Future trends in earthquake-resistant design of structures

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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 complete probabilistic analysis and design approach; (b) performance-based design codes; (c) multiple annual probability hazard maps for response spectral accelerations and peak ground accelerations with better characterization of site soils, topography, near-field effects; (d) new structural systems and devices using non-traditional civil engineering materials and techniques; and (e) new refined analytical tools for reliable prediction of structural response, including nonlinearity, strength and stiffness degradation due to cyclic loads, geometry effects and more importantly, effects of soil–structure interaction. Some significant developments that the coming years will witness are discussed in this paper.

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 professionals 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 acceptable 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 probabilistic 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 earthquake 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 construction; 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 vulnerable 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 performance 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.

Nature of the EQRD problem

The basic design criterion, which any earthquake-resistant structure must satisfy, is the following:

$$\text{Seismic demand} \leq \text{Computed capacity}$$

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'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 dynamic loading environment (created by earthquakes), the demand and capacity of a structure are very strongly coupled. One invisible requirement in the criterion shown above is that a structure must meet all functional requirements 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 precisely 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 distributions 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 performance[1] 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.

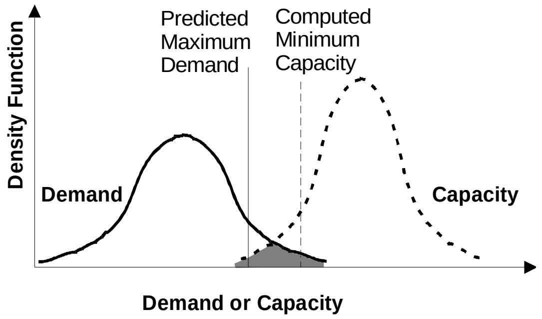


Figure 1. Probability distributions of demand and capacity.

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, structural 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 problem of having loads and structures interacting in such a complex, hard-to-predict fashion requires that EQRD involves specialists from other disciplines, including geoscientists, seismologists, structural engineers, geotechnical 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.

Treatment of design uncertainties through probabilistic approach

Most often, the prime objective of the designer is to satisfy 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 confidence) but its total safety cannot be guaranteed. To make matters worse, the uncertainties associated with earthquake engineering are perhaps more than those in *any other* field of engineering? Thus, it appears that having a consistent account of all uncertainties is the only rational way for proper decision-making.

Probability theory and Bayesian statistics provide an adequate mathematical framework to account for uncertainties on the *capacity side* of the design equation. Issues like the variation in material properties, construction uncertainty, dimensional errors and errors in modelling, analysis and design can thus be accounted for. Unfortunately, a similar mathematical formulation is not possible 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 situation 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 empirical fashion which can be described, at best, as ‘deterministic’. Luckily, people are collecting *more* observed data of late, which means that with the development of *more* complete reliability-based codes and procedures, probabilistic analyses of structures should become *more* and *more* commonplace[2].

Defining acceptable risk through performance objectives

What is ‘the level of acceptable risk’ to be used in designing 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 effectiveness. 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 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 institutions, beneficiaries and policy makers as well[3]. 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 performance 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 earthquakes. The Structural Engineers Association of California (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 earthquake[4]. ‘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 immediate 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 occurrences of seismic events. In this framework, by specifying

