Earthquake Loads & Earthquake Resistant Design of Buildings

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1. Summary

The primary objective of earthquake resistant design is to prevent building collapse during earthquakes thus minimising the risk of death or injury to people in or around those buildings. Because damaging earthquakes are rare, economics dictate that damage to buildings is expected and acceptable provided collapse is avoided.

Earthquake forces are generated by the inertia of buildings as they dynamically respond to ground motion. The dynamic nature of the response makes earthquake loadings markedly different from other building loads. Designer temptation to consider earthquakes as ‘a very strong wind’ is a trap that must be avoided since the dynamic characteristics of the building are fundamental to the structural response and thus the earthquake induced actions are able to be mitigated by design.

The concept of dynamic considerations of buildings is one which sometimes generates unease and uncertainty within the designer. Although this is understandable, and a common characteristic of any new challenge, it is usually misplaced. Effective earthquake design methodologies can be, and usually are, easily simplified without detracting from the effectiveness of the design. Indeed the high level of uncertainty relating to the ground motion generated by earthquakes seldom justifies the often used complex analysis techniques nor the high level of design sophistication often employed. A good earthquake engineering design is one where the designer takes control of the building by dictating how the building is to respond. This can be achieved by selection of the preferred response mode, selecting zones where inelastic deformations are acceptable and suppressing the development of undesirable response modes which could lead to building collapse.

2. Earthquake Design - A Conceptual Review

Modern earthquake design has its genesis in the 1920’s and 1930’s. At that time earthquake design typically involved the application of 10% of the building weight as a lateral force on the structure, applied uniformly up the height of the building. Indeed it was not until the 1960’s that strong ground motion accelerographs became more generally available. These instruments record the ground motion generated by earthquakes. When used in conjunction with strong motion recording devices which were able to be installed at different levels within buildings themselves, it became possible to measure and understand the dynamic response of buildings when they were subjected to real earthquake induced ground motion.

By using actual earthquake motion records as input to the, then, recently developed inelastic integrated time history analysis packages, it became apparent that many buildings designed to earlier codes had inadequate strength to withstand design level earthquakes without experiencing significant damage. However, observations of the in-service behaviour of buildings showed that this lack of strength did not necessarily result in building failure or even severe damage when they were subjected to severe earthquake attack. Provided the strength could be maintained without excessive degradation as inelastic deformations developed, buildings generally survived and could often be economically repaired. Conversely, buildings which experienced significant strength loss frequently became unstable and often collapsed.

With this knowledge the design emphasis moved to ensuring that the retention of post-elastic strength was the primary parameter which enabled buildings to survive. It became apparent that some post-elastic response mechanisms were preferable to others. Preferred mechanisms could be easily detailed to accommodate the large inelastic deformations expected. Other mechanisms were highly susceptible to rapid degradation with collapse a likely result. Those mechanisms needed to be suppressed, an aim which could again be accomplished by appropriate detailing.

The key to successful modern earthquake engineering design lies therefore in the detailing of the structural elements so that desirable post-elastic mechanisms are identified and promoted while the formation of undesirable response modes are precluded.

Desirable mechanisms are those which are sufficiently strong to resist normal imposed actions without damage, yet are capable of accommodating substantial inelastic deformation without significant loss of strength or load carrying capacity. Such mechanisms have been found to generally involve the flexural response of reinforced concrete or steel structural elements or the flexural steel dowel response of timber connectors.

Undesirable post-elastic response mechanisms within specific structural elements have brittle characteristics and include shear failure within reinforced concrete, reinforcing bar bond failures, the loss of axial load carrying capacity or buckling of compression members such as columns, and the tensile failure of brittle components such as timber or under-reinforced concrete.

Undesirable global response mechanisms include the development of a soft-storey within a building (where in-elastic deformation demands are likely to be concentrated and therefore make high demands on the resistance ability of the elements within that zone), or buildings where the structural form or geometry is highly irregular, which puts them outside the simplifications made within the engineering models used for design.

3. Earthquake Resisting Performance Expectations

The seismic structural performance requirements of buildings are often prescribed within national building codes. For instance Clause B1 'Structure' of the New Zealand Building Code [1] prescribes that the building is to retain its amenity when subjected to frequent events of moderate intensity, and that it is to remain stable and avoid collapse during rare events of high intensity. The Building Code of Australia [2] prescribes the performance expectations in similar rather vague terms. It is left to the Loadings Standards of New Zealand [3] and Australia [4,5,6,7] to interpret 'moderate' and 'high' loading intensities. This they do by equating the 'amenity' retention as the **Serviceability Limit State** and collapse avoidance as the **Ultimate Limit State** loads and combinations of loads. Thus for compliance with the mandatory provisions of the national building codes the following requirements need to be satisfied:

A. For amenity retentions (Serviceability Limit State): *The building response should remain predominantly elastic, although some minor damage would be acceptable provided any such damage does not require repair. Buildings should remain fully operational. Preservation of the appropriate levels of lateral deformation to protect non-structural damage is the primary control parameter. The loading intensity for this limit state is to be relatively low (say 5% probability of exceedance in any year).*

B. For collapse avoidance (Ultimate or Survival Limit State): *The risk to life safety is maintained at acceptably low levels. Building collapse is to be avoided. Significant residual deformation is expected within the buildings with both structural and non-structural members experiencing damage. Building repair may not be economical. The loading intensity used for design can be equated to rare earthquakes with long (500+ years) return periods. This is the single most important design criterion since it relates to preservation of life. It demands that the system possess adequate overall structural ductility to enable load redistribution while avoiding collapse.*

There are examples in the new generation of earthquake loading specifications [8] of additional, performance orientated, limit states being introduced. For example **Continued Occupancy** (being somewhat beyond the serviceability limit state where although damage is minor, it will require repair but the building will be posted for continued use after the event), and **Damage Control Limit State** (where significant damage to both structural and non-structural elements is experienced but the building can be repaired economically to its condition before the event). Such provisions are not currently mandatory. They are, however, available to building owners (and their insurance providers) to form the basis of performance orientated objectives.

4. Key Material Parameters for Effective Earthquake Resistant Design

Compliance with the performance criteria of the various limit states outlined above requires different material properties. The serviceability limit states criteria demand that certain stiffness and elastic strength parameters be met and is primarily concerned with the linear stress/strain deformation relationships associated with elastic system response. The ultimate limit state criteria generally demand that an appropriate level of post-elastic ductility capacity is available so as to avoid collapse.

There are important ramifications with this concept in regard to both the material and sectional properties assumed for members during the analysis, and also during the translation of the results derived using elastic modelling techniques into the inelastic response domain.

For compliance with the serviceability limit state performance provisions, the simple linear stress/strain relationships of materials are needed. These are the conventional parameters used to assess the structural resistance to other loads. Provided the structural system remains predominantly elastic, damage avoidance can reasonably be expected and compliance thus assured. Simple elastic engineering models can be used to ascertain building response in these conditions. Thus for concrete and masonry structures, the cracked sectional properties are appropriate for the serviceability limit state, although significant yield of the reinforcing steel (and the subsequent retention of wide residual cracks) is to be avoided.

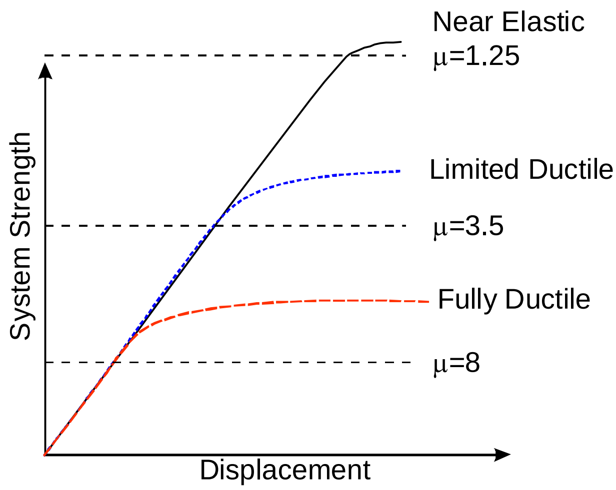

Figure 1 Post-elastic (Ductility) System Capacities

For compliance with the ultimate limit state performance provisions, the post-elastic response of the structure, including large post-elastic member deformation, needs to be considered. Often traditional engineering models break down at this stage. There is thus little to be gained by using highly sophisticated engineering modeling techniques to demonstrate compliance with the ultimate limit states criteria (ie collapse avoidance) unless there is a high degree of confidence that the relationship between the elastic and inelastic structural response is realistic. The simple elastic stress/strain relationships and the elastic engineering models used to ascertain the load distribution between members within the structural system no longer apply. It is to address this particular post-elastic response condition, being the primary objective of good earthquake engineering design, that the principles of capacity design of structures were developed and subsequently introduced into many modern design standards.

5. Earthquake Design Level Ground Motion

A fundamental parameter contained within all earthquake loading standards is the earthquake induced ground motion which is to be used for design. This is generally prepared by seismologists and geotechnical engineers. It is typically presented to the structural designer in three components, namely the elastic response of the basement rock (usually as acceleration spectra), the relative seismicity at the site (commonly presented as a suite of zonation maps), and a modification function which is applied to the motion at bedrock beneath the site to allow for near surface soil conditions (presented as either a simple amplification factor or as a more complex soil property related function).

5.1. Elastic Response Spectra

Engineers traditionally have used acceleration response spectra to represent the motion induced by the design earthquake. These spectra are generally presented as a response function (acceleration, velocity or displacement) against the response period of a single-degree-of-freedom oscillator considered to represent the structure (refer Figure 2). Spectra are developed by calculating the of response a single mass oscillator (usually with 5% critical damping present) to the design level earthquake motion. Engineers traditionally have shown a preference for acceleration spectra, since the resulting coefficient, when multiplied by the seismic mass, results in the lateral base shear for the building. In Australia [7] and the Uniformed Building Code used in the western USA [9] these spectra are presented as a simple uniform coefficient followed by an exponential decay. The New Zealand Loadings Standard [3] prescribes an elastic response spectrum, derived using a uniform risk approach, for each soil class. The modern trend as indicated by the European Earthquake Standard [10] and also in the proposed National Earthquake Hazard Reduction Programme (NEHRP) specification [8] is to acknowledge that the response spectra is building period dependent. This is achieved by publishing the design spectra in parametric form where the ordinates of each parameter and the characteristics of the curve between them are read from a series of seismic zonation maps of the region.

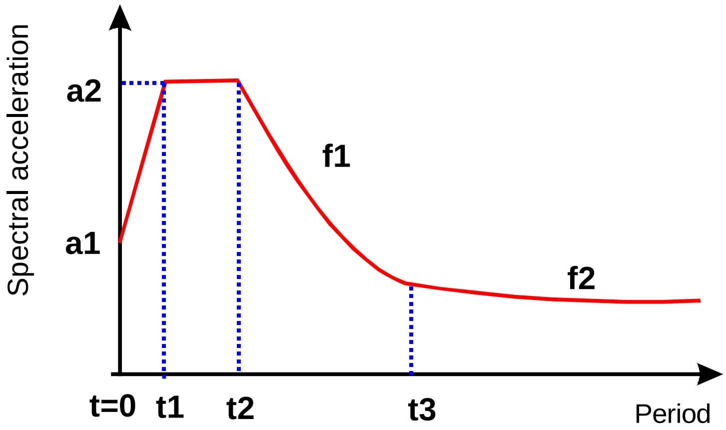

Figure 2 A Form of Parametric Acceleration Response Spectrum

5.2. Relative Seismicity

The current generation of earthquake loading standards uses a single seismic zonation map with iso-seismal contours to represent the relative seismicity between locations. An example of one for New Zealand is shown as Figure 3. The product of the zone factor, Z, and the lateral acceleration coefficient derived from the design spectrum is used for design.

The next generation of earthquake loading standards are expected to specify spectral acceleration as a function of the response period and also design event return peroid. The simple linear scaling of a standard spectral shape will no longer be acceptable. Instead we may expect, for example, a suite of three series of maps to reflect different probabilities of exceedance (0.05 (20 year return period) 0.002 (500 year return period) and 0.0005 (2000 year return period)). Each set will comprise 4 maps each with spectral ordinates for periods of perhaps T=0, T=0.2 seconds, T=1 second and T=2.5 seconds). The complete suite may therefore comprise 12 regional maps which will enable the development of different shaped elastic response spectra for different return periods.

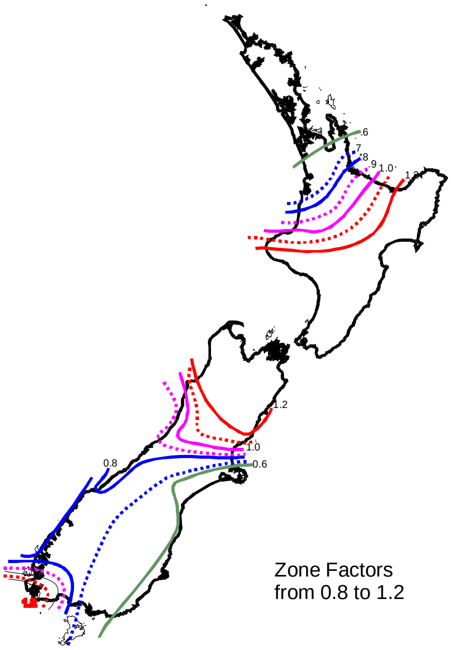

Figure 3 Typical Seismic Zonation Map
(interpolation between iso-seismals is acceptable)

This approach is likely to have significant impact on regions of low to moderate seismicity. Reference to Figure 4 indicates that while, as expected, the peak ground acceleration is much higher in high seismicity regions than it is in low seismicity ones (ratio of 3.5:1), the differential is markedly reduced as the probability of exceedance increases (2:1 for 0.0005 probability of exceedance) with the PGA being approximately equal to that of the normal design event within a high seismicity area. It is likely that important key facilities of the future will be required to survive earthquakes with exceedance intervals of this order. The design requirements may well be quite similar regardless of regional seismicity in such events.

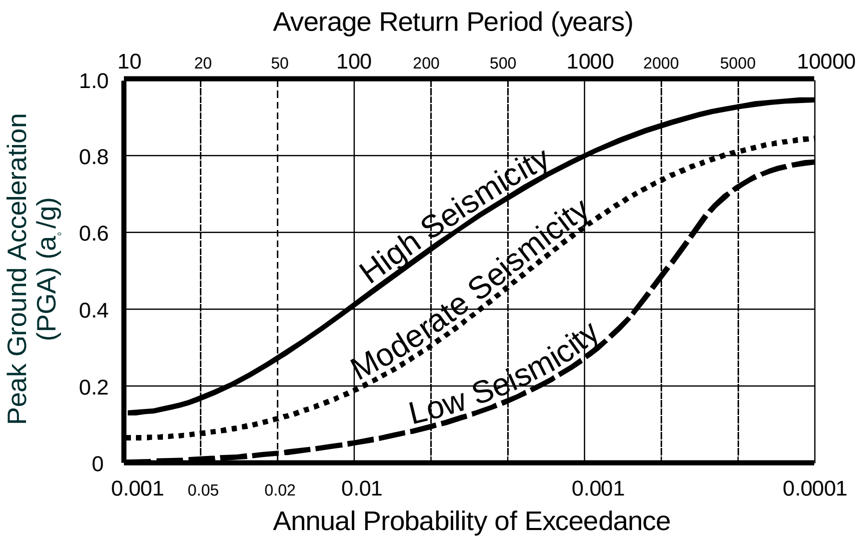

Figure 4 Variations of PGA against Probability of Exceedance with Seismicity
(from Paulay & Priestley [11])

5.3. Soil amplification

Earthquakes are usually initiated by rupture over a fault rupture plane, often deep within the earth's mantle. The ground motion experienced on the surface results from the transmission of energy waves released from that bedrock source transmitted first through bedrock and then undergoing significant modification by soil layers as the energy waves near the earth's surface. Typically rock sites experience high short period response but more rapid decay. Thus, short duration high intensity motion may be expected in such locations. Conversely soft soils, particularly when they extend to moderate depths (>50 metres) are likely to filter out some of the short period motion and usually amplify longer period response, particularly in cases where the soil mass has a natural period similar to the high energy component of the earthquake. While such resonance effects can be taken into account when site specific spectra are being developed, it is usually impractical to include such effects in a loadings standard. Soft soil response spectra have a flatter, broader plateau (refer Figure 5).

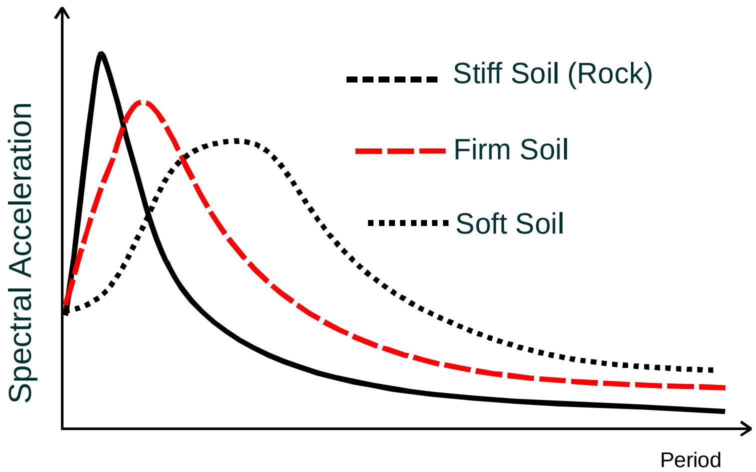

Figure 5 Typical Spectral Response Curves Modified for Soil Effects.

6. Derivation of Ductile Design Response Spectra

Most modern earthquake design standards acknowledge the reality that buildings will experience damage when they are subjected to severe earthquake attack. Attempts are made to quantify the post-elastic capacity of different building and material types by including some form of ductility based adjustment factor. This has the effect of reducing the elastic response coefficient down to a more convenient level below which elastic response with little or no damage is expected, but beyond which some damage is accepted while collapse avoidance is to be assured.

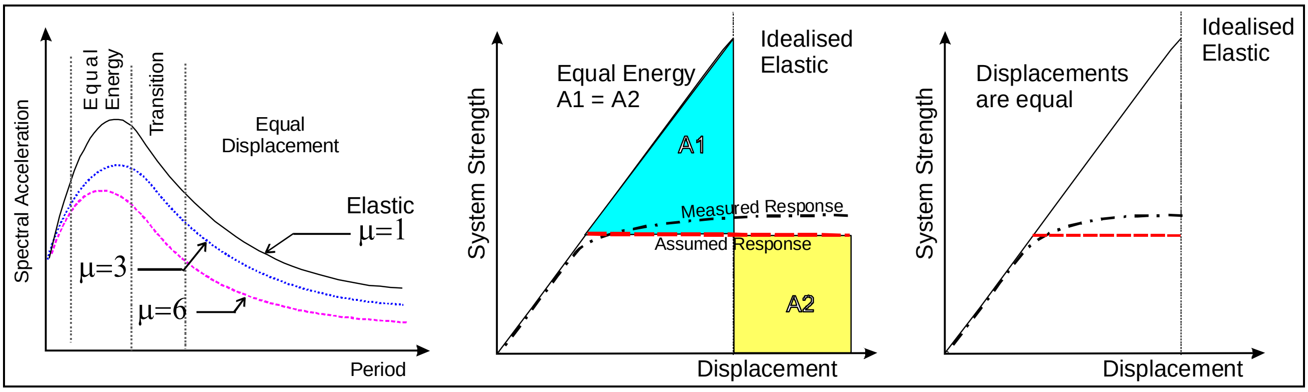

Figure 6 Basis for Translation of Elastic Response Spectra to Inelastic Design Spectra

Earthquake standards differ in how they translate the elastic response spectra derived for the site (which includes both the seismic zonation factor and the local soil factors) into inelastic spectra which can be used as the basis for structural design. The two most common methods are to use a combination of structural ductility and structural performance factors. Within the New Zealand Loadings Standard [3] this is a combination of the ductility factor, μ, and the structural performance factor, S_p. The European Earthquake standard, EC 8 [10] combines these as a structural behaviour factor, q. The earthquake standards of Australia [7] and the UBC [9] used in the western USA use a structural response factor, R_f. Both q and R_f are period independent and are therefore direct scaling factors of the site response spectra. The various inelastic response spectra published within the New Zealand Standard introduce period dependency with equal energy concepts being applied to short period structures and equal displacement to long period ones, with a transition zone in between (refer Figure 6). For very long period structures, a constant displacement response can be expected.

The ability of the structure to sustain levels of inelastic deformation implicit in these ductility values is dependent on the material and detailing used. Both the structural ductility and the structural performance factors depend on both the structural form selected and the materials used. As such they need to be prescribed within the seismic provisions of the material design standards along with the specific material detailing provisions which ensures that the inelastic deformation implicit in the ductility assumed can be attained.

7. Analysis and Earthquake Resistant Design Principles

7.1. The Basic Principles of Earthquake Resistant Design

Earthquake forces are generated by the dynamic response of the building to earthquake induced ground motion. This makes earthquake actions fundamentally different from any other imposed loads. Thus the earthquake forces imposed are directly influenced by the dynamic inelastic characteristics of the structure itself. While this is a complication, it provides an opportunity for the designer to heavily influence the earthquake forces imposed on the building. Through the careful selection of appropriate, well distributed lateral load resisting systems, and by ensuring the building is reasonably regular in both plan and elevation, the influence of many second order effects, such as torsional effects, can be minimised and significant simplifications can be made to model the dynamic building response.

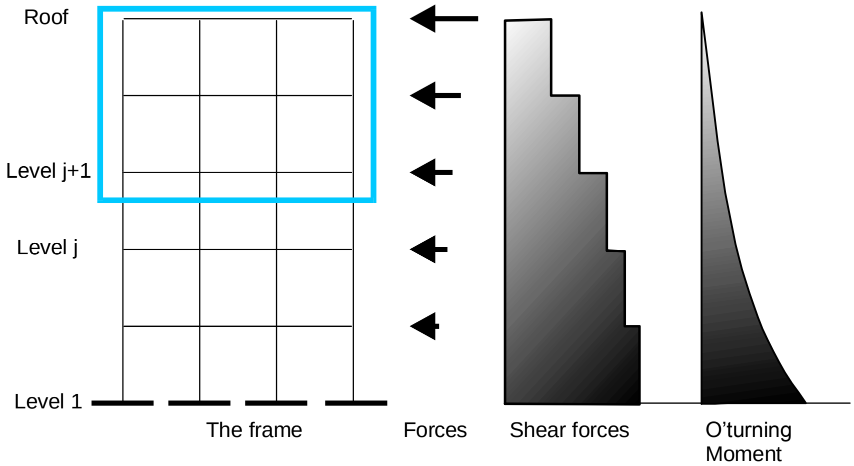

Figure 7 Loading Pattern and Resulting Internal Structural Actions

Most buildings can be reasonably considered as behaving as a laterally loaded vertical cantilever. The inertia generated earthquake forces are generally considered to act as lumped masses at each floor (or level). The magnitudes of these earthquake forces are usually assessed as being the product of seismic mass (dead load plus long-term live load) present at each level and the seismic acceleration generated at that level. The design process involves ensuring that the resistance provided at each level is sufficient to reliably sustain the sum of the lateral shear forces generated above that level (ref Figure 7).

7.2. Controls of the Analysis Procedure

A schematic of the earthquake design process in presented in Figure 8 below. The essential features of the process are as follows:

1) Structural designers are usually given the site location and intended occupancy of the building as part of their brief.
2) The national building code normally includes the requirements for the following;
   - the design philosophy acceptable for buildings (Limit States or Working Stress Design)

- the performance objectives for the prescribed occupancy class
- the structural importance classification (which transcribes into the acceptable design event return period) and
- the proportion of live load considered to be present during a rare event (such as a major earthquake).

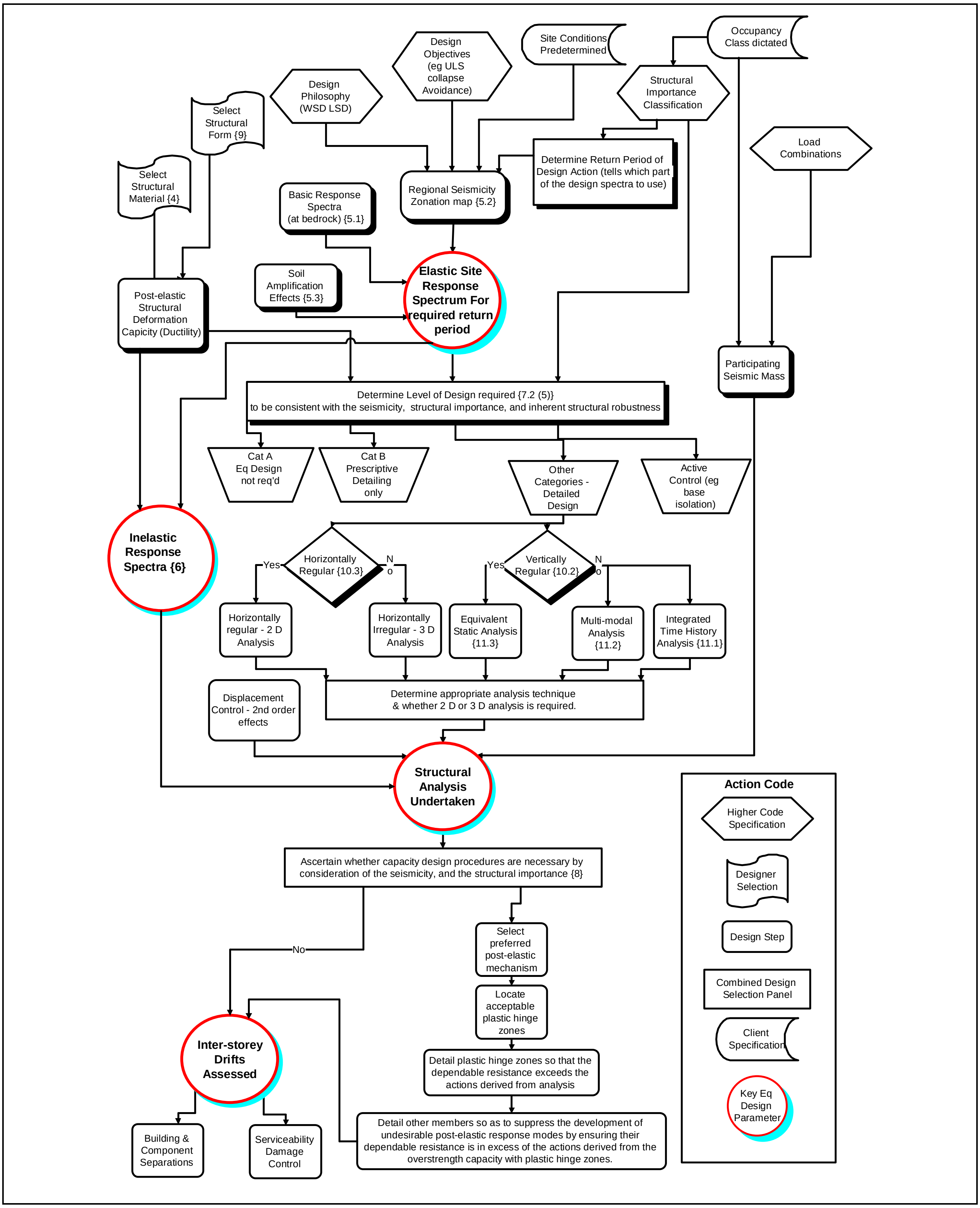

Figure 8 Schematic of the Earthquake Design Procedure

3) Derive the peak ground acceleration (i.e. elastic response spectrum for T=0) for the design intensity earthquake ground motion from consideration of the seismicity of the region (selected to match the design event return period) modified by the near surface soil modification factor (refer Section 5).
4) Select a suitable structural configuration with consideration for the following parameters;
   - the characteristics of the various lateral load resisting structural forms available (refer Section 9)
   - the desirability of matching the strength and stiffness of the structural frame to that expected under the dynamic loading of the building itself (ie strength and stiffness decreasing uniformly up the height of the building). *(Note this will influence the distribution of the base shear over the building height and as such may dictate the method of analysis acceptable for the building so as to ensure soft-storey collapse is avoided - refer Section 10.2)*
   - the desirability of a regular building plan with well balanced lateral load resisting systems, evenly distributed about the building plan. (*Note: Irregular plan will usually require three dimensional analysis and may experience severe torsional response - refer Section 10.3),*
   - the material from which the structural system is to be constructed and thus the post-elastic curvature (ductility) which can be accommodated through specific detailing.
5) Determine the level of design required. (*Note: There will be many normal occupancy buildings in regions of low seismicity which do not require any specific earthquake resistant measures to be introduced. Other levels of design involve a) simply tying elements together so as to ensure a continuous, rational load path exists for earthquake induced lateral loads; or b) detailed analysis of the building subjected to both gravity induced loads and a rationally derived lateral loading pattern which reflects the earthquake generated forces.)*
6) Ascertain the fundamental period of response of the building based on assumed member sections and properties *(Note: Several empirical formula are available as the basis for determining the fundamental period of buildings. It is generally preferable to assess the building response based on a realistic distribution of seismic mass at each level up the building and appropriate inter-level structure stiffness - for concrete a cracked section is appropriate.)*
7) Ascertain from the horizontal regularity of the structure (refer Section 10.3) whether a simple two dimensional or the more complex three dimensional analysis model required.
8) Ascertain by consideration of the vertical regularity of the structure (refer section 10.2) whether the structural response will be dominated by the first mode response of the structure (in which case the simplified equivalent static design procedure can be used) or whether, because of vertical structural irregularity, multi-modal analysis is required to enable the base shear distribution to be established.
9) If equivalent static analysis (refer section 11.3) is acceptable then;
   - calculate the design level base shear force from the product of the seismic mass and the lateral force coefficient (derived from the inelastic response spectra)
   - distribute the base shear to each level of the building and between lateral load resisting systems in accordance with horizontal and vertical regularity of the structure
   - use elastic analysis techniques to determine actions induced on members from load combinations which include earthquake forces.
10) If multi-modal analysis (refer section 11.2) is required then;
   - ascertain the period and deformed shape for each mode
   - ascertain the contribution of each mode from the base shear of each mode (derived from the elastic response spectra lateral acceleration at each respective modal period) distributed between levels according to each mode shape
   - combine the contribution from each mode using an appropriate modal combination technique.
11) Scale the elastic deformation obtained from the analysis to allow for post-elastic deformations and check that the overall deformation of the structure and that the inter-storey drift limits are within acceptable limits. *(Note: The overall building deformation checks usually control boundary edge clearance requirements to avert blocks pounding each other. The inter-storey drift limits control the onset of non-*

structural damage (a Serviceability Limit State criteria) and also the necessity to consider second order P-Δ effects.)

7.3. The 'Conventional' Earthquake Design Procedure

The conventional engineering design approach is to use the actions for members derived from the above elastic analysis as the basis for determining the dimensions and structural capacity. Significant changes in dimension will affect the building stiffness and may require re-analysis. The resulting sizes are then checked against those assumed during the analysis and provided a reasonable match is attained, the design verification process is considered complete.

Earthquake design has three important distinctions from other loadings. Firstly there is the acceptance that damage to both non-structural and some structural elements will occur, but collapse is to be avoided (refer to section 3). Secondly earthquakes are highly variable dynamic events which designers tend to simplify into a set of quasi-static lateral loads. This approach enables relatively simple analysis and design, but noticeably departs from reality. It is therefore important to build into the structure a degree of toughness or robustness which will avoid the development of undesirable collapse mechanisms. Thirdly, although there is geological and seismological understanding of how earthquakes are initiated and how the energy release mechanisms translate into surface ground motion, earthquakes still inherently contain a higher level of uncertainty than do other forms of loading.

Several modern earthquake design standards, particularly those which apply to regions of moderate or high seismicity [8,9,10,12], permit designers to make special provisions to accommodate the anticipated level of damage, provided they also take additional measures to ensure the collapse prevention mechanisms are robust enough to avoid overloading. This can be achieved when the designer takes control of the structure, and dictates which and where post-elastic mechanisms are to occur. The designer should also ensure the post-elastic demands are within levels acceptable for the material being used and that undesirable possible collapse mechanisms are suppressed within the elements themselves and within the structure as a whole. This approach is known as Capacity Design.

8. The Capacity Design Philosophy for Earthquake Resistance

8.1. General Approach

The capacity design philosophy for earthquake resistant design involves the following procedures:

1) Clearly define plastic hinge regions within the structure and the structural mechanism which is to be employed within those regions. (*Note these are usually flexural mechanisms located within the end zones of beam elements, the base region of cantilever shear walls, the link beams of coupled shear walls and the mid-span region of eccentrically braced frames.)*

2) Detail the capacity of the elements within the plastic hinge zones so that their dependable strength matches AS CLOSELY AS POSSIBLE the combined gravity and earthquake loads derived from the conventional structural analysis.

3) Detail these zones so that other, less desirable post-elastic mechanisms are suppressed. When the flexural behaviour is chosen as the preferred post-elastic mechanism, the PROBABLE OVER-STRENGTH OF THE SECTION WITHIN THE PLASTIC HINGE ZONE (including the strength contribution which may be made to the section by secondary components such as slab reinforcing) needs to be considered, with the dependable strength of other, less desirable failure mechanisms having a DEPENDABLE STRENGTH WELL IN EXCESS OF THIS. The following are considered unreliable (and thus undesirable) failure mechanisms with the recommended precautionary measures being indicated within brackets;

    - the loss of anchorage (by avoiding bar laps within the plastic hinge zones)

- shear failure within the element (by the provision of closely spaced transverse reinforcing stirrups within the plastic hinge zone so as to assure diagonal shear crack development within the concrete is inhibited.),
- buckling of the flexural compression steel (by closely spacing well anchored lateral ties)
- loss of axial load carrying capacity (by containing concrete column cores and avoiding buckling of main column reinforcing steel by using closely spaced, well anchored lateral ties).

4) The resulting structure has now effectively been tuned by the design process so that the post-elastic deformations will only occur within the well detailed plastic hinge zones of the structure, and that all other potential failure mechanisms have been suppressed, REGARDLESS OF THE INTENSITY OF GROUND SHAKING.

8.2. The Implications of Capacity Design

By using a capacity design technique, CONTROL OF THE STRUCTURE IS WITHIN THE HANDS OF THE DESIGNER. Through the selection of a preferred post-elastic mechanism, which is detailed in a manner to ensure the inelastic deformation demand of the structure occurs with in pre-assigned plastic hinge zones, it is possible to detail those zones so they accept the deformation demands placed upon them while ensuring the structure remains elastic elsewhere. In so doing undesirable potential collapse mechanisms are avoided.

This approach dictates the strength hierarchy throughout the structure. Fundamental to achieving this goal is that the over-strength capacity of sections within the plastic hinge zones must be realistically assigned. THE OLD ADAGE THAT STRONGER IS BETTER NO LONGER APPLIES. Within plastic hinge zones it is important that the dependable strength matches as closely as practicable the imposed actions as derived by analysis and that the over-strength capacity of the section within the plastic hinge zone be controlled to fall within the design range assumed (typically 30% for reinforcing steel). This places a responsibility on the material supplier to satisfy both the minimum strength range specified AND THE DEPENDABLE SYSTEM OVER-STRENGTH. This is a relatively new concept and requires changes by material suppliers to match these specifications.

With these provisos, the adoption of the capacity design philosophy will ensure that the principle objective of earthquake resistant design, namely avoidance of building collapse under severe earthquake attack, is satisfied. It has been reasonably argued that this is indeed the only method which can assure compliance with this fundamental performance objective, particularly, considering the uncertainties of the random character of earthquake induced ground motion, the large influence that local site effects will have on this motion, and the ongoing rather crude engineering modelling methods available to simulate the actual post-elastic dynamic response of the building to that motion. The author commends the excellent text prepared by Professors Paulay and Preistley [11] as further reading on the capacity design approach to be used for reinforced concrete structures.

9. Earthquake Resