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EARTHQUAKE-RESISTANT DESIGN OF STRUCTURES

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Abstract: Earthquake-resistant design of structures has grown into a true multi-disciplinary field of engineering wherein many exciting developments are possible in the near future. Most notable among these are: (a) a com-plate probabilistic analysis and design approach;
performance-based design codes; (c) multiple annual probability hazard maps for response spectral accelerations and peak ground accelerations with better character Sedation of site soils, topography, near-field effects; (d) new structural systems and devices using non-traditional civil engineering materials and tech-antiques and (e) new refined analytical tools for reliable prediction of structural response.

I. INTRODUCTION

WHENEVER there is an earthquake-related disaster in the news with pictures of collapsed buildings and other structures strewn all over the place, one may probably think that earthquake-resistant design (EQRD) of structures is still in the dark ages. Of course, the objective of profes-sionals engaged in the area of EQRD is to create various cost-effective design solutions to make structures less vulnerable to earthquakes, even large earthquakes. But have we learned enough over the years about building structures that will behave predictably and within acce-ptable damage limits? Is there a bright future in this field?

Actually, there is. As a multi-disciplinary field of engineering, the design of earthquake-resistant structures is at a threshold from where many exciting developments are possible in the coming years. Developments of new techniques and shifting to new materials, which are not traditionally used in civil engineering structures, offer significant promise in reducing seismic risk. Notable improvements have been made in our understanding of earthquakes and the response of structures. Advances in modelling ground motions; development of more involved and complex analysis tools; larger and better quality database to predict ground motions; a shift towards proba-bil and reliability-based design approaches and a gradual replacement of descriptive codes by performance-based design procedures are some of the significant changes in this direction.

Seismic risk is a function of seismic activity and vulnerability of the built environment in a given area. Since the earthquake engineer has no control over the earth-quake itself, mitigation of seismic risk means conceiving of structures which can safely resist and negotiate the actions of earthquake ground motions, preferably with minimum cost implications. Briefly then, EQRD involves developing the structural configuration; determining the size and shape of various elements; the materials of con-struction; and the method of fabrication. The 'modern' design techniques were developed primarily during the last five decades, mostly in developed countries with active seismic regions such as the United States, Japan and New Zealand. However, it should be kept in mind that traditional structures in earthquake-prone areas did include special construction features, which made them less vul-nerable to earthquakes.

Of course, the future of EQRD is a function of the past performances of such designs. Fortunately, our past experience is rich with many centuries of construction (mostly trial-and-error) and at least a hundred years of systematic study of earthquake effects, of which the last fifty years led to EQRDs as we know them now. Today, we understand to a great deal, how our built environment will respond to a wide range of earthquake motions. The challenges therefore are, to develop new techniques and to improve on the existing practices so that the perfor-mance of the structures is predictable and acceptable. In this article, a brief summary of the main aspects of EQRD will be presented, followed by a discussion of ongoing research efforts, prevailing viewpoints, and future trends that are most likely to emerge in the next few years.

II. NATURE OF THE EQRD PROBLEM

'Seismic demand' is the effect of the earthquake on the structure. 'Computed capacity' is the structure's ability to resist that effect without failure. In short, the structure should not fall down. It should be noted that in the dyna-mic loading environment (created by earthquakes), the demand and capacity of a structure are very strongly cou-pled. One invisible requirement in the criterion shown above is that a structure must meet all functional require-ments at minimum economic cost.

