STRUCTURAL DESIGN FOR EARTHQUAKE RESISTANCE: PAST, PRESENT AND FUTURE

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Contents

Summary

Natural disasters teach lessons on preventive measures and preparedness to mankind and earthquakes are no exception. All previous earthquakes which have caused structural collapses and fatalities have also helped engineering communities to improve seismic design provisions throughout the world. Amendment of design practices after a major earthquake often tempts the designers to believe that an absolute safe design practice had been achieved; a false sense of confidence which would be shattered by the next big earthquake. In reality, this sequence of "learning from disasters" and "improving the design practice" seems to be never-ending.

In the last century, seismic design has undergone significant advancements. Starting from the initial concept of designing structures to sustain no or minimal damage (i.e. loosely referred as responding elastically) during an earthquake, the modern design philosophy allows structures to respond to seismic ground motions in an inelastic manner, thereby sustaining damage in earthquakes that are significantly less intense than the largest possible ground motion at the site of the structure. This major shift has occurred through several transitional phases such as load and resistance factor design, limit state design, capacity design, performance based design etc. These phases were founded on the new knowledge unearthed by the then ongoing research and novel concepts developed at the time leading to that phase. Current multi-objective seismic design methods are characterized mainly by their aims to ensure life-safety by preventing collapse in large and rare earthquakes and to limit structural damage in frequent and moderate earthquakes. Lately, more emphasis is being given to financial implications of a seismic event rather than on measures of structural response and/or damage. This has led to a concept of loss optimization seismic design, which looks likely to be the basis for future seismic design approaches.

1. Introduction: Earthquakes and Seismic Hazard

Earthquakes are defined as the phenomena of fault rupture which releases the strain energy stored inside the earth's crust. The release of the energy results in vibratory waves propagating through the surface in all directions. While doing so, the earthquakes create several hazards such as: surface rupture, ground and slope failure, tsunamis, ground shaking etc. Although all of these hazards pose threat to infrastructures, what is commonly termed as seismic design considers the ground shaking hazard only. The ground shaking hazard at a site is a combination of hazards due to all possible earthquake sources (e. g. tectonic plate boundaries and faults) in the vicinity of the site. The contribution of each earthquake source to ground shaking at a site depends on the magnitude of earthquakes originating at the source, the source-to-site distance, the directivity of the fault rupture process, and the geological condition of the soil between the source and the site.

When earthquakes strike, functionality of manmade infrastructures like buildings, bridges, dams, roads, canals, pipelines may be disturbed. The extent of disturbance, however, depends on the severity of the earthquake-induced ground shaking at the site and the robustness of the infrastructure. The robustness of an infrastructure depends on the design, materials, and construction practice prevailing in the region at the time when the infrastructure was built. Similarly, the ground motion severity depends, among others, on the soil conditions at the site and on the proximity of the location to tectonic plate boundaries and inter-plate faults. Seismic design aims to avoid/minimize the damage to infrastructures due to ground shaking resulting from all possible earthquake sources in the vicinity. Clearly, planning and constructing earthquake-resistant infrastructure is a multi-disciplinary task which requires a sound knowledge of engineering seismology and structural engineering.

Structures are designed to safely resist a combination of actions; such as self weight (i.e. dead loads), superimposed (i.e. live) loads, snow loads, wind forces and earthquake forces. Where natural hazards such as earthquake, wind, snow do not pose a major threat, structural design is mainly governed by the dead and live loads. Such designs are also known as “gravity design”. On the other hand, where the earthquake induced ground shaking is a major hazard, the design load is dominated by seismic forces and such designs are known as “seismic design”. Seismic design is significantly different from gravity design as seismic loading on structures is highly uncertain and can occur very infrequently. Thus, it is uneconomical to design structures to sustain the maximum likely ground motion an earthquake rupture can produce, and it is, therefore, a common practice to design structures to respond inelastically to earthquake shaking, but allow sufficient ductility to prevent structural collapse. The method to design structures to resist earthquake induced forces (commonly called “seismic design”) has undergone major advancement in the last few decades. This chapter summarizes the progress of seismic design philosophy from the past to the present and also projects the future of seismic design as indicated by the current research trend. While doing so, the main emphasis is given to buildings but the discussion is not facility specific; the historical advances of seismic design philosophy described herein are equally relevant to other infrastructures as well.

