Seismic Evaluation of Tall Buildings: Transparency Using a Building Specific Earthquake Demand and System Capacity Uncertainty Analysis

G.C. Hart, PhD, PE
Principal and Emeritus Board of Directors, Weidlinger Associates Inc.
Professor Emeritus, University of California, Los Angeles

15 WCEE
LISBOA 2012

SUMMARY
Structural engineering evaluation and strengthening of a tall building with a Peer Review panel can now be done with the benefit of results from structural analysis computer models and structural reliability methods that benefit the profession and the owners. This paper shows that the time for transparency is now for tall buildings and the building code committee decisions that are good for low rise building are not acceptable for tall buildings. The inclusion of professional experience, Bayesian methods, is also essential in tall building evaluation and strengthening.

Keywords: Buildings, evaluation, strengthening, structural reliability

1. INTRODUCTION

This paper describes the work performed by the author as part of the Los Angeles Tall Building Structural Design Council committee developing a procedure for the Evaluation and Strengthening of Tall Buildings in the Los Angeles region. The work is based upon the mathematics of Structural Reliability Theory and scientifically incorporates the professional experience of the structural engineer of record and the project peer review committee using Bayesian methods. My goal which has been accepted by the committee was to present a procedure for evaluating an existing tall building for future earthquakes based on my over forty years of work in the area of structural reliability. The procedure incorporates the past work of many others but is customized to be focused and most appropriate for tall buildings. Bayesian decision theory is an important part of the work because it enables the "art" of structural engineering to be incorporated in the evaluation and strengthening. This recognition of incorporating this art is even more important today than it was over 50 years ago as stated then by Blume, Newmark and Corning in their classic 1961 book entitled "Design of Multistory Reinforced Concrete Buildings for Earthquake Motions":

"Considerable knowledge has been gained in the last three decades about the phenomenon of ground motions, the characteristics of structures, and their behavior in earthquakes. Despite this progress the complexities are still so great that earthquake-resistant design is not yet capable of complete and rigorous execution solely by means of mathematical analysis, design codes or rules. It is an art as well as a science, and requires experience and judgment on the part of the engineer."

The presented procedure addresses the following important parts of the evaluation: What to do with and benefit from limited field test data; modeling of structural members that do not have the database of information that code design is currently built upon; the roles of both linear and nonlinear time history analyses; and bounding of uncertainty factors for limit states. In a very basic sense this work can rationally be viewed as an extension of the work in many excellent textbooks on structural reliability, the classic Applied Technology Council Report ATC-3, the foundation of the ASCE 7-10 load and resistance factors, the material in ASCE 41-06 Supplement #1, PEER / ATC 63, and PEER / ATC 72-1.

Persons unfamiliar with structural engineering of buildings, and sometimes recently graduated engineers, often do not appreciate the complexity of the role of the structural engineer and the requirement for continuous learning. It is the objective of this paper to show how Structural Reliability Theory provides a vehicle for the continued incorporation into structural engineering learning from analysis, testing and observing damaged buildings to rapidly incorporate a more rational treatment of loading (*Demand*) and strength (*Capacity*) uncertainties. By such incorporation, it becomes possible to discuss more rationally and with transparency the safety of buildings.

Good structural engineers realize that there are always options in evaluating and strengthening a building. These options relate to the analysis in for example selecting the computer program to be used for the analysis. Structural reliability as presented in this book recognizes this and also offers the structural engineer options that all can be applied to meet or exceed the safety levels for performance that existing new building codes require and also as it relates to serviceability limit states the goals that the client requests be satisfied. This paper presents one option.

A word on the Structural Reliability analysis option called Monte Carlo Simulation. This is clearly the choice that becomes more "user friendly" each year. It requires minimal mathematics because it just repeats a deterministic structural analysis many times where each time a new set of computer input values are used. Structural engineers already perform a Monte Carlo Simulation when they use the Los Angeles Tall Buildings Structural Design Council new building design procedure adopted by the City of Los Angeles. This procedure requires the geotechnical engineer to provide a minimum of seven earthquake ground motion time histories for the Ultimate (or Collapse) Limit State. Each time history represents one sample in a Monte Carlo Simulation. All seven time histories are used and seven runs of the computer program are completed. In the LATBSDC case, the Expected Value of the seven Monte Carlo Simulations is used to evaluate the Ultimate Limit State. The Monte Carlo approach is especially attractive nonlinear time history structural analyses.

