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PERFORMANCE-BASED DESIGN OF TALL BUILDINGS IN SOUTHERN CALIFORNIA

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ABSTRACT: This paper describes the general design process of tall buildings in California with a central reinforced concrete core. Some cities in California, such as Los Angeles and San Diego, have developed guidelines for the design of tall buildings using a performance-based approach. Three levels of performance are usually adopted (1) serviceability under a frequent earthquake with a 47-year return period, (2) limited damage under a code-based design earthquake, and (3) collapse prevention under a rare earthquake with a 2500-year return period. Objectives 1 and 2 are usually studied and checked using conventional linear analysis adopting different levels of stiffness. Objective 3 is checked through nonlinear dynamic analyses of more complex 3-D models of the building. This document provides a detailed summary of the design process using a performance-based approach based on the experience of projects in Los Angeles and San Diego that have been approved for construction.

1. Introduction

The California Building Code, CBC (2013), referring to the American Building Code, ASCE 7 (2011), accepts the use of non-prescriptive methods for the analysis and design of buildings with a seismic load resisting system that is not within scope. In particular, the code does not define a prescriptive method for reinforced concrete buildings with a single structural shear wall system when the above-grade height of the tower is beyond 240 feet. The structural engineer in this case can either adopt a dual system (shear wall system combined moment frames) or probe that by means of an alternative method the analysis and design this system works under earthquake loading. A performance-based design philosophy has been widely accepted by many cities in the west coast of US, e.g. Los Angeles, San Diego, San Francisco, Seattle, Portland, which is in line with the alternative methods described in the building code. In this document, a typical reinforced concrete building refers to a system comprised of flat slabs and rectangular columns with a single core system to resist earthquake loads. Fig. 1 shows a typical configuration of a tall building that has followed a performance-based design approach in California.

The research community has developed work and guidelines for the performance-based design of buildings since the early nineties. However, structural engineers have only adopted this approach for the design of tall buildings in the last 5 to 10 years. The adoption of a performance-based design approach requires the use of concepts and tools that are not readily available in a design office and requires the interaction with highly trained engineers in several fields of Earthquake and Geotechnical Engineer. The author assumes that the concept of performance-based design is widely known and understood by the reader and it is simply referred in this document as the design of a building to attain different structural performances under different earthquake loads.

Currently, some cities in California have adopted two performance-based approaches that are available in the form of code-alternative methods to engineers. One approach is based on the recommendations of the Structural Engineer Association of Northern California, SEAONC (2007), that defines stiffness and resistance limits for structural components to allow for a code-based design compliance, a serviceability performance under a recurrent earthquake and a severe damage performance under a rare earthquake. This approach has been the basis of the accepted alternative method for cities like San Francisco, San

Diego and Seattle. The city of Los Angeles, instead, has adopted a slightly different but fundamentally different approach based on recommendations made by the Los Angeles Tall Building Design Council, LATBSDC (2014), recommending capacity-based design principles that can limit the severe damage under a rare earthquake and be in service under a recurrent earthquake.

This document is mainly a summary of the overall process for the performance-based design of tall buildings in the West coast of US, including some relevant administrative and technical aspects that have been developed and followed during the last 5 years in cities such as Los Angeles, San Diego and Seattle. Specific and key items covered in this document are the peer review process, the development of design criteria, definition of seismic hazard, modeling aspects, delivery of the information to reviewers and the city officials. Most important comments along with recommendations, advantages, disadvantages and directions of future projects based on the experience of the author during the last years are also summarized in this document.

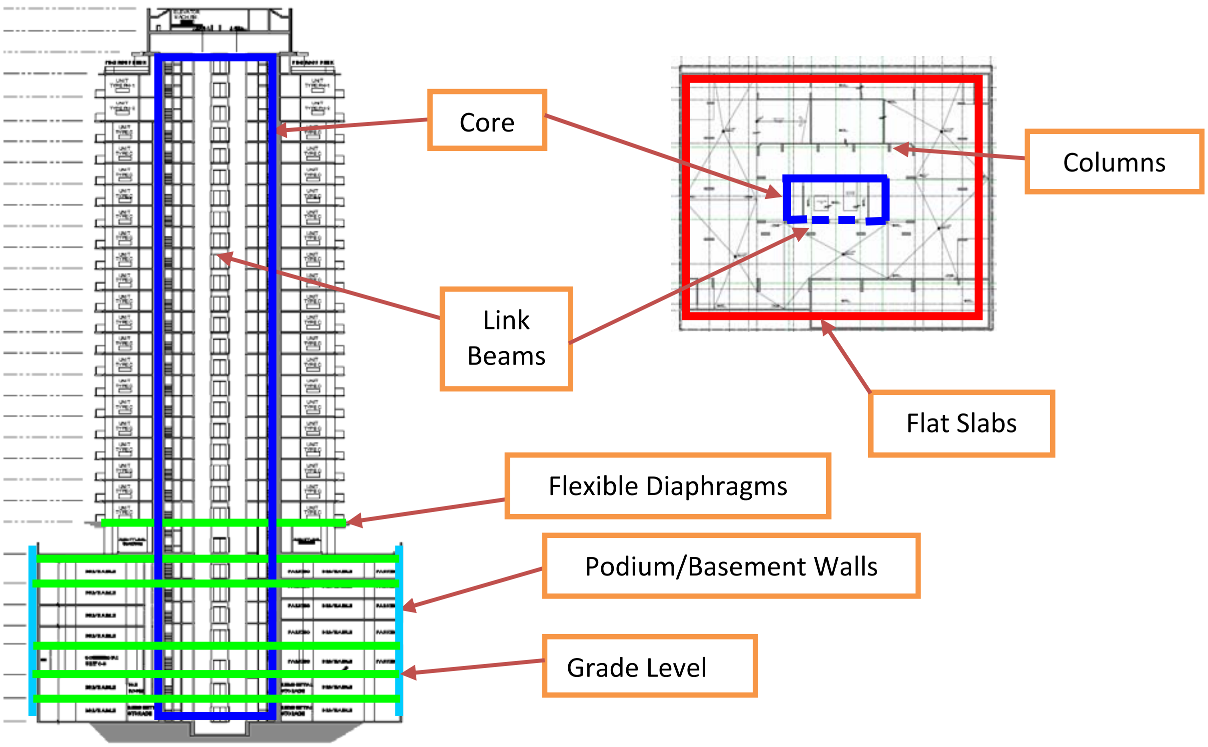

Fig. 1 – Elevation and plan layout of a typical tall building and its main structural components designed with a performance-based approach in California

2. The Seismic Design Process

2.1. General

For a proper and efficient process, the performance-based design of a building in California involves several administrative and technical steps. The main goal is to improve the review process and to shorten the times for the approval of construction permits. In general, this process can be divided in the following items: (1) peer review committee, (2) design criteria, (3) other consulting services, (4) design, (5) peer review process and (6) permits.

2.2. Peer review committee

Any project that has a structural configuration that is not specifically included in the prescriptive requirements of the code will require of an alternative seismic analysis/design with a strict peer review process. First, the city needs to gather basic information of the project to appoint a seismic peer review panel that will act in representation of the "authority under jurisdiction". In a preliminary stage, the engineer of record prepares a preliminary document that contains a brief description of the building, a list of exceptions to the code and design criteria of the alternative design. The city uses this document as the kicked-off for the peer review process.

The peer review panel is usually comprised of experts on both Earthquake and Geotechnical Engineering fields who are part of an extensive list that each city has. Regularly, this list has most well known engineers, professors and researchers on Earthquake Engineering with vast experience in the design and review of tall building projects. This group should have great experience in topics such as seismic hazard analysis, nonlinear dynamic analysis, structural modeling, and design and testing of main structural components under cyclic/earthquake loading.

The city, through its Permits Department, appoints a minimum of three reviewers. The main idea is to cover at least three main general topics during the review process such as geotechnical information, dynamic analysis and seismic design/detailing. One member is usually a Senior Geotechnical Engineer that support on all matters regarding soil reports, foundation issues, seismic hazard assessments, and selection of ground motions. Another member is normally part of the academia teaching and researching on advanced seismic performance of structural components and systems under earthquake loading. One or two other members will be Senior Structural Engineers that have used alternative methods in the past for the design and construction of buildings in California.

2.3. Design Criteria

Every project that requires an alternative design method must commence with an official document, called as the “Design Criteria”, which includes a list of exceptions to the code, clear performance objectives, quantitative measures of performance, modeling aspects and a list of deliverables for the review process. The Structural Engineer of Record, SEOR, develops this document entirely, which the peer review panel reviews and approves. Section 3 describes the content of the Design Criteria with more detail.

2.4. Other consulting services

Also part of the design criteria of a performance-based design project is the information required for the definition of the seismic hazard, the design under wind loads and the instrumentation plan. The client/owner directly contracts this type of work with recommendations made by the SEOR. Due to the nature and complexities associated to these other services, the information gathered and used for the performance-based design is considered to be part of Other Consulting Services category that is outside the scope of the SEOR service. The official document, however, makes respective references to the independent documents prepared by other specialists.

2.5. Design

Upon approval of the Design Criteria, the SEOR engages in a design process that frames within the performance requirements defined and approved for the project. A preliminary design is normally conducted to define key structural components, such as coupling beam reinforcement, shear wall dimensions and confined reinforcement. In a parallel task, the Geotechnical Engineer of Record, GEOR, works in the definition of the seismic hazard and a set of ground motion records. In a second stage, the SEOR runs a series of nonlinear dynamic analysis to quickly check the first design estimates using the information provided by the GEOR. Several documents and guidelines, e.g. Deierlein et al. (2010) and PEER (2010), are used to model and analyse the nonlinear models of the building. After several iterations, a final design is attained and used for reporting results and preparing documentation and drawings for the review process. Based on experience, the design of most of these types of buildings are mainly governed by the maximum shear forces in walls, maximum rotations of outrigger beams, and maximum inter-storey drift resulting from the analysis under code-defined maximum credible earthquake, MCE (ASCE 7, 2010). More details on the design aspect of these buildings are presented in Section 4.

2.6. Peer review process

A complete calculation package, drawings and other relevant documents and models are shared with the peer review panel. It takes usually about two weeks for receiving a set of comments back from the reviewers, which can go from basic modeling assumptions to actual design and detailing aspects of structural components. A series of meeting are held after the first round of comments, which most likely involve further analyses, and sensitivity studies for certain relevant aspects of the building and its configuration. After several discussions and studies, a final set of calculations and drawings are prepared for the project and submitted for a construction permit.

2.7. Permits

In some cases, the analysis/design process can be broken into two or three stages for partial submittals and preliminary construction permits, such as excavation or foundation permits. A plan checking process can be performed in parallel and substantially shorten due to the peer review process. A plan check and its approval is considered to be the last step of the building permit process.

3. Design Criteria

3.1. General

The Design Criteria is a document that includes the following: a list of exceptions to the building code, details of the alternative method adopted, modeling aspects, analysis parameters, enhancements to the code, performance-based acceptance criteria, and deliverables. The SEOR follows guidelines from the city or recommendations given by the peer reviewers for the content and format of this document.

3.2. Exceptions

The main exception to the building code for these projects is the use of a single reinforced concrete core system for a building taller than 240 feet. Other important exceptions refer to special detailing options for structural components and design parameters not specifically defined in the code for this system, such as the force reduction R factor and the over-strength factor.

3.3. Performance Objectives

Two main objectives are defined for these types of buildings: 1) Keep the building in service or in operation under a frequent earthquake event with a return period of 475 years, and 2) Avoid extensive damage in the building under a rare earthquake event with a the code-based Maximum Credible Earthquake, MCE (approximately a 2475 year return period earthquake). Most cities also require a code-based design as the basic starting point and the two performance objectives described above.

Spectral accelerations for a very wide range of structural periods represent both frequent and rare earthquakes. These accelerations are the result of site-specific studies that include fault identification studies, site-response analyses and seismic hazard analyses. The ASCE 7 (2010) defines the work frame for these site-specific studies.