2. Evolution of Structural Design Concepts

During the initial phase of evolution of design concepts, “structural design” involved estimating the structural size so that it could withstand a perceived level of maximum expected load. When structures started to be designed, no consideration was given to any other aspect apart from load and resistance. Notwithstanding the regular amendments, all structural design philosophies, in general, are governed by the “capacity greater than demand” criterion which is commonly expressed mathematically as:

$$S_{\mathrm{d}} \leq \varphi S_{\mathrm{n}} \qquad (1)$$

where, S_{n} is the nominal capacity of the structure and S_{d} is the required demand. The demand corresponds to design actions applied to the structure. In order to account for the uncertainty in estimating the capacity of a structure, a factor φ (less than one) is commonly used to multiply the nominal strength estimated from an analysis. Instead of using this strength reduction factor, material factors are also used to modify characteristic strengths of materials (e. g. the cylinder strength of concrete and measured yield stress of reinforcing bars) and the demand is compared to the capacity calculated based on the reduced material strengths. In some design approaches, more than one factor are employed to ensure that the *estimated minimum capacity* is greater than the *perceived maximum demand*. Demand is commonly expressed either in terms of design load (the term “load” usually refers to gravity, earthquake and wind induced demands are expressed as seismic/wind “forces”) or corresponding stress in the critical part of the structure, and capacity is measured in terms of structural resistance (maximum load that could be resisted) or the strength of the materials used. Since its inception, the underlying principle of structural design has always been “capacity greater than demand”, which has been interpreted differently in the different structural design concepts that have evolved throughout the last century.

2.1. Working Stress Design Method

The concept of working stress design method (also known as allowable stress design ASD) started around the beginning of the 20th century. In this method, structures or members are proportioned such that the stresses induced due to prescribed working loads are less than the allowable stresses (representing the elastic limit) specified in the codes. In other words, the service load should not exceed the allowable load, which is calculated as the nominal strength divided by a factor of safety to account for uncertainties. Designed structures are intended to remain within elastic range and linear analysis is sufficient to estimate the working stresses. All uncertainties (in demand and capacity) are combined in a single factor of safety which is used to reduce the ultimate strengths of materials to be used as the allowable stresses.

2.2. Ultimate Strength Design Method

The concept of ultimate strength design started to evolve in 1950s and this design concept started to appear in the design codes from the late 1960s. Ultimate strength design is based on the requirement that the design load effects multiplied by the specific load factors are less than the computed nominal strengths multiplied by specified strength reduction factors. As explained earlier, the strength reduction factor is not needed if the nominal strength is calculated using the nominal material strengths divided by appropriate material factors. The concrete design codes were the first to adopt this design philosophy. Steel design codes adopted the ultimate strength design in the form of Load and Resistance Factor Design (LRFD) but also allowed the working stress method to be used. Timber is the only material that appears to be still following the working stress design. This is because timber is basically a brittle material, and ultimate strength and elastic strength are essentially the same. One of the major advantages the ultimate strength design (or LRFD) offers over the allowable stress design is the use of separate factors to account for the uncertainty in capacity and demand. The factors to multiply the capacity (i.e. strength reduction factors) are less than one and differ for different materials and mechanisms; i.e. smaller values are used when there is less confidence on the estimation of the capacity corresponding to a type of failure mode (shear, flexure etc.). As the variation in concrete strength is more than in steel, typically a smaller factor is used for concrete than for reinforcing and structural steel. Similarly, the factors to multiply the demand (i.e. the load factors) are greater than one and different factors are used to multiply different forms of loads (i.e. live, dead, wind, seismic etc), which are then combined to come up with the factored design load. In determining the specific magnitude of the load factors, more deterministic loads are given lower factors than highly variable loads. For example, as live loads are more difficult to predict than the dead loads, typical live load values are multiplied with a greater load factor than that used for the dead load.