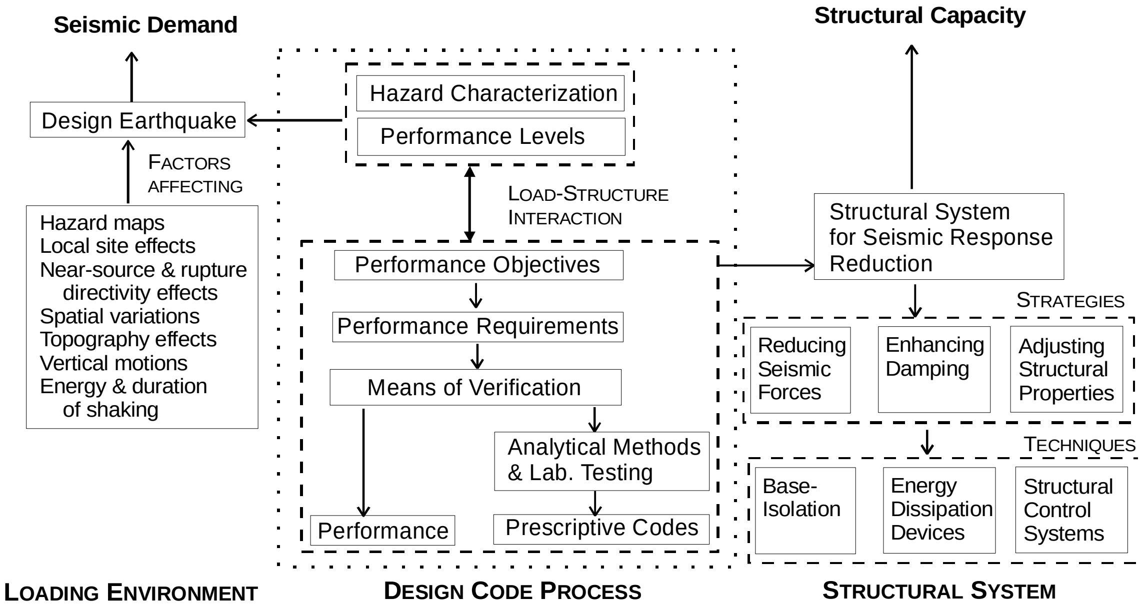


Figure 2. Inter-relationship between seismic demand and structural capacity as applied to EQRD.

which performance objective is acceptable for various earthquakes under consideration, a level of acceptable risk would be clearly indicated.

Damage sustained by the structure while dissipating energy during an earthquake is dependent on inelastic deformations (displacements) which the structure experiences. 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 capacity, d_c, can be identified corresponding to various performance levels in increasing order of d_c and hence damage from immediate occupancy to collapse prevention. For a given structure, a global displacement capacity limit d_c 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 inelastic behaviour. Similarly, displacement demands, d_d, 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 combined plot provides a complete picture of the risk associated with a particular design of the structure. A structure meets a specific performance objective if the corresponding ratio, (d_c/d_d), 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 parameter for various design alternatives of the structure. For a specific performance objective, the intersection of a global displacement capacity value with the corresponding 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 displacement-based analysis procedures, such as NSPs and multiple hazard levels[5,6].

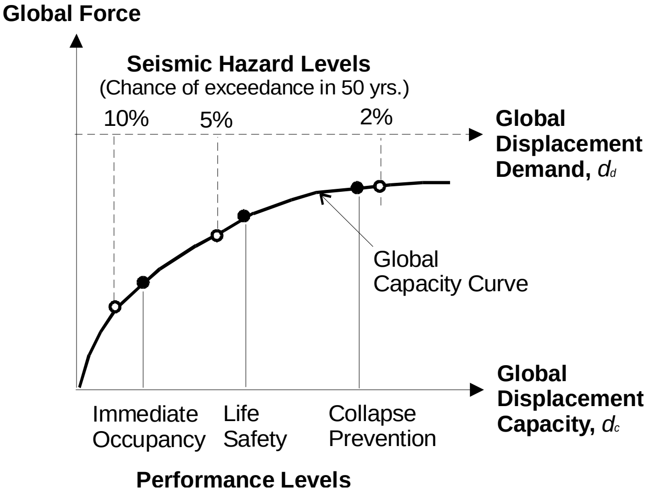


Figure 4. Global displacement demands and capacities.

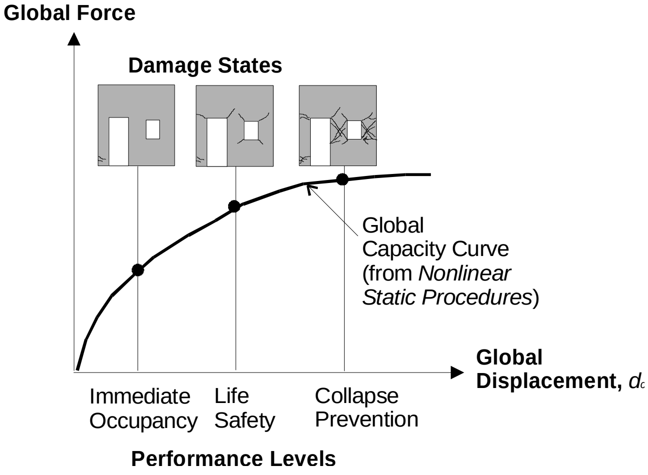


Figure 3. Global displacement capacities for various performance levels.

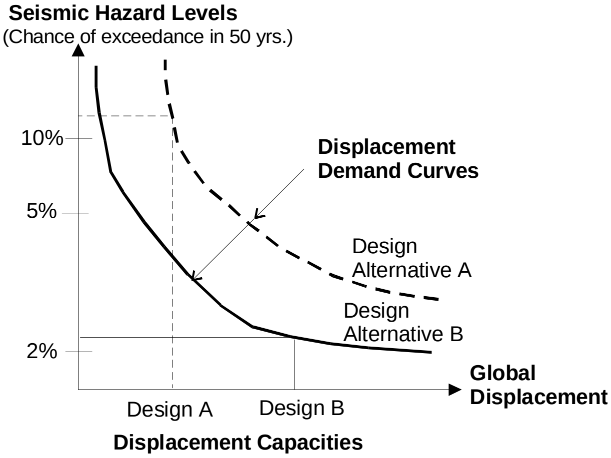
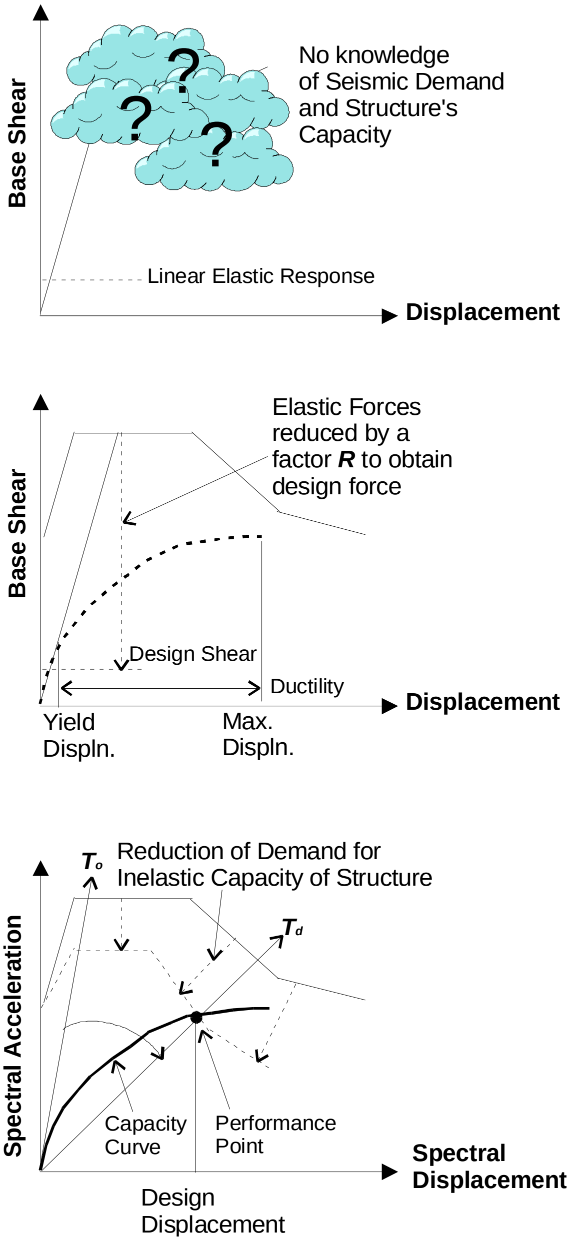


Figure 5. Risk associated with various designs for a specific performance level, say, life safety.

Performance-based design codes

The evolution of seismic design procedures can be summarized as shown in Figure 6 (ref. 7). Initial design procedures recognized that seismic forces acting on the structure are inertial forces caused by earthquake accelerations and therefore, would be proportional to the structure's weight. Over the years, advances in the knowledge of actual behaviour of structures have resulted in modification to this basic procedure to reflect the fact that structural demands generated by earthquake accelerations are functions of strength and stiffness properties of the structure, in addition to its weight. Conventional codes are prescriptive in nature and are based on specific observations, which were then generalized to cover a wide variety of structures. So we should not be surprised that there are numerous inconsistencies and omissions associated with these building codes. Seismic risk and the expected performance of a structure are not explicitly defined in these codes and they cannot indeed be expressed in such a manner. Moreover, conventional codes have not followed the development of new ideas quickly enough.