For the MCE assessment (severe damage performance objective), a set of seven pairs of ground motions is defined and submitted by the GEOR to run nonlinear dynamic analyses. The mean response and 1.5 times the mean response are the statistical values adopted for checking the MCE performance. For the service level check, SLE, a linear analysis is preferred using the spectral values obtained from the site-specific studies directly.

3.4. Performance Criteria

The criteria to assess the performance to the objectives defined above are based on the results of linear dynamic analyses for service level check and of nonlinear dynamic analyses for MCE assessment. Service is measured in terms of the capacity to demand ratio, C/D, of key components such as shear in walls and coupling beams, and maximum inter-story drift ratios. Common limits for the capacity to demand ratio will depend on the type of mechanism, giving a wider range of acceptance to those mechanisms that could yield to a ductile behaviour under much larger earthquake loads. For example, the C/D limit for actions in walls outside the plastic hinge region is normally limited to 0.7 and inside the plastic hinge region is limited to 1.5.

The performance criteria for an MCEr level is measured in terms of the maximum average response of most components included in the 3D nonlinear model. This is the most time consuming and critical part of the design, and therefore introduces a degree of conservatism for some type of mechanisms. The LATBSDC (2014) defines limitations for actions that involved either a fragile or ductile behaviour of components. For example for the MCEr check, the maximum shear in walls is usually limited to the maximum shear defined in the ACI 318 (2011) while the maximum inter-storey drift of any particular ground motion is limited to a 4.5%. Table 1 shows part of these performance limits that have been adopted from different documents and adapted to some projects in the city of San Diego, California.

Table 1 – Acceptance criteria for MCEr performance level for some component actions

Component/Response	Limit and its computing procedure	Source
Maximum Inter-storey drift	3.0% for the average maximum of the 7 analyses 4.5% for the maximum of any of the 7 analyses	LATBSDC (2014), PEER (2010)
Maximum Residual Inter-story Drift	1.0% for the average maximum of the 7 analyses 1.5% for the maximum of any of the 7 analyses	LATBSDC (2014), PEER (2010)
Maximum Header Beam Rotations	0.06 for the average maximum of the 7 analyses	Naish (2010)
Vertical Reinf. of Shear Walls – Strain Gauge in Tension:		Recommendations from past projects
Within Plastic Hinge	0.05 for the average maximum of the 7 analyses	
Outside Plastic Hinge	$2\varepsilon_y$ for the average maximum of the 7 analyses	
Vertical Reinf. of Shear Walls – Strain Gauge in Compression:		Mander et al. (1988), ACI 318 (2011)
Within Plastic Hinge	0.015 for 1.5 times the average maximum of the 7 analyses	
Outside Plastic Hinge	0.003 for 1.5 times the average maximum of the 7 analyses	
Shear in Walls	$V_u \leq \phi V_{n,e}$ Demand Vu considered as 1.5 times the average maximum of the 7 analyses. Expected shear resistance, Vn,e, computed using Equation 21.6 of ACI 318 (2011) with expected material properties and reduction factors, $\phi = 1.0$, outside the plastic hinge and $\phi = 0.85$, within the plastic hinge region..	LATBSDC (2014), PEER (2010)

3.5. Modeling

3.5.1. Stiffness Reduction

The Design Criteria includes very specific details of the models adopted for components that are expected (defined) to go in the linear and nonlinear ranges. For the service level check, the structural components are modeled linearly plus some modifications in the stiffness properties of some components for expected cracking under service earthquake loads. Even though the nonlinearity of some components can be modeled with complex elements, it is preferred to use some simplified models that also require the proper definition of stiffness reduction factors to account for cracking and other effects. Most of the stiffness reduction factors are available in the literature based on extensive testing (PEER, 2010, ATC 72-1, 2007, and ASCE 41, 2013). The LATBDC (2014) defines very specific numbers for projects in the city of Los Angeles for both service and sever damage performance levels. It is also accepted in some projects to define a range of options after some sensitivity studies. Table 2 shows typical stiffness reduction factors for most common structural components considered in the models.