It is the structural engineer's choice of approach, but it is essential for tall buildings that the structural analyses models and structural reliability analyses be reviewed and approved by a Project Peer Review team.

2. STRUCTURAL SYSTEM AND STRUCTURAL MEMBER SECTION LIMIT STATES

As structural engineers, we are educated to evaluate structural members and structural systems to quantify, in scientific terms, performance. We use structural analysis mathematics to quantify this performance. We evaluate alternative structural designs prior to selecting the best structure for a building. We also evaluate the structural design of a building developed by other structural engineers. This we call Peer Review. We also evaluate the performance of an existing, or As-Built, building to determine if it needs to be strengthened. And if the building needs to be strengthened to meet a defined performance objective, then we evaluate alternative structural options for doing this strengthening. Therefore, structural engineering evaluation through structural analysis is at the core of our profession. The Structural Evaluation of a building requires a definition of what we are going to evaluate. The area of structural engineering called Structural Reliability provides a scientific basis for evaluation. In Structural Reliability, we use Limit States that define the performance of the structural system and its structural members as thresholds of system / member behavior under specified load hazard levels. We use two basic types of limit states and they are called Structural System Limit States and Structural Member Section Limit States.

An example of a Structural System Limit State is when the displacement of the top floor, or roof, reaches and exceeds the level at which the building structural system will fail and the building will collapse. This is called an Ultimate Limit State and is referred to as "Ultimate Limit State: Collapse of Structure". Another example of a Structural System Limit Sate is when building occupants start feeling the building move in high winds. We call this a Serviceability Limit State and it is referred to as “Serviceability Limit State: Human Perception”.

The building also has what we call in our Structural Reliability language Structural Member Section Limit States. For example, a Structural Member Section Limit State is when the internal member forces / deformations reach and exceed the level at which cracking of the concrete occurs with a corresponding significant loss of stiffness of the structural member. This is called “Structural Damage Limit State: Cracking of Concrete”. Another Structural Member Section Limit State occurs when the strain in a steel reinforcing bar is so large that the bar will yield and when the load is removed the steel bar will not return to its undeformed condition. This is called the “Structural Damage Limit State: First Yield of Reinforcing Steel”.

3. QUANTIFICATION OF UNCERTAINTY

Uncertainty is typically quantified by structural engineers using the Structural Reliability term called *Coefficient of Variation*. Table 3.1 provides acceptable values for the Coefficient of Variation of several structural engineering variables. A larger value of the Coefficient of Variation corresponds to more uncertainty.

Table 3.1 Coefficient of Variation (%)

Rolled Steel Yield Stress	8
Grade 50 Steel Tension Member	9
Reinforcing Bars (Grade 60) Yield Stress	9
Concrete Control Cylinders Compressive Strength (Excellent)	10
Concrete Control Cylinders Compressive Strength (Average)	15
Concrete Control Cylinders Compressive Strength (Poor)	20
Damping in Concrete Building	30
Concrete Modulus of Elasticity	20
Concrete Poisson Ratio	10
Steel Modulus of Elasticity	6
Damping in Steel Frame Building	20
Live Load	25
Maximum Annual Wind Speed	16
Maximum 50-Year Wind Speed	12
Demand and Capacity Prediction from Structural Element Analysis Models that have been calibrated / verified with a large amount of test data (High Confidence)	20
Demand and Capacity Prediction from Structural Element Analysis Models that have been calibrated / verified with limited test data (Limited Confidence)	30
Demand and Capacity Prediction from Structural Element Analysis Models that have been calibrated / verified with very little test data (Little Confidence)	40
ATC 63 Quality Rating Superior Confidence	10
ATC 63 Quality Rating Good Confidence	20
ATC 63 Quality Rating Fair Confidence	35
ATC 63 Quality Rating Poor Confidence	50

4. COMMUNICATING WITH THE OTHER WORLD

As structural engineers who have knowledge of Structural Reliability theory, we need to answer this question in a meaningful way to decision makers who are typically not structural engineers (i.e. communicating with the non-structural engineering world). To bridge this potential communication gap, we use the confidence scale given in Table 4.1 which is based on the American Society of Civil Engineers publication called *Degrees of Belief*. The term Very Certain is used in place of Almost Certain and are the same.

Table 4.1 Confidence Scale

Confidence	**Probability**	**Single Number Probability**
Almost Certain	90 to 99.5% sure	90%
Very Likely or Very Probable	75 to 90% sure	80%
Likely or Probable	60 to 75% sure	70%
Medium Chance	40 to 60% sure	50%

It is also often very important in our communication with others to present the concept of *Exposure Time*. In ASCE/SEI 7-10 this is called a *Service Life*. This is especially important when we discuss with the decision maker or even among ourselves what limit states to consider and how to evaluate the consequences of failure.