Performance-based design codes not only represent a radical shift from the conventional prescriptive codes but also aim to overcome most of their limitations[8]. However, designing for performance requires a higher level of understanding of the structural behaviour, such as the nonlinear relations between forces and deformations,



Historical Approach:
Design seismic forces were assumed proportional to structure's mass and typically varied between 5-10% of the mass. Linear design is used with appropriate factors of safety to account for uncertainty in seismic demand and capacity.

Traditional Codes:
Design seismic forces for linear design are obtained by reducing elastic demand by a factor ***R*** which varies based on typical inelastic response of structural type. The reduction is justified by *expected* ductility, overstrength and redundancy.

Future Trend:
Inelastic seismic demands are based on inelastic capacity of structure. As inelastic displacements increase, the period of structure lengthens, damping increases and demand reduces. The Capacity Spectrum Method generates Performance Point where displacement is consistent with the implied damping. Design is based on displacement corresponding to the Performance Point, which implies a unique damage stage related to a specific hazard level.

Figure 6. Evolution of seismic design procedure (adapted from ATC-40).

complex analysis procedures such as NSPs, collapse or yield mechanism of the structural system, etc. Some of the major developments towards performance-based designs are the *capacity spectrum approach* for determining design loads (see the ATC-40 and FEMA-273 documents and the SAC Joint Venture), the development of *displacement-based design procedures* and specifications for performance levels as proposed in SEAOC's Vision 2000 document[9–11]. Another idea is to use the balance between the seismic energy input with the energy dissipation capacity of the structure as a basis for performance-based design. This concept is not new and its implementation is still a challenge, but it is a promising area to explore[12].

Characterization of design ground motions

The key issues for specifying a design earthquake or ground motion are: (1) seismic hazard maps (zoning maps), (2) local site effects, (3) near-source effects on horizontal ground motions, and (4) spatial variations of ground motions. There are also other issues related to the effects of the vertical component, energy and duration of ground motions. In conventional engineering design – despite a large variability in the ground motion characteristics – a simplified deterministic approach is followed. This procedure is based on a simple parameterization of earthquake magnitude, distance, and site category[13]. Newer research efforts use numerical ground motion models based on seismological theory to analyse the origins of these variabilities so that the uncertainty in estimating ground motions can be reduced.

Seismic hazard (zoning) maps: The expected earthquake motion at any given site varies tremendously and a zoning map gives an idea of the size of the earthquake to be used for design. Zoning maps usually give the magnitude of a design ground motion, such as the peak ground acceleration (PGA) for a certain probability of exceedance, typically 10% in 50 years. The response quantities of a structure, which are of interest to engineers, are more closely related to the spectral acceleration (SA), rather than the PGA, of the base motion. The new set of hazard maps of the U.S. Geological Survey (USGS) are based on contours of 5% damped elastic SA for periods of vibration of 0.2, 0.3 and 1.0 seconds. In addition, these maps use probabilities of exceedance of PGA by 10%, 5% and 2% in 50 years (corresponding to approximate return periods of 500, 1000 and 2500 years, respectively)[14].

These multiple annual probability maps of exceedance allow designers to choose the appropriate scenario for a specific objective in a performance-based design approach. For example, for a prevention-of-collapse performance criterion, a 2% probability of exceedance in 50 years can be chosen. Engineers can develop complete design response spectra using the hazard maps, by taking three periods of vibration (0.2, 0.3 and 1.0 s) as control periods. In addition to the response spectra, a suite of strong motion time histories can be specified for time-domain analysis of nonlinear structures. Accuracy of these maps is based on the following three factors: (1) characterization of seismic sources and attenuation relations used for ground motions, (2) the process by which the maps are prepared, and (3) how the maps compare with detailed site-specific studies. The coming years will see major refinement in the hazard maps because of better appreciation of the above-mentioned factors. Clearly, the latest USGS maps are a major improvement in the representation of ground motion and should serve as a good model to follow.

Local site effects: Seismic waves propagating from bedrock to the earth surface are significantly modified (usually amplified) by the underlying alluvium and ground features (Figure 7). In engineering design codes, this effect of local soil sites is considered in a very simplistic fashion by *site factor*. The 1994 Northridge and 1995 Kobe earthquakes provided substantial data on evaluating site effects on ground motions, and analyses of these data validated the existing site factors for stiff and soft soil sites[15]. However, these simple factors do not account for modifications in seismic waves such as duration, energy and frequency content. Very simple one-dimensional beam models and wave propagation theory are currently used to obtain design seismic waves. The availability of affordable, large computing power these days is enabling

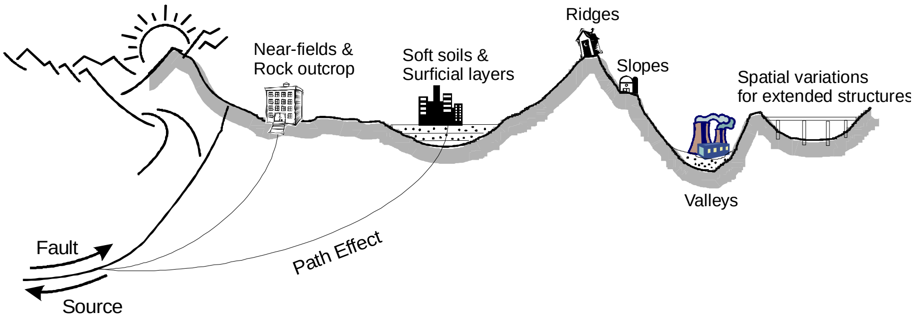


Figure 7. Ground motions modified by underlying alluvium deposits and ground features.

researchers to try more ambitious ideas such as modelling earthquake source mechanisms or generating design seismic waves from 2D and 3D models of soil stratum. These studies would provide the much needed insight into the effect of ground features (topography, i.e. valleys, slopes, basin edges, and their focusing effects) on ground motions – issues that are currently ignored in engineering design.

Near-source effects on ground motions: It is a well-established fact that characteristics of ground motions near the source are different from those at greater distances from the epicentre. Many recent devastating earthquakes – Chi-Chi (1999, Taiwan); Izmit (1999, Turkey); Northridge (1994, USA); Kobe (1995, Japan) – have indicated that the most significant aspect of ground motion is the presence of a large, intermediate to long-period pulse of ground motion. For example, in the case of Northridge and Kobe earthquakes, it was about 1 to 2 s. This pulse is observed to be larger in the direction perpendicular to the strike of the fault, as opposed to those in the direction of the fault (i.e. rupture directivity effects). Analyses have shown that the presence of these large period pulses (also referred to as *flings*) at the beginning of the motion can cause peak ground velocities as high as 175 cm/s, imposing exceptionally large displacement demands on large period structures such as bridges, tall buildings and base-isolated structures[16].

Although these effects were noted in many earlier Californian earthquakes, the engineering community has yet to include these observations in the design process! Destruction caused by more recent earthquakes has focused attention again on the effects of the severe pulses in near-field regions[17]. The 1997 UBC (Uniform Building Code) first introduced the idea of near-source factors in determining design forces, but this simplistic approach is highly questionable for its reliability in estimating the effects of severe pulses in ground motions[18]. In a few site-specific studies, these pulses have been included in design ground motions, but they are still not a part of our standard design specifications.

Spatial variations of ground motions: Spatial variations of ground motion for multiple-supported structures include incoherent base motion, wave passage effects, attenuation effects and differential site response, as schematically shown in Figure 8 (ref. 19). Wave passage effect refers to non-vertical propagation of seismic waves, whereas variable distances of the multiple supports of the structure give rise to attenuation effects. Extended source effects are due to mixing of wave types from different points on the fault, i.e. waves originating from source segment A will interfere with source segment B. The ray path incoherence is caused by scattering of waves and complex 3D wave propagation. Although there was some minimal research done showing that the effect of spatial variations is not significant if the differential site response is small, it is still not sufficiently clear when these effects can be neglected. In the case of extended structures such as bridges, the current practice is to ignore spatial variations of ground motions, an example of neglecting what we do not understand.

New structural systems and materials

In recent times, many new systems and devices using non-conventional civil engineering materials have been developed, either to reduce the earthquake forces acting on a structure or to absorb a part of the seismic energy. Figure 9 shows four major types of techniques employed to control structural response during earthquakes. There are many variations under each broad category and many new techniques are being developed, evaluated and implemented, as discussed below.

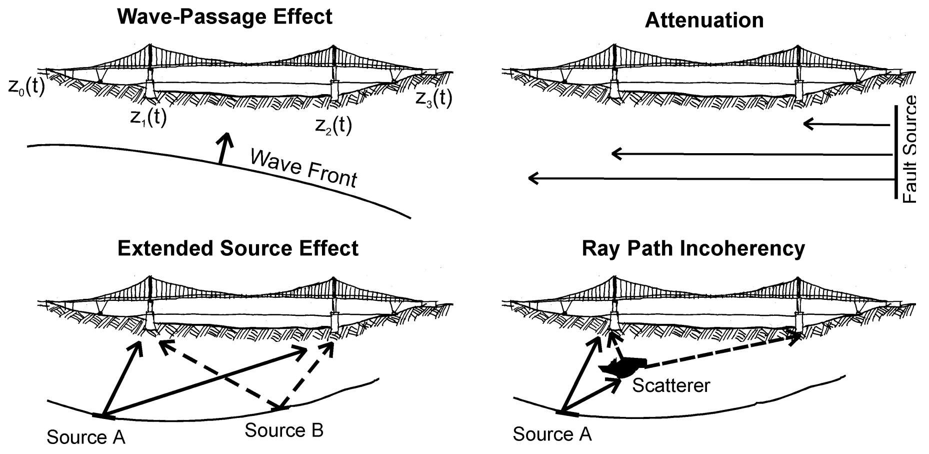
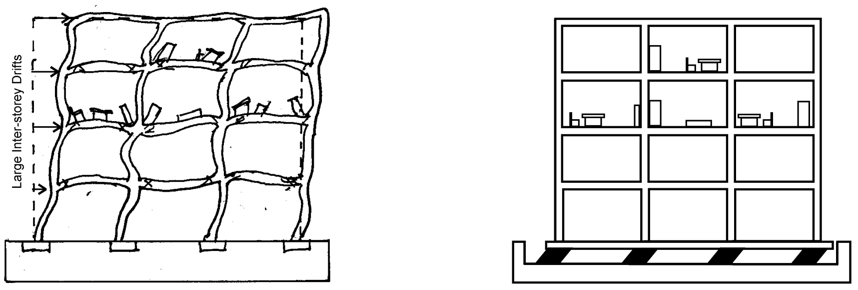


Figure 8. Factors contributing to spatial variation of ground motion for extended structures (adapted from Abrahamson[19]).

Base-isolated systems: Conventional earthquake-resistant structural systems are fixed-base systems that are ‘fixed’ to the ground. They derive their earthquake resistance from their ability to absorb seismic energy in specially designed regions of the structures, such as in beams near beam-column joints of RC frames. These regions should be capable of deforming into an inelastic range and sustaining large reversible cycles of plastic deformation, all without losing strength and stiffness to a level where it would jeopardize the stability and integrity of the structure. These inelastic activities also mean large deformations in primary structural members resulting in significant amount of structural and non-structural damage.