Table 2 - Element stiffness properties for Serviceability and MCE assessments (adapted from LATBSDC, 2014)

Element	Serviceability	MCE
Structural Walls **Flexural**	In-plane – 0.75 Ig Out-of-plane – 0.25 Ig	In-plane – 1.0 *Ec* *,** Out-of-plane – 0.25 Ig
Shear	In-plane – 1.0 Ag Out-of-plane – 1.0 Ag	In-plane – 0.5 Ag Out-of-plane – 0.25 Ag
Basement and podium Walls **Flexural**	In-plane – 1.0 Ig Out-of-plane – 1.0 Ig	In-plane – 0.8 Ig Out-of-plane – 0.8 Ig
Shear	In-plane – 1.0 Ag Out-of-plane – 1.0 Ag	In-plane – 0.8 Ag Out-of-plane – 0.25 Ag
Essentially elastic Walls* **	Flexural – 1.0 Ig Shear – 1.0 Ag	Flexural – 0.8 Ig Shear – 0.8 Ag
Coupling Beams	Flexural – 0.3 Ig Shear – 1.0 Ag	Flexural – 0.2 Ig Shear – 1.0 Ag
Diaphragms (in-plane only)	Flexural – 0.5 Ig Shear – 0.8 Ag	Flexural – 0.25 Ig Shear – 0.25 Ag
Gravity Columns	Flexural – 0.9 Ig Shear – 1.0 Ag	Flexural – 0.7 Ig Shear – 1.0 Ag

* Nonlinear fiber elements automatically account for cracking of concrete because the concrete fibers have zero tension stiffness.

** Modulus of elasticity is based on the following equations:

$Ec = 57000\sqrt{f_c'}$ for $f_c' \leq 6000$ psi

$Ec = 40000\sqrt{f_c'} + 1\times10^6$ for $f_c' > 6000$ psi (per ACI 363R-92)

*** The essentially elastic walls correspond to any discontinuous wall in the building. The stiffness values defined here are justified by comparing the flexural moment from the analyses to the cracking moment of the wall.

3.5.2. Non-linear models

Typical models for measuring the performance under MCE loads include the geometry and the nonlinear properties of the material of key structural components (see Fig. 1) that are expected to undergo large inelastic deformations, such as the vertical concentrated rebar in walls, the shear deformation of coupling beams and the out-of-plane deformation of slabs around columns. Fig. 2 shows the hysteretic loops adopted for modeling the shear deformation of coupling beams and the typical nonlinear stress-strain deformation curves adopted for concrete and steel rebar in shear walls. Nonlinear material properties are assigned to fibers in shear walls that simulate the inelastic axial deformation of concrete and the vertical rebar – feature to model walls in Perform 3D (Powell, 2007). Other components behaviour, such as the out-of-plane rotation of slabs around columns and walls, are also modeled with simplified frame elements (outrigger beams) with lumped plasticity at both ends. The reader can find more information on the modeling aspects for these and other structural components in buildings in the ATC 72-1 (2010).

3.5.3. Plan eccentricity

For all performance levels, models should include the effect of plan irregularities in plan, such as potential eccentricities in plan and large inertial forces developed in massive transfer slabs, such as podium roof or grade levels. The LATBDC (2014) defines a simplified approach to deal with potential plan accidental eccentricities. In a first instance, the model under service earthquake load should be used to assess the level of in-plane rotations based on the Ax factor of the ASCE 7 (2010). If the Ax factor indicates potential torsional deformations at the service level, then this torsional assessment should be done at the MCE performance level by moving the center of mass and checking the impact for one pair of ground motions. The difference captured for several responses should be then reported and used to reduce the limitations for the MCE performance acceptance criteria.

3.5.4. Podium Effect (Backstay effect)

A substantial change in geometry from one level to another could lead to large inertial forces being transfer to other structural components above and below and then returning to a regular pattern in other levels. This effect, also known as the backstay effect, could clearly affect structural components not intended to carry large forces. To account for this effect in the models, slabs with substantial changes in geometry and mass are modeled in a way that the mass and stiffness is well distributed. Additional levels above and below this major changes in plan are also included in the model with their mass and stiffness distributed in plan. Additional bounding analyses are conducted to assess different structural responses for a range of stiffness reduction factors for slabs and other components.