Unfortunately, it must be recognized that no structure can be completely safe. One, we cannot perfectly predict the seismic demand due to earthquake loads; two, the computed versus actual capacity of a designed structure may not match perfectly; three, there could be human errors in design and construction. Earthquake loads are inertia forces resulting from ground movements and they impose certain demands on the structures related to strength, ductility and energy. The magnitudes of these demands are highly variable and are dependent on the seismicity of the region and the dynamic characteristics of the structure – which is why they cannot be predicted pre-cisely and can be expressed only in probabilistic terms. Simplistically, it is graphically shown in Figure 1, where probability density functions of demand and capacity are plotted. The design demand is the predicted maximum value of seismic demand for design purposes and actual distribution indicates that there is some probability that it would be exceeded. Similarly, the computed capacity is obtained by accepted methods of analysis and design. The distribution for capacity suggests that there is some probability that the actual as-built capacity may be less than the computed value. However, due to extra conservatism in design process, there is greater probability that it would be larger. The shaded area in Figure 1 where both distri-butions overlap indicates that there is some probability of failure, where capacity is less than demand.

The inter-relationship between these two entities of the design process, i.e. demand and capacity is shown in Figure 2. Various quantities that determine demand and capacity and how design codes try to define them and specify a standard process for the design of a structure of acceptable performance1 are also shown in Figure 2. Various strategies for providing adequate capacity for the attenuation of the seismic response in a structure have been listed as well. Similarly, on the demand side, various factors characterizing the ground motion that determines the severity of the demand are listed.

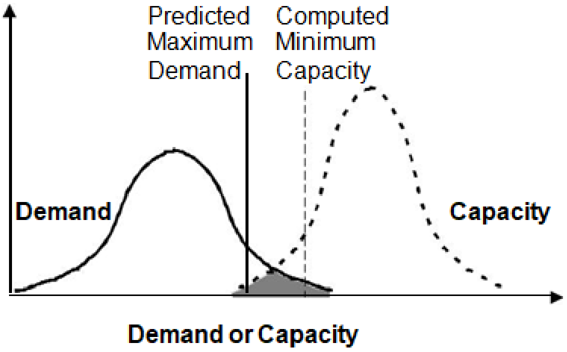

Figure 1. Probability distributions of demand and capacity.

Major efforts in earthquake engineering research are directed towards reducing the level of uncertainties in predicting the ground motion at a site and the response of a structure due to that ground motion. Currently, struc-tural responses can be predicted fairly confidently, but the prediction of ground motion is far from satisfactory. Many new devices, techniques and strategies have been continuously developed for the structural system to either reduce the seismic demand or to enhance the strength, ductility or energy dissipation capacity. Clearly, the prob-lem of having loads and structures interacting in such a complex, hard-to-predict fashion requires that EQRD involves specialists from other disciplines, including geo-scientists, seismologists, structural engineers, geotechni-cal engineers and professionals from other allied branches of engineering and that is where the future is heading to.

Emerging future trends

In view of the above discussion on the nature of the EQRD problem, it is not very difficult to identify future growth areas. In addition to identifying those areas, I will also discuss the factors which will define the success of EQRD concepts, approaches and techniques in the coming years.

for the demand side. After all, how would one construct a complete probability model with the paucity of observed data about earthquake effects, source mechanisms, ground motion characteristics and all other details that define the earthquake loads on structures? Thus, we are in a situa-tion where a poor database cannot yield a good model. So up to now, most EQRD processes have been accounting for these uncertainties of seismic loads in a rather empiri-cal fashion which can be described, at best, as ‘determi-nistic’. Luckily, people are collecting more observed data of late, which means that with the development of more complete reliability-based codes and procedures, proba-bilistic analyses of structures should become more and more commonplace2.

Defining acceptable risk through performance objectives

What is ‘the level of acceptable risk’ to be used in design-ing an earthquake-resistant structure and who decides it? Risk is expressed in terms of hazard and vulnerability. In our context, an earthquake is the hazard and susceptibility of structures to damage is the vulnerability. Now let us consider the issue of risk mitigation in terms of the cost involved and how different groups consider the cost effec-tiveness. It must be understood here that acceptable levels of risk are different for various groups. To engineers and designers (who, by the way, feel personal responsibility for the performance of every structure) a design that causes minimum loss of life and damage to structures is acceptable, even if the cost is high. On the other hand, owners who pay for the structure tend to accept a higher risk on the occurrence of earthquakes rather than make