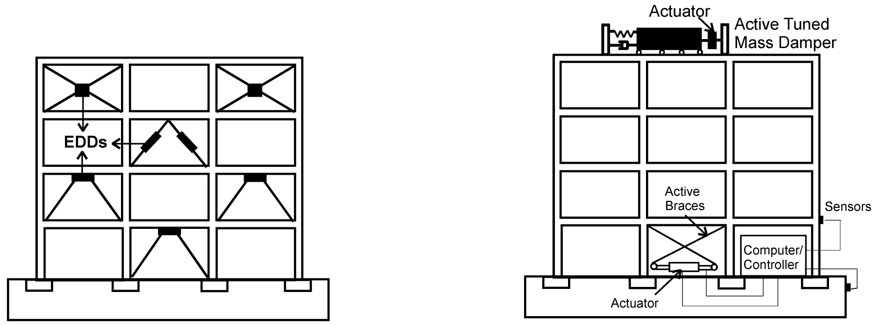
However, in *base-isolated systems,* the superstructure is isolated from the foundation by certain devices, which reduce the ground motion transmitted to the structure[20–22]. These devices help decouple the superstructure from damaging earthquake components and absorb seismic energy by adding significant damping. In comparison to fixed-base systems, this technique considerably reduces the structural response and damages to structural as well as non-structural components. A significant number of base-isolation devices have been developed, some of which have already found applications in real life structures. Designing a base-isolated system is still a complex process, and its dynamic response tends to be more complicated than the fixed-base system. Presently, only certain types of structures are best suited for base-isolation for earthquake resistance, although technology is gradually overcoming these limitations. There is considerable interest now in base-isolated systems among earthquake engineers – especially in countries like Japan, USA and New Zealand – with an eye towards developing cheaper systems with broader applications. For example, in the recently held 12th World Conference of Earthquake Engineering in New Zealand, a significant 8% of the papers presented were only about base-isolation systems and/or their applications.

Passive energy dissipation systems: Conventional fixed-base systems rely on strength and ductility to control seismic response. A current strategy, widely favoured for enhancing the seismic performance of fixed-base systems, involves dissipating the seismic energy through various Energy Dissipating Devices (EDD). These devices are like ‘add-ons’ to conventional fixed-base system, to share the seismic demand along with primary structural members. A good design reduces the inelastic demand on primary structural members, leading to significant reduction in structural and non-structural damage. A quick survey of the engineering literature reveals that a number of EDDs using metal hysteresis, viscous damping, friction and



(a) Fixed-Base Systems:
Conventional structures absorb seismic energy through inelastic deformations in structural members. Large Inter-storey drifts cause structural and nonstructural damage, however, loss of life and collapse is prevented.

(b) Seismic Isolation Systems:
Structures are supported on isolators which decouple structures from damaging earthquake components and absorb seismic energy adding substantial damping.



(c) Energy Dissipation Systems:
Energy Dissipation Devices (EDDs) absorb seismic energy thereby reducing the demand on primary structural members. Structural and nonstructural damage is signficantly reduced.

(d) Active Control Systems:
Lateral strength, stiffness and dynamic properties of a structure are adjusted during the earthquake to control its response. Complex control mechanisr and elaborate hardware is required.

Figure 9. Major techniques for structural response control during earthquakes.

visco-elasticity have been proposed, quite a few of them have already been applied in the field. The supplemental damping provided by EDDs helps to control excessive deformation and damage to fixed-base systems at a minimal additional cost. However, there are many issues related to the integration of these devices into structural systems, their analysis, design, construction methodologies and architectural aspects, which will be the focus of research and development in the coming years.

Active, semi-active and hybrid control systems: In contrast to the earthquake-resistant systems mentioned earlier, there is another expanding class of systems referred to as ‘smart’ or *active control systems*. The active systems differ from the passive systems in the sense that they control the seismic response through appropriate adjustments within the structure, as the seismic excitation changes. In other words, active control systems introduce elements of dynamism and adaptability into the structure, thereby augmenting the capability to resist exceptional earthquake loads. A majority of the proposed techniques involves adjusting lateral strength, stiffness and dynamic properties of the structure during the earthquake to reduce the structural response. Many studies and a few field applications have emphasized their potential in reducing the structural response. However, many serious problems exist with respect to the time delay in control actions, modelling errors, inadequacy of sensors and controllers, structural nonlinearities and reliability, not to mention the high operational costs. Researchers are experimenting with many novel concepts to overcome these limitations and to develop a cost-effective hybrid and semi-active class of systems which can combine the robustness of passive systems with the adaptability of active systems [23].

New materials and devices: Many non-conventional civil engineering materials are making inroads into earthquake-resistant construction techniques. Steel, concrete, timber and masonry are no longer good enough. Recently developed techniques use materials such as rubber, lead, copper, brass, aluminium, stainless steel, fibre-reinforced plastics and even expensive shape-memory alloys. These materials are strategically used to modify the force–deformation response of structural components and/or enhance their energy dissipation potential. For example, fibre-reinforced plastic fabrics and sheets are an attractive alternative over steel or concrete jacketing to restore the load-carrying capacity of earthquake-damaged reinforced concrete beams or beam–column joints. They are lightweight, quick to install and can be easily epoxy-bonded. More new materials can be expected as researchers look for better seismic control techniques outside of the narrow confines of traditional civil engineering materials.