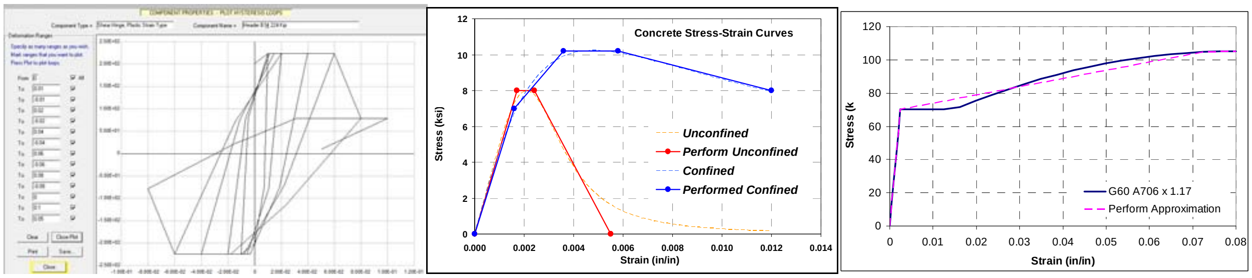

Fig. 2 – Hysteretic loops adopted for coupling beams and concrete and steel nonlinear properties assigned to fibers in shear wall components.

3.6. Results

The Design Criteria also specifies the content and format of the information that is submitted for review. Different sets of results are defined for every performance level with the goal of checking all performance limits defined in the criteria. For the service level check, typical results submitted are: Capacity over Demand ratios, C/D, for shear in beams and walls, reinforcement, and details of the model (self-weight per level, distribution of components in plan, modeling parameters of diaphragms, and typical elevations).

For the MCE performance level check, the list of results is more exhaustive than the one for service level check. This list normally include the modeling aspects and responses of all components included in the model. Typical information for the MCE performance level check includes: location of strain gages, id names of beams and wall piers, location of columns and outrigger beams, points where maximum deformations are recorded. All responses that are required to check against the performance acceptance criteria are reported graphically plus explanations of all calculations.

Most critical component responses are amplified by a factor of 1.5 to protect critical behaviours under extreme earthquake loads and thus ensure a capacity design approach. Special attention must be paid in the shear demands of shear walls, the out-of-plane rotations of outrigger beams and diaphragm forces for these types of buildings when modeling/analyzed/design using a performance-based approach.

3.7. Additional Requirements

The city of Los Angeles (LATBSDC, 2014) requires a minimum number of instruments in a building that has been designed using an alternative approach. This extra requirement involves coordination with local monitoring agencies, such as the California Geological Survey, that can take care of the maintenance and use/access to the information for future earthquake events. The number of instruments (channels) varies with the number of floors of a building. For buildings between 35 to 40 storeys, 24 channels is the most typical number of instruments required in the instrumentation plan.

Another strict requirement from the city is the assessment of the quality of concrete materials during construction. The idea is to ensure that the minimum strength specified during the performance-based design is met and that the over capacity is within estimations (critical step when adopting a capacity design approach). The SEOR must define a program to control and report the compression strength of the concrete poured on shear walls during construction.

4. The design process

This section describes aspects of the design when checking the MCE performance level. The analysis and performance check of the service and code-based levels fall within conventional practice using standard analysis and design in structural engineering offices.

4.1. Capacity Design

The capacity design approach is common practice in Canada, but is not specifically mentioned or intended in American codes for the design of buildings. In general, the idea is to locate or define the location of potential fuses in the building that can develop large deformations while still sustaining forces under large earthquake demands. These fuses are usually associated to large shear deformations in coupling beams due to the relative movement of contiguous walls and to large flexural demands in walls. A third mechanism is also identified when slabs interact between shear walls and surrounding columns under large lateral deformations of the building. A proper design should trigger all the above mechanisms under a code-based approach, but it is hard to achieve them at the same time or in a way that is normally intended during the design.

The use of nonlinear dynamic analysis in the design process can greatly benefit the main intent of a capacity design approach and inherently amplify forces of components that are intended to behave in a linear elastic manner. This type of approach is an explicit one in the LATBDC document and avoids the use of a prescriptive code-based design approach to calibrate base shears, to reduce factors or to amplify demands due to over-strength.

4.2. Modeling example

The first model is likely to reach the required performance under MCE limits if it's the result of a true capacity design approach. A typical model of a building using a performance-based approach is shown in Fig. 3. This model includes: a) panel elements with cross sections defined in terms of fibers, i.e. each fiber is the axial performance of concrete or steel in the cross section of a wall, b) coupling beams modeled with lumped plasticity due to excessive shear deformations between connected walls, and c) columns connected with outrigger beams that represent the out-of-plane behaviour of slabs and the framing effect of surrounding columns to the core system. Critical components under earthquake loading, such as discontinuous walls, columns, basement walls and in-plane deformation of slabs are modeled with elastic components with modified stiffness properties defined in Table 2.

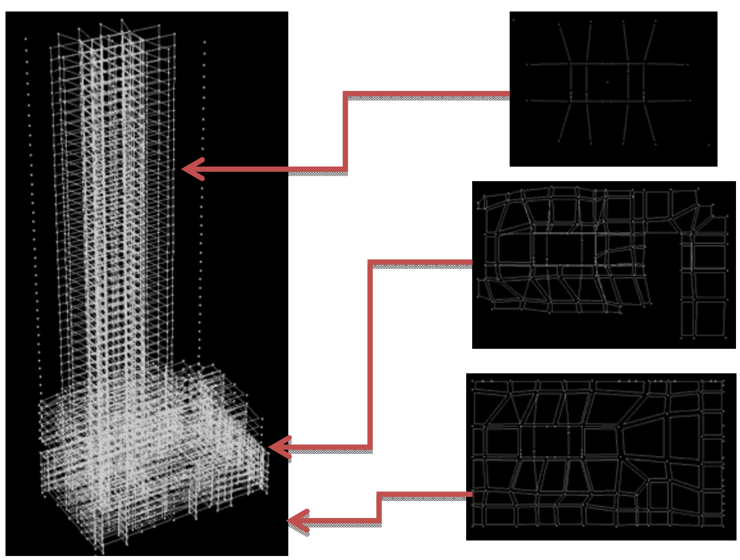

Fig. 3 –Typical tall building elevation and plans modeled in Perform 3D (Powell, 2007).

4.3. Analysis and Post-processing

To optimize the model to meet each performance level, several nonlinear dynamic analyses need to be performed for the set of ground motions selected for the project. The running time for each of these analyses can be substantial and clearly impact the overall schedule/plan of a project. High-performance computers with multi-processors are required as well as investment on parallel computing techniques/tools. The results obtained from the several nonlinear dynamic analyses are a vital part for the design of other components that are not necessarily part of the seismic design, such as foundation, columns and slabs under gravity loads and diaphragm forces. To improve this part of the process, parallel computing techniques as well as the use of cloud-computing has been tested and implemented for some of the projects. As an example, the running time of a typical nonlinear model of a 30-storye building in Perform-3D computer program can take between 6 to 12 hours, depending mainly in the number of slab elements in the model and the length of the records.

The post-processing depends directly on the computer program adopted for analysis and the interaction of data with the user (database management). This stage is on the authors experience the most time consuming part of a performance-based design project and can easily take as long as 5 to 8 days to process the main information for submission/revision. Several companies and engineering firms are investing resources on developing their own database systems to process the massive information coming from all dynamic analyses and create automatic reports for the review process. Fig. 4 shows some typical plots for reviewing the responses of some components at each level that were automatically created by in-house developed tools.

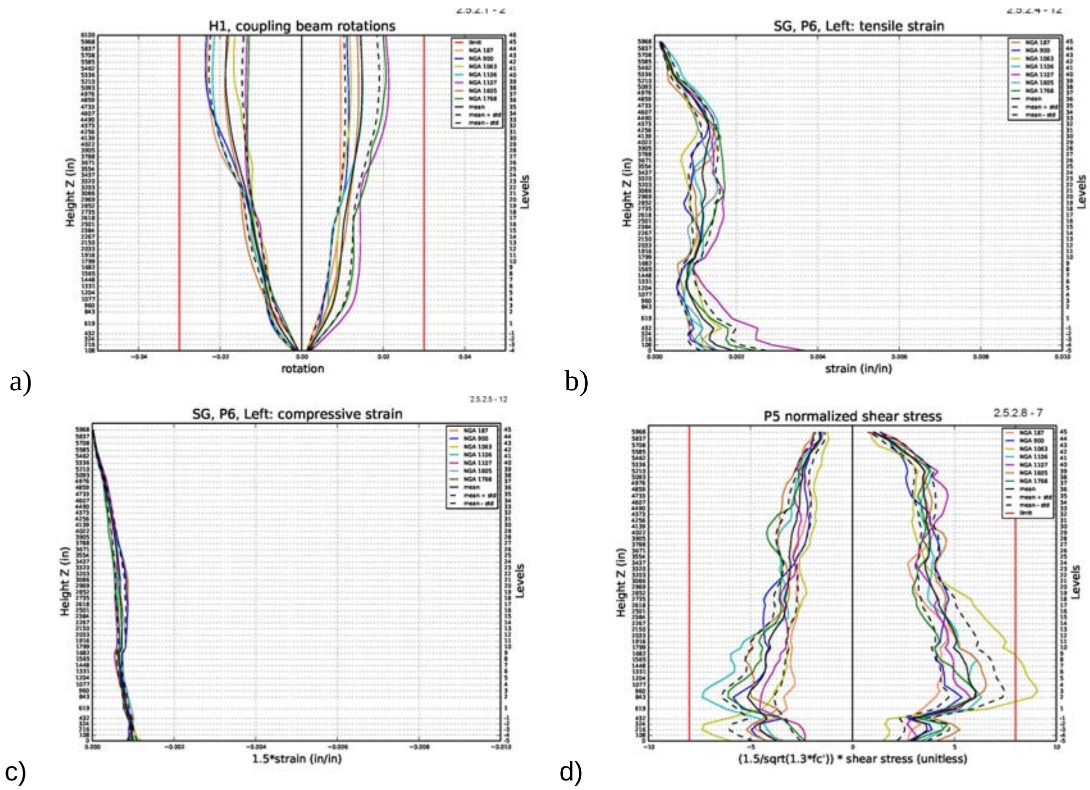

Fig. 4 – Plots showing maximum responses of structural components modeled and analyzed using MCE loading: a) maximum rotation of header beams, b) maximum tensile strain in walls, c) maximum compression strain in walls, and d) normalized shear forces in walls.

5. Final Remarks

The performance-based design of tall buildings goes beyond the conventional practice of design of tall buildings and clearly involves more time from structural engineers and other consultants to reach several performance levels under different earthquake loads. Nevertheless, the use of a performance-based approach in design is becoming a reality and part of practice of many structural engineering offices in the West coast of North-America. The use of current technology, such as powerful computer processors, database management software programs and efficient computing techniques is bringing the performance-base design to a competitive level and delivering much more efficient and better designs of tall buildings in California and other parts of the west coast of North-America.

Clear guidelines and official documentation is already in place in cities such as San Diego, Los Angeles, San Francisco and Seattle, which increases the chances of owners/clients of adopting these alternative design techniques in their projects. As an example, the author has already participated in the performance-based design of more than 5 different projects of tall buildings in the cities of Los Angeles, San Diego and Seattle in the last 4 years, forecasting an exponential increase in the next 3 to 5 years. Even though developers still see the use of alternative designs only as a legal requirement to finish a project, many of them are being educated in that the use of these new approaches in design can improve the performance of their buildings, reduce significantly the construction costs and involved professionals that can improve the project during construction.

To keep within reasonable efficiency levels and during the expected deadlines set by the clients, it is important to improve some of the reviewing processes as well as to develop new technology for the processing and post-processing stages of the design. A new industry that can work in this direction can be a feasible solution to structural engineers that are currently involved in these types of projects and potentially raising the bar to more complex analyses and even better designs. The development of new technologies and the use of complex tools can also allow for the use of valuable and available resources that cannot only contribute to science in an academic environment but also in practice engineering.

6. Acknowledgements

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