution of seismic demand in the various components of building at the state of inelastic behaviour under strong seismic events.

In contrast to the prescriptive design approaches, performance-based design provides a systematic methodology for assessing the performance capability of a building, system or component. The performance-based design explicitly evaluates the response of the building under the potential seismic hazard, considering the different probable site-specific seismic demand levels as well as the uncertainties in the post-yielding response and behaviour of the building.

The case study building is a high-rise residential tower, which is 57-story high-rise building, approximately 192 meters from ground level to lower roof deck level. The building is the second tower of two-tower residential development project, sharing a common podium with 4-story below-grade parking. The seismic force-resisting

system is a bearing wall system, comprised of special reinforced concrete shear walls. Post-tensioned flat slab is used in the floor system of towers while beam and slab system is used in the podium levels.
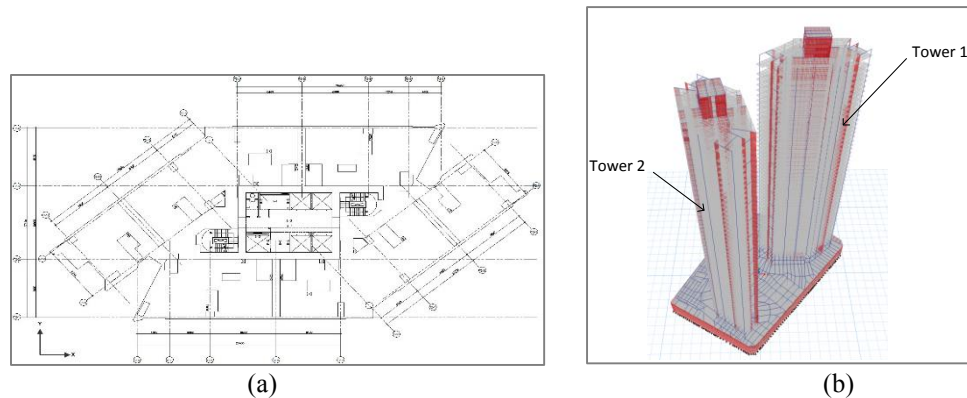

Figure 1 (a) Typical floor plan, (b) Isometric view of towers

OVERALL METHODOLOGY

The overall methodology performance-based design followed "Tall Buildings Initiative, Guidelines for Performance Based Seismic Design of Tall Buildings, 2010" developed by Pacific Earthquake Engineering Research Center.

Initially, a schematic design was carried out to achieve the good performance and cost effectiveness of the structural system. Following the schematic design, the preliminary design was carried out in accordance with conventional building code procedure, ASCE/SEI 7-05 and ACI 318-08, applying the seismic loading of Design Basis Earthquake (DBE) level and wind loading, to determine the size of the members and reinforcement.

After substantial completion of code-based design, performance-based evaluation was carried out to check the performance at two levels of earthquakes; Service/Frequent Earthquakes (SLE) and Maximum Considered Earthquakes (MCE). The design was revised as appropriate, based on the performance-based evaluation results and findings in order to meet the seismic performance objectives and acceptance criteria set for the project. Probabilistic site-specific seismic hazard assessment was carried out to determine the seismic hazard of the project site, considering all possible earthquake occurrences and ground shakings to determine a combined probability of exceedence that incorporates the relative frequencies of occurrence of different earthquakes and ground-motion characteristics. Seven pairs of ground motion records were selected and scaled spectrally for MCE level evaluation.

Modelling and Analysis Procedures

Complete, three-dimensional elastic computer models including the tower and the entire podium were analysed using ETABS. The elastic models were used for wind, SLE and DBE level earthquake analysis. The models included the shear walls, columns, coupling beams, girders, beams, slabs, and foundation. Shell elements were used to model the floor slabs, considering the diaphragm flexibility. Soil springs were applied to the mat foundation.

Non-linear verification model was created in Perform-3D for MCE level evaluation. Tower and the entire podium were modelled in nonlinear model. Equivalent "slab-beams" were used in the model in order to determine the nonlinear response of post-tensioned slab, interaction with shear walls and columns. Floor mass was lumped at centre of mass location and rigid diaphragm assumption was applied in the tower floors. The model included inelastic member properties for elements that were anticipated to be loaded beyond their elastic limits. These include the flexural response of shear walls, coupling beams and slab-outrigger beams. Elements that were assumed to remain elastic were modelled with elastic member properties. In order to account the soil-structure interaction, a rigid "bathtub" modelling approach was used to model the basement wall. Nonlinear elastic bar elements were connected between the rigid bathtub and basement wall.

Response spectrum analysis was conducted to check the performance under SLE level earthquakes while nonlinear response history analysis (NLRHA) was conducted to check the performance under MCE level earthquakes.

SEISMIC PERFORMANCE OBJECTIVES

The specific performance objectives for the design of the building at two levels of earthquake hazards are shown in the Table 1.

Table 1 Seismic performance objectives

Level of Earthquake	Seismic Performance Objective
Frequent/Service: 50% probability of exceedance in 30 years (43-year return period), 2.5% of structural damping	Serviceability: Limited structural damage, should not affect the ability of the structure to survive future Maximum Considered Earthquake shaking even if not repaired.
Maximum Considered Earthquake (MCE): 2% probability of exceedance in 50 years (2475-year return period), 2 to 3% of structural damping	Collapse Prevention: Building may be on the verge of partial or total collapse, extensive structural damage; repairs are required and may not be economically feasible.

OVERALL ANALYSIS RESULTS

In modal analysis, the first two modes are translation in Y and X directions respectively while the third mode is in torsion. Figure 2 compares the elastic base shear percentage of SLE, DBE, MCE and inelastic base shear of MCE (average base shear of NLRHA), in terms of weight of building above 3rd floor level of tower. Nonlinear base shear at MCE level is approximately 0.5 and 0.4 times less than the elastic base shear in X and Y directions respectively.

Table 2 Natural periods of the building

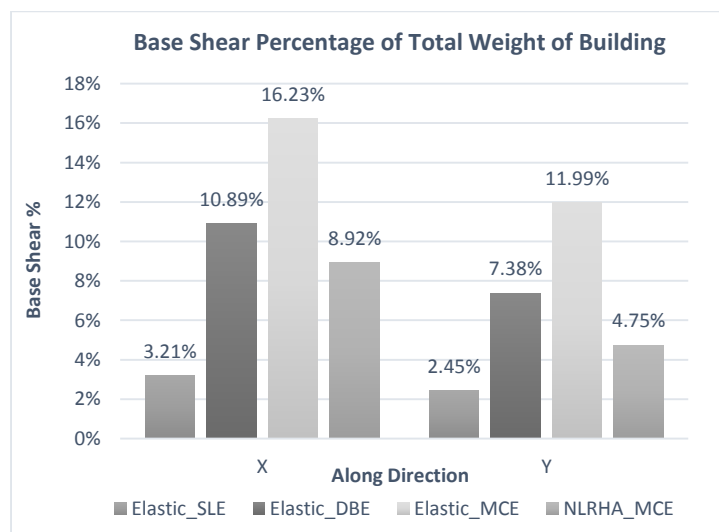| Mode	Period (s)	Modal Mass Participation Ratio	
		X (%)	Y (%)
1	7.39	7.44	39.74
2	5.35	38.91	8.17
3	4.23	0	0

Figure 2 Base shear comparison (Weight of building = 1,040,200 kN)

DIAPHRAGM DESIGN

In seismic design of buildings, diaphragms transfer in-plane forces, comprising of inertial forces and transfer forces to vertical members of seismic forces-resisting system. Inertial forces are generated from the mass of the floor system under ground shaking. Transfer forces are in-plane forces, transferred from one vertical element of

seismic force-resisting system to another. Transfer forces are significant at discontinuities in the vertical elements commonly lateral force transfer between shear walls in tower and basement walls and lateral force transfer between multiple towers, through the podium slab.

Generally, in code-specified procedures, diaphragms are designed for the maximum of design seismic force from structural analysis of seismic force-resisting system and diaphragm design force, which is determined based on acceleration times mass. Since the overall design philosophy provides essentially elastic diaphragm, diaphragm components, such as collectors, distributors, and diaphragm slab are designed, multiplying the design forces with structural overstrength factor, Ω_0. The structural overstrength factor varies approximately 2 to 3, depending on the seismic force-resisting system.

Tower Diaphragm

In case study building, story accelerations from nonlinear response history analysis under MCE level earthquakes were used to determine the diaphragm design forces. Since equivalent slab-beams and rigid diaphragm assumption were used in the nonlinear verification model at MCE level, diaphragm design forces could not be extracted directly from the nonlinear model. Diaphragm design forces were checked from ETABS model in which the slabs were modelled with shell elements. Response spectrum analysis was conducted in ETABS, using MCE level response spectrum. The appropriate scale factors for response spectrum analysis was determined, by scaling between average story acceleration from nonlinear response history analysis and response spectrum analysis since the inertial forces were governing the design rather than transfer forces in the tower diaphragms. The scale factor of 0.75 and 0.5 were used to scale the elastic forces from response spectrum analysis at MCE level. Figure 3 presents the scaling of story acceleration at MCE level in response spectrum analysis.
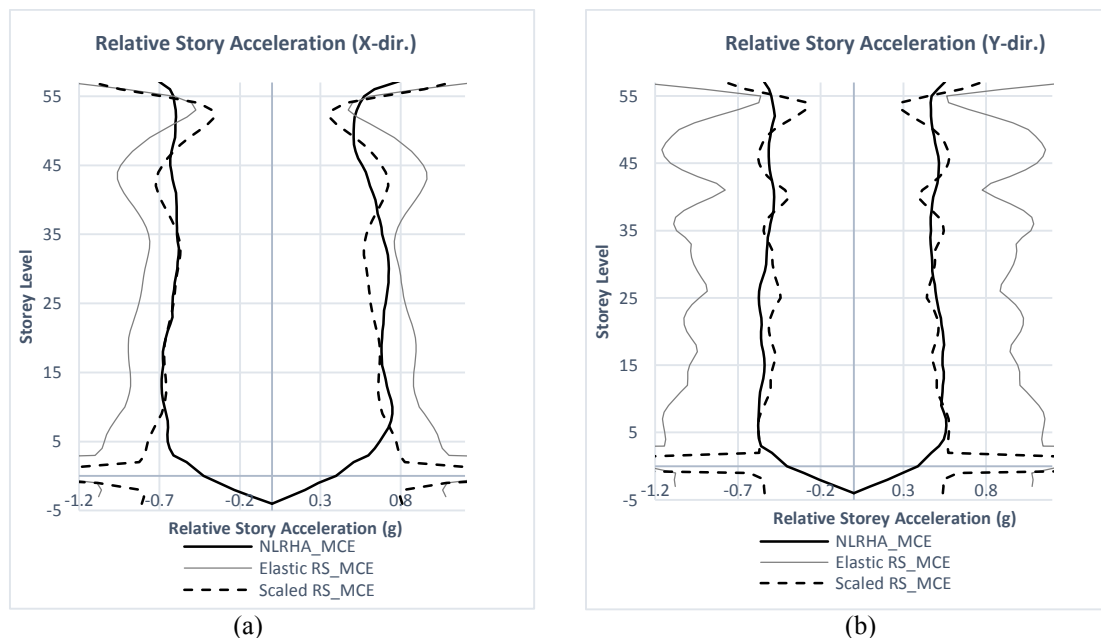

Figure 3 Scaling of story acceleration in response spectrum analysis at MCE level: (a) X-direction, (b) Y-direction

As diaphragm was idealized with finite element model, diaphragm was designed according to stress fields from analysis and non-uniform shear flow was taken into account. Section cuts were assigned to determine the design forces of diaphragm components based on the stress fields. Diaphragm components were designed for forces from section cuts, without amplification with structural overstrength factor, Ω_0. Factor of 1.5 was used to account for uncertainty in the maximum mean force demand in ground motions. Diaphragm strength was calculated in accordance with ACI 318-08, using expected material properties and code-specified strength reduction factors.

The diaphragm design was compared between code-specified procedure and performance-based procedure. In code-based procedure, DBE level response spectrum analysis results were scaled down to estimate the inelastic demand forces, using seismic response modification factor, R, in accordance with code-specified procedures.

The diaphragm forces were multiplied with structural overstrength factor of 2.5 and redundancy factor of 1.0 to determine the diaphragm design forces. In both response spectrum cases at DBE and MCE levels, orthogonal effects were considered in design, applying 100% of seismic forces in one principal direction combined with 30% of seismic forces in the orthogonal direction. Figure 4 verifies the diaphragm load path with the inertial force of the diaphragm at Level 20, from MCE level response spectrum analysis in Y-direction. Orthogonal effects and load factor of 1.5 was not considered in the load path verification.

Diaphragm design forces and the required reinforcement in collector and shear friction transfer in sample locations at Level 20 were compared between performance-based design at MCE level and code-based design at DBE level. Figure 5 presents the sample locations of section cut for collector and shear friction transfer at Level 20. It was found that performance-based design provides more reliable and cost-effective design, considering more realistic responses under seismic events.
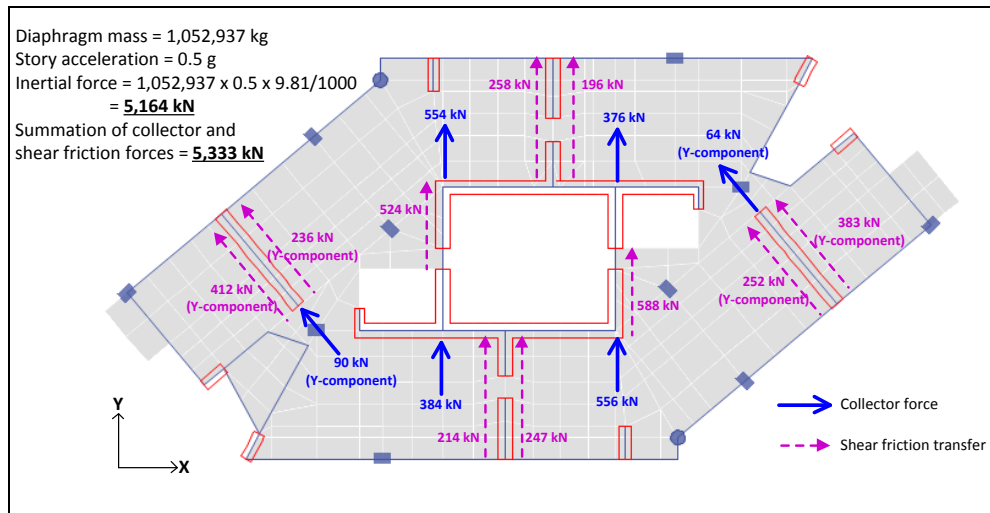

Figure 4 Verification of diaphragm load path under MCE level earthquake in Y-direction

Table 3 Comparison of collector design forces and reinforcement

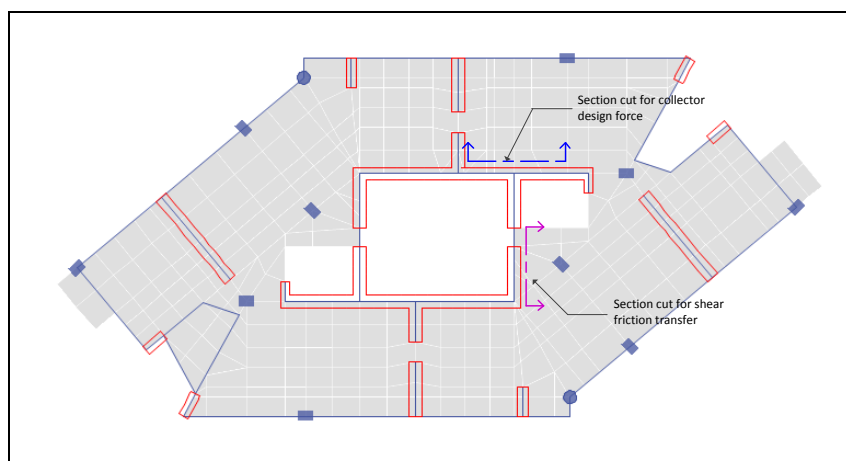| Design	Seismic Level	Collector		Shear Friction	
		Design Force (kN)	Reinf.	Design Force (kN)	Reinf.
Code-based	DBE	1019	8-DB25	1621	DB12@100 mm
Performance-based	MCE	608	4-DB25	1045	DB12@175 mm

Figure 5 Section cut for collector and shear friction transfer at sample locations

Podium Diaphragm

For diaphragm design at ground and basement levels, combined complete two-tower ETABS model was used to check the transfer forces in diaphragm. MCE level response spectrum analysis results were scaled to average

nonlinear base shear since the transfer forces from towers were governing the design. Also, simplified ETABS model was created with two towers up to 2nd floor and apply the forces equivalent to the MCE average nonlinear base shear of each tower at 2nd floor with different scenarios to consider the in-phase and out-phase effects. Linear static analysis was conducted for the simplified model. Diaphragm shear, tension and compression between two towers were checked based on the results from complete two-tower model and simplified model.
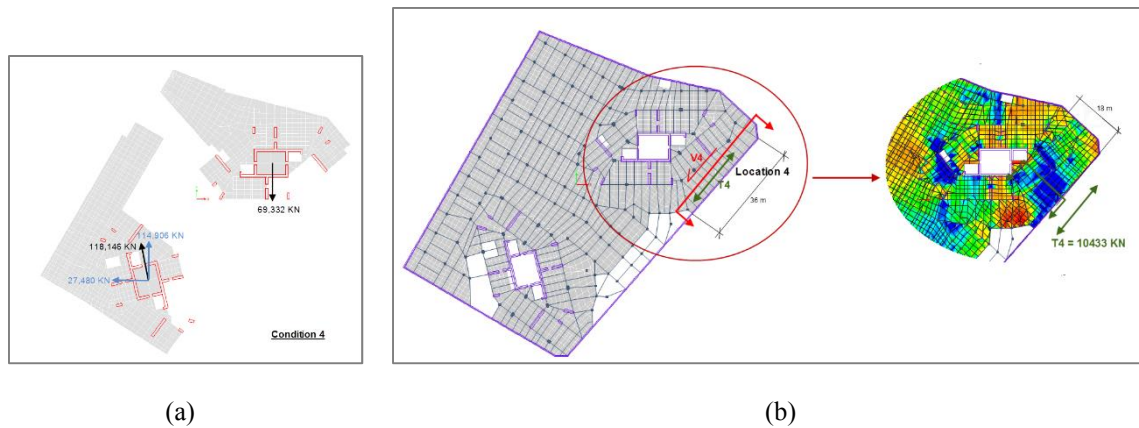

(a)   (b)

Figure 6 (a) Sample scenario of in-phase and out-phase effect, (b) Sample section cuts for diaphragm shear transfer and chords at Ground floor level

CONCLUSIONS

Performance-based design approaches explicitly check the global and component responses of the building against the detailed acceptance criteria for multiple seismic events rather than application of modification factors to estimate the forces and deformation under single code specified seismic demand level. PBD approaches capture the more reliable behaviour of diaphragms in seismic design which can lead the better structural performance and cost effective design.

REFERENCES

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

American Society of Civil Engineers (2005). "Minimum Design Loads for Building and Other Structures (ASCE/SEI 7-05)", Alexandar Bell Drive, VA, USA.

Moehle, J. P., Hooper, J. D.; Kelly, D. J.; and Meyer,T. R. (2010), "Seismic Design of Cast-in-Place Concrete Diaphragms, Chords, and Collectors: A Guide for Practicing Engineers," NEHRP Seismic Design Technical Brief No. 3, National Institute of Standards and Technology, Gaithersburg, MD, NIST GCR 10-917-4.

Pacific Earthquake Engineering Research Center (2010). "Tall Buildings Initiative, Guidelines for Performance Based Seismic Design of Tall Buildings", University of California, Berkeley, CA, USA.