Analytical tools for dynamic analysis of structures

Analysis is the means by which the engineer works towards the dream of designing the ultimate perfect structure. Good analytical tools predict the response of the structure as reliably as possible and compare its performance against the acceptability criteria applied in the design. EQRD applications require dynamic time-history analyses of numerical models of structural systems for simulated ground motions. However, a simplified equivalent static analysis (pushover analysis) may be adequate for certain structures. Performance-based design procedures will require more sophisticated analytical tools for determining the available capacity of the system.

Structural analysis tools can be broadly grouped into two categories based on the level of discretization used for idealizing the structure: structural component models and finite element models. In structural component models, the structure is idealized such that there is a one-to-one correspondence between the structural members (the beams, columns, braces, etc.) and the elements of the model. These analysis tools are semi-empirical in nature as they use phenomenological models to characterize the force–deformation behaviour of elements, usually obtained from testing. These tools have been used extensively for nonlinear analysis of various earthquake-resistant structures in time domain, primarily because of their simplicity and computational efficiency. The advent of new devices such as seismic isolators and various types of EDDs will require new numerical models to be developed and integrated with existing computer programs.

Analysis tools which use more refined, 3D models of structures are becoming possible for earthquake applications, due to the easy availability of faster computers. However, such tools are quite complex and difficult to use by design offices. Simple and robust analysis tools for frame-like models will continue to be used for designing in the near future. Improvements to these models may take place in the way of additional calculations for the effect of nonlinearity, strength and stiffness degradation under cyclic loads and secondary effects as well.

Appropriate modelling of soil–structure interaction is another area which is expected to undergo major development due to better characterization of soil properties and the availability of vast computing power. The soil–structure interaction is perhaps the least understood problem in the field of earthquake engineering. The ground motion input and the response of structures are strongly coupled, and base motions can be greatly modified by the presence of structures – however, most design codes ignore this effect for the vast majority of the structures, arguing that non-consideration of the interaction effects are on the conservative side. This approach is highly questionable and a more realistic approach should be adopted which takes into account wave propagation and radiation of energy from the vibrating structure. Numerical models which can represent true properties of the soil continuum and which are compatible with typical structural idealizations can promise significant improvements in predicting structural response in the future.

Conclusions

In the coming years, the field of EQRD of structures is most likely to witness the following significant developments:

(1) A complete probabilistic analysis and design approach that rationally accounts for uncertainties present in the structural system will gradually replace deterministic approaches, especially in the characterization of the loading environment.
(2) Performance-based design processes will take centre stage, making conventional descriptive codes obsolete.
(3) The acceptable risk criterion for design purposes will be prescribed in terms of performance objectives and hazard levels.
(4) Multiple annual probability maps for response spectral accelerations and peak ground accelerations – along with more realistic predictions of the effects of site soils, topography, near-source rupture mechanisms and spatial variation – should provide better characterization of design earthquakes and expected ground motions.
(5) The development of new structural systems and devices will continue for base-isolation, passive energy dissipation and active control systems, along with the proliferation of non-traditional civil engineering materials and techniques.
(6) Analytical tools for reliable prediction of structural response (essential tools in performance-based design processes) will continue to improve and be updated frequently to include new devices and materials.
(7) The area of soil–structure interaction – perhaps the least understood aspect in the field of earthquake engineering – is poised to witness the emergence of new numerical techniques to model nonlinear soils and structures in a manner that was not possible until now, due to the enormous computational efforts required.

It is fairly well accepted that earthquakes will continue to occur and cause disasters if we are not prepared. Assessing earthquake risk and improving engineering strategies to mitigate damages are the only options before us. Geologists, seismologists and engineers are continuing their efforts to meet the requirements of improved zoning maps, reliable databases of earthquake processes and their effects; better understanding of site characteristics and development of EQRDs. As for the engineer, the ultimate goal will remain the same: to design the perfect, but cost-effective structure, that behaves in a predictable and acceptable manner. The ongoing research and development activities in the area of EQRD of structures offer significant promise in realizing that goal in the coming years.

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