2.3. Limit State Design Method

Limit state design is an extension of the concept of LRFD, the only difference being that it requires the structure to satisfy more than one design requirement (termed as limit states). A limit state is a set of performance criteria (e.g. vibration, crack width, deflection, buckling, and collapse) which must be met when the structure is subjected to a level of load. In general, two principle limit states are used: the serviceability limit state (SLS) and the ultimate limit state (ULS); although an intermediate limit state (i.e. damageability limit state) is also used sometimes. SLS is intended to ensure that the structure remains functional and no discomfort is caused to the occupants through excessive sway/deflection/vibration when subjected to routine loading. A structure is considered to have satisfied the SLS criteria if the estimated deflection, vibration, crack widths are within permissible limits specified in the codes. Elastic methods of analysis are generally acceptable for checking SLS criteria. A structure not fulfilling the SLS criteria will not necessarily fail structurally. ULS is to ensure that a designed structure does not collapse when subjected to the peak design action. A structure is deemed to satisfy the ULS criteria if all the design strengths (nominal strengths in flexure, shear etc multiplied by the corresponding strength reduction factor, or nominal strength calculated by using factored material strengths) equal or exceed the design actions (sum of load factored actions).

3. Evolution of Seismic Design

The concept of seismic design started in early 20th century. Discussions on deficiencies of structural systems and the resulting damage due to the 1906 San Francisco earthquake can be found in abundance in the literature. Since those days, people in seismically active countries like USA (especially the west coast), New Zealand, and Japan have been working towards forming a robust earthquake resistant design. The first active step in mitigating seismic risk was taken by the Seismological Society of America in 1910, when it identified three earthquake-related issues requiring further investigation: phenomenon of earthquakes (when, where and how they occur), the resulting ground motions, and their effect on structures. The seismic performance of then-existing structural forms had been perceived to be weak. Records show that structural engineering communities throughout the world had understood that earthquakes expose structures to lateral forces that are different from the vertical gravity loads and structures need to be specially designed to withstand earthquake induced ground shaking. A review of historical seismic design codes of different countries reveals that the definition of seismic safety has undergone gradual changes towards making it more concise, specific and performance-based. To accommodate these sophistications, several important concepts have evolved through the years. Through all these revisions of seismic design philosophies, the underlying design concept of "capacity greater than demand" has remained pivotal. Nevertheless, the meaning of the general terms "capacity" and "demand" has been interpreted differently at different stages of this journey.

3.1. Strength Based Design

Until the 1960s, seismic design provisions were largely based on "induced stress less than allowable stress" criterion. The induced stresses were calculated by applying lateral seismic design forces which were taken as a fraction of the weight of the structure and the structure was designed such that the stresses induced by the design seismic forces when combined with gravity loads were less than the allowable stress levels. This was the "working stress method" applied in seismic design. In seismic design a truly elastic design approach is difficult to correlate with expected structural response. After all, by definition, a design earthquake is an ultimate-strength event. From the 1970s onwards, the concept of "ultimate strength design" started to appear in the seismic design codes. This change also brought the need to take inelastic behavior into account; mainly to conduct nonlinear analysis to calculate the ultimate strength of a member. The ultimate strength based seismic design basically involved calculating the design strengths and comparing them against factored seismic design actions.

3.2. Multi-Objective Prescriptive Design

When the ultimate strength design method was being commonly used in seismic design, earthquake engineers realized that just ensuring that a designed building does not fail in an ULS earthquake is not enough and the building also needs to respond to smaller and more frequent earthquakes without causing any significant discomfort to its occupants. This led to the use of limit state design where both the serviceability and ultimate limit states would need to be satisfied. The serviceability criteria required buildings to sustain no or minimum damage (loosely referred to as remaining elastic) in frequent earthquakes (typically with 50% probability of exceedance in 50 years) and the ULS required the building not to collapse (to ensure life safety) in a design level earthquake (5% probability of exceedance in 50 years). This was a significant advancement as for the first time a building needed to satisfy more than one performance criteria. This marked also the beginning of multi-objective performance based seismic design, where multiple performance criteria corresponding to different levels of earthquakes (usually specified in terms of their probability of occurrence) are checked in a precise and quantitative manner. An example of this prescriptive approach can be found in the Uniform Building Code (UBC) which specified the performance requirements for a building as shown in Table 1.

Earthquake intensity	Frequency of occurrence	Desired performance
Minor	Several times during the building's service life	No damage to structure or non-structural components
Moderate	One or more times during the building's service life	No significant damage to structure and limited damage to non-

		structural components
Major	Rare event as large as any experienced in the vicinity	No collapse of structure or other damage that would create a life safety hazard

Table 1. Required building performances for different levels of ground motions (UBC)

Similarly, Structural Engineers Association of California (SEAOC) seismic design manual stated that the lateral force requirements are to produce structures that should be able to resist: a small earthquake with no damage, medium earthquake with some nonstructural and contents damage but no significant structural damage, and the largest earthquake predicted at the site with significant damage of structural components but without structural collapse. Design of structures following today's design standards, although having many different forms and equations, generally still follow the same philosophy presented in the SEAOC document mentioned above.

One of the features of these guidelines is that the demand and capacity are not concisely defined; vague and subjective terms such as "moderate", "one or more times", "limited damage" are used. Three levels of performance against three different levels of earthquake are required, but only the largest earthquake intensity (i.e. major) is quantified as 10% probability of exceedance in 50 years. The ambiguity of the definitions can lead to wide variations in the interpretation of the code.

3.3. Performance Based Seismic Design

Until late in the 20th century, all design codes had prescriptive guidelines to achieve serviceability and safety. In doing so, the codes specified a common value of response parameter that the designed structures shall not exceed in limit state events. The concept of performance based design evolved when designers started realizing that such a prescriptive design was not always the most appropriate method. Different structures have different performance requirements and it is not appropriate that the same prescriptive criteria be used for designing different structures. For example, the ULS for a water tank refers to cracking as no cracks should be permitted to enable the tank to store water which is its main purpose, whereas ultimate state for a residential building is prevention of collapse (to ensure life safety). Obviously, these two limit states correspond to drastically different values of critical response parameters (such as lateral drift).

In performance based design, the aim is to satisfy the performance requirements of a structure rather than to ensure that the response is within a prescribed limit. The performance requirements are structure specific; for a residential building severe damage in an extreme event is permitted whereas any damage in a hospital or an emergency facility (even in an extreme event) is required to be minor so that the functionality of such important facilities are not interrupted after an earthquake. Currently, many seismic design codes require structures to satisfy more than one seismic performance requirement. In such a multi-level seismic performance based design concept, in addition to verifying the prevention of collapse in an extreme earthquake, structural performances in smaller levels of earthquakes also need to be checked.

Typically, required performances against three different seismic hazard levels are specified in modern performance based seismic design codes for buildings. The three seismic hazards are generally categorized as frequent earthquakes (usually with 100 years return period; 50% probability of exceedance in 50 years), design basis earthquake (DBE) with 475 years return period (i.e. 10% probability of exceedance in 50 years), and maximum considered earthquake (MCE) with 2475 years return period (i.e. 2% probability of exceedance in 50 years). The actual earthquake intensities corresponding to these hazard levels depend on the seismicity of the location of interest. As shown in Figure 1, the required performance of buildings in these three hazard levels depends on the importance of buildings. Obviously, buildings that house emergency facilities are more important than normal residential buildings and need to be functional even after rare earthquakes. In general, performance requirement can be categorized into four classes as operational (functioning fully after an earthquake), immediate occupancy (slightly damaged but any minor repair could be done without disrupting the function of the building), reusability (also referred to as life safety) (damaged but reparable although the building may need to be evacuated for repair), and collapse prevention (does not collapse although the building may be severely damaged requiring demolition).

The first and the last categories can be verified more easily than the remaining two; "operational" means the structure must avoid significant damage and "collapse prevention" means the structure remains standing regardless of the extent of damage when subjected to the specified seismic hazard level or its equivalent action. The interpretation of the remaining two categories can be subjective. For the verification of immediate occupancy slight inelastic response along with minor damage, such as cracking and minor yielding are acceptable, whereas for reusability any reparable damage such as spalling of cover concrete are accepted but irreparable damage such as buckling and fracture of reinforcing bars are not. In extreme earthquakes (i.e. MCE), normal buildings are required to satisfy the collapse prevention criteria whereas more important buildings may be required to satisfy the reusability criteria. From the previously described categorization it appears as if life safety is compromised in MCE for normal buildings, but it is not actually so. In contrast to the names of the categories, threat to life-safety originates mainly from collapse rather than from severe damage; therefore life-safety will be achieved if collapse prevention is ensured. In DBE, normal structures are required not to sustain severe (irreparable) damage (i.e. reusability criteria), whereas more important structures are required to be available for immediate occupancy/use. Similarly after frequent earthquakes, normal structures are allowed to undergo minor damage, the repair of which does not require the building to be closed (i.e. immediate occupancy), whereas more important structures are required to remain perfectly undamaged (i.e. operational).

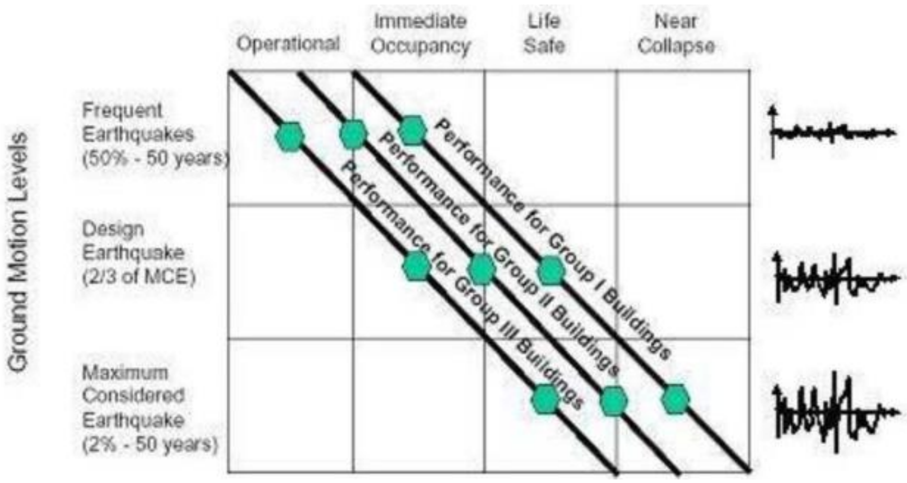

Figure 1. Framework for performance based seismic design of buildings

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Biographical Sketch

Rajesh P Dhakal received a Bachelor degree in Civil Engineering from Tribhuvan University, Nepal in 1993, a Master of Engineering degree with specialization in Structural Engineering from the Asian Institute of Technology (AIT) in 1997, and a PhD in Civil Engineering from the University of Tokyo in 2000. After working as a Research Fellow for almost three years in Nanyang Technological University, Singapore, he joined the University of Canterbury, New Zealand in 2003, where he is currently a Professor. His teaching and research involvements are in the areas of Structural and Earthquake Engineering. He has authored more than 240 technical peer-reviewed papers in the areas of reinforced concrete, earthquake engineering, and structural fire engineering. He is the recipient of four best paper awards, three best academic performance awards, and three best researcher awards including the prestigious Ivan Skinner award and the Otto Glogau award. He is a member of several national and international expert review panels and has served in the editorial board of a number of International Structural/Earthquake Engineering journals including the ASCE Journal of Structural Engineering, Earthquakes and Structures, and Structural Engineering and Mechanics. Currently, he is the Chief Editor of, the Bulletin of the New Zealand Society for Earthquake Engineering.