Treatment of design uncertainties through probabilistic approach

Most often, the prime objective of the designer is to sat-isfy the design inequality with the least possible cost and maximum functional satisfaction. However, there are numerous uncertainties associated with the determination of both demand and capacity and the design inequality can be satisfied only in a probabilistic manner. In other words, the odds of failure of the structure can be reduced to an acceptable minimum (with the desired level of con-fidence) but its total safety cannot be guaranteed. To make matters worse, the uncertainties associated with earthquake engineering large investments into extra safety measures for a large earthquake event that rarely happens. Conflict of interest can arise among other stakeholders such as financial insti-tutions, beneficiaries and policy makers as well3. Such issues are important especially in regions of higher risk, where insurance companies can be liable to make large payments and the government agencies have to spend large sums in rescue, relief and rehabilitation activities, in the event of a major earthquake.

The engineering community, which had been mainly focused on reducing threats to life safety up to now, is also beginning to consider various performance objectives to define the level of acceptable risk, which is a basic shift in the earthquake-resistant design process in the recent times. In other words, more than one performance objective is used during the design process. These per-formance objectives vary from code minimums (which are usually based on Life Safety as the performance objective for the rare event of a large earthquake) to operational capability for the more frequent moderate-size earth-quakes. The Structural Engineers Association of Califor-nia (SEAOC) in their Vision 2000 document defines performance objectives for buildings as the building's expected performance level, given a certain level of expected ground motion in an earthquake4. 'Expected performance level' can be one of the four damage states: fully operational, operational, life safety, and collapse prevention. In order to simplify, the first two damage states can be grouped in one performance level of imme-diate occupancy. These performance levels are combined with the expected ground motions at a particular site to determine the acceptability criteria for the structure. Hazard levels can vary from frequent to very rare occur-rences of seismic events. In this framework, by specifying which performance objective is acceptable for various earthquakes under consideration, a level of acceptable risk would be clearly indicated.

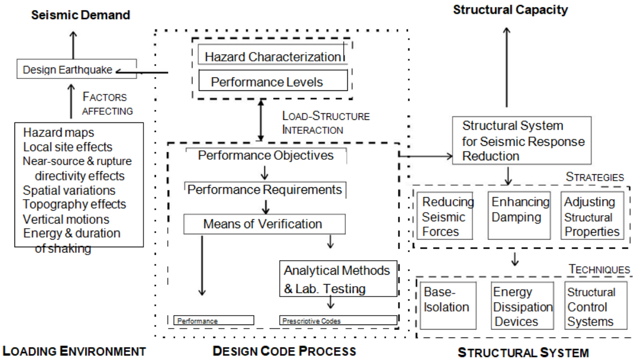

Figure 2. Inter-relationship between seismic demand and structural capacity as applied to EQRD.

Damage sustained by the structure while dissipating energy during an earthquake is dependent on inelastic deformations (displacements) which the structure experi-ences. As a result, displacement parameters of a given structure provide the realistic evaluation of effects of earthquake damage. Nonlinear Static Procedures (NSPs) of structural analyses are simplified numerical tools to obtain the structure's capacity curve, which relates an appropriate global deformation parameter to a global force parameter. For example, in the case of buildings, roof displacement and base shear force can be two such quantities. As shown in Figure 3, the displacement capa-city, dc, can be identified corresponding to various per-formance levels in increasing order of dc and hence damage from immediate occupancy to collapse preven-tion. For a given structure, a global displacement capacity limit dc for a specific performance level is based on prior experience of damage in terms of observed width and extent of concrete and masonry cracks or similar inelas-tic behaviour. Similarly, displacement demands, dd, due to various levels of seismic hazards can be generated using NSPs in conjunction with an appropriate capacity curve.

In Figure 4, displacement demands for various hazard levels are plotted on the upper horizontal axis, whereas limits on displacement capacities for various performance levels are plotted on the lower horizontal axis. This com-bined plot provides a complete picture of the risk associ-ated with a particular design of the structure. A structure meets a specific performance objective if the correspond-ing ratio, (dc /dd), of displacement demand and capacity is 1.0 or greater. In Figure 4, the hypothetical structure does meet the performance objectives of immediate occupancy and life safety, but fails to meet the collapse prevention performance objective. As shown in Figure 5, the global displacement demand can be plotted versus a risk para-meter for various design alternatives of the structure. For a specific performance objective, the intersection of a global displacement capacity value with the correspond-ing displacement demand curve allows an estimate of risk that the performance level would exceed for a given design alternative. For example, if Figure 5 is drawn for life safety performance level, then for design alternative A, the chance that global displacement demand would exceed the life safety capacity is slightly higher than 20% in 50 years, whereas, say, for more expensive design alternative B, the risk is reduced to just above 2%. This is an illustration of how acceptable risk can be defined through performance objectives, which employ displace-ment-based analysis procedures, such as NSPs and multi-ple hazard levels[5,6].

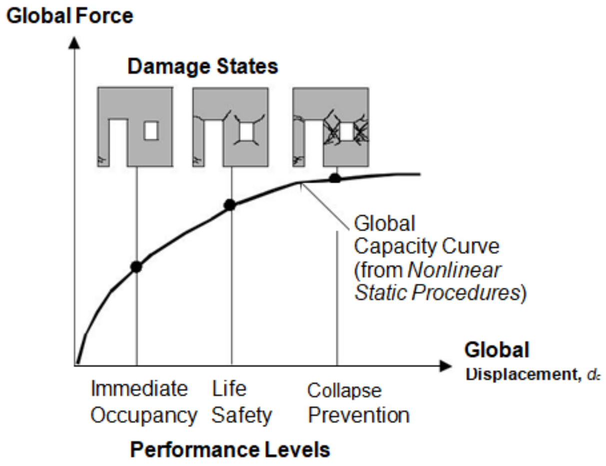

Figure 3. Global displacement capacities for various performance levels.

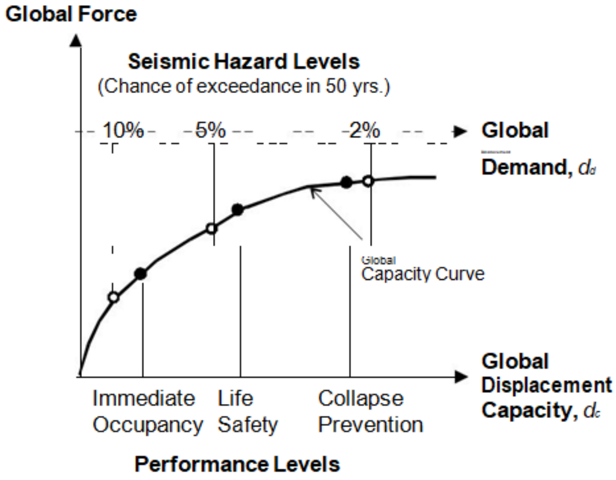

Figure 4. Global displacement demands and capacities.

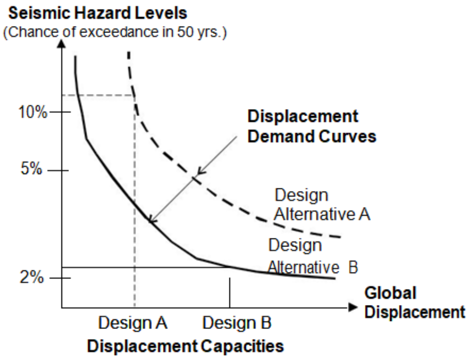

Figure 5. Risk associated with various designs for a specific per-formance level, say, life safety.

III. CONCLUSIONS

In the coming years, the field of Earthquake Resistant Designing of structures is most likely to witness the most reliable structure which could withstand the effect of earthquake in all kinds of zones.

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