To illustrate this note in earthquake engineering, there are two levels of earthquake that have more common usage than others. They are the *Maximum Considered Earthquake* which corresponds to an earthquake that has a 2% probability of being exceeded in 50 years. A second and more frequent earthquake is one with a 50% probability of not being exceeded in 30 years. This is often called a Serviceability (or Frequent) Earthquake. Table 4.2 illustrates the relationship between Exposure Time and Probability of Exceedence.

Table 4.2 Return Period (in years) for Given Exposure Time and Probability of Exceedance

	Probability of Exceedance			
Exposure Time (years)	**2%**	**10% (Almost Certain)**	**20% (Very Likely)**	**50%**
2	99	19	9	3
5	247	47	22	7
10	495	95	45	14
20	990	190	90	29
30	1485	285	134	43
50	2475	475	224	72
100	4,950	949	448	144

5. THE ASCE 7-10 VIEW OF THE WORLD

Don’t panic! What is done here in this section is to just quote the text in parts of the ASCE 7-10 structural engineering document as it specifically relates to the evaluation and strengthening of existing buildings. The quotations are in italics, and my text is not italicized.

DESIGN STRENGTH: The product of the nominal strength and a resistance factor.

LIMIT STATE: A condition beyond which a structure or member becomes unfit for service and is judged either to be no longer useful for its intended function (serviceability limit state) or to be unsafe (strength limit state).

LOAD FACTOR: A factor that accounts for deviations of the actual load from the nominal load, for uncertainties in the analysis that transforms the load into a load effect, and for the probability that more than one extreme load will occur simultaneously.

My Note: The above recognizes uncertainty as an essential factor that we must account for in evaluation and design.

Assumptions of stiffness, strength, damping, and other properties of components and connections incorporated in the analysis shall be based on approved test data or referenced Standards.

Testing used to substantiate the performance capability of structural and nonstructural components and their connections under load shall accurately represent the materials, configuration, construction, loading intensity, and boundary conditions anticipated in the structure. Evaluation of test results shall be made on the basis of the values obtained from not less than 3 tests, provided that the deviation of any value obtained from any single test does not vary from the average value for all tests by more than 15%. If such deviation from the average value for any test exceeds 15%, then additional tests shall be performed until the deviation of any test from the average value does not exceed 15% or a minimum of 6 tests have been performed.

My Note: The above shows that we need tests that are for structural members similar to what we see in the existing structure. Otherwise we must perform laboratory structural member tests.

6. DEMAND AND CAPACITY FOR LIMIT STATE

Building codes and standards for many years use the following equation

$$\gamma \bar{D} = \phi \bar{C} \tag{6.1}$$

This is the form of the Load and Resistance Factor Design equation expressed in terms of the Mean Demand ($\bar{D}$) and Mean Capacity ($\bar{C}$). Note that it is the Mean Capacity that is multiplied by a Capacity Reduction Factor (ϕ) and the Mean Demand that is multiplied by a load factor (γ).

It is useful to define

$$\text{Design Demand} = \gamma \bar{D} \tag{6.2}$$

$$\text{Design Capacity} = \phi \bar{C} \tag{6.3}$$

It can be shown that

$$\gamma = e^{+0.72 \beta \rho_D} \tag{6.4}$$

$$\phi = e^{-0.72 \beta \rho_C} \tag{6.5}$$

where

β = Reliability, or Safety, Index

ρ_D = Coefficient of Variation in Demand

ρ_C = Coefficient of Variation in Capacity

The Design Capacity must be greater than or equal to the Design Demand.

Now consider the following

$\bar{D}$ = Expected Value of Demand using a specified exposure time (e.g. 50 years)

and define the Demand from the MCE earthquake to be

D_{MCE} = Demand from MCE

where

$$\alpha = \left(D_{MCE} / \bar{D} \right) \tag{6.6}$$

Note that α is greater than one, since the MCE is greater than the Expected Value Earthquake demand in a 50 year exposure time.

Now equate Design Demand and Design Capacity from Eqns. 6.2 and 6.3 to obtain

$$\begin{gathered}\text{Design Demand} = \text{Design Capacity} \\ \gamma \bar{D} = \phi \bar{C}\end{gathered} \tag{6.7}$$

The MCE Design Demand is now expressed as

$$\text{MCE Design Demand} = D_{MCE} = \alpha \bar{D} \tag{6.8}$$

Therefore, substituting Eqn. 6.8 into Eqn. 6.2, we obtain

$$\gamma \bar{D} = \gamma \left(D_{MCE} / \alpha \right) \tag{6.9}$$

Eqn. 6.7 now becomes

$$\left(\gamma D_{MCE} / \alpha \right) = \phi \bar{C} \tag{6.10}$$

So it follows that

$$D_{MCE} = \left(\alpha \phi / \gamma \right) \bar{C} \tag{6.11}$$

Now define the MCE Capacity Reduction Factor (ϕ_{MCE}) to be

$$\phi_{MCE} \equiv \left(\alpha \phi / \gamma \right) \tag{6.12}$$

Substituting Eqn. 6.12 into Eqn. 6.11, we obtain

$$D_{MCE} = \phi_{MCE} \bar{C} \tag{6.13}$$

Combining Eqns. 6.4, 6.5 and 6.12, we obtain

$$\begin{aligned}\phi_{MCE} &= \alpha \left[\exp\left(-0.75 \beta \rho_C \right) \right] / \exp\left[0.75 \beta \rho_D \right] \\ &= \alpha \exp\left[-0.75 \beta \left(\rho_C + \rho_D \right) \right]\end{aligned} \tag{6.14}$$

Eqn. 6.14 incorporates the ratio α of the demand from the MCE (D_{MCE}) to the Expected Value of the Demand ($\bar{D}$). It also incorporates the uncertainty in the demand and capacity by the inclusion of the Coefficients of Variation of the Demand (ρ_D) and Capacity (ρ_C).

Now consider the situation where the structural engineer prescribes an earthquake other than the MCE and wishes to perform a reliability-based design. Similar to the above, it follows that

D_{PL} = Demand from Prescribed Load

$$\alpha = \left(D_{PL} / \bar{D} \right) \tag{6.15}$$

$$\gamma \bar{D} = \phi \bar{C} \tag{6.16}$$

$$D_{PL} = \left(\alpha\phi / \gamma \right) \bar{C} \tag{6.17}$$

Define the Prescribed Load Capacity Reduction Factor to be

$$\phi_{PL} \equiv \left(\alpha\phi / \gamma \right) \tag{6.18}$$

Therefore, the Prescribed Design Load Demand and Design Capacity Equation for the limit state can be expressed as

Design Demand = Design Capacity

$$D_{PL} = \phi_{PL} \bar{C} \tag{6.19}$$

where

$$\begin{aligned} \phi_{PL} &= \alpha \left[\exp\left(-0.75\beta\rho_C \right) \right] / \exp\left[0.75\beta\rho_D \right] \\ &= \alpha \exp\left[-0.75\beta \left(\rho_C + \rho_D \right) \right] \end{aligned} \tag{6.20}$$

The above incorporates the ratio α of the demand from the prescribed load, D_{PL} , (e.g. MCE) to the Expected Value of the Demand ($\bar{D}$). It also incorporates the uncertainty in the demand and capacity by the inclusion of the Coefficients of Variation of the Demand (ρ_D) and Capacity (ρ_C).

What is beautiful about this formulation is that it helps in communicating with our clients and also lets us update the Design Capacity and Demand at different stages (i.e. money spending levels) as a project evolves. For example, knowledgeable structural / earthquake engineers can estimate if they wish a “first cut” estimate of each term in Eqns. 6.19 and 6.20 in a few hours. Also, the value of the Reliability Index (β) can be selected for many structural member types or conditions in the existing building depending on the consequences of failure.

7. CONCLUSIONS

The structural engineer performing evaluation and strengthening can define the limit states and for each select a load that is desired to address (e.g. MCE) then using experience, test data and structural model analyses, calculate D_{PL}, $\bar{C}$, ρ_C, ρ_D and ϕ_{PL}. Then based on the consequences of failure select β. The Design Demand, D_{PL}, and Design Capacity, $\phi_{PL}\bar{C}$, then follow.

ACKNOWLEDGEMENT

The author wishes to thank Professor Joel Conte, Dr. Kidong Park and the members of the LATBSDC Evaluation and Strengthening Committee who are Gregg Brandow, Larry Brugger, Lauren Carpenter, Nick Delli Quadri, Sampson Huang, Ifa Kashefi, Colin Kumabe and Marshall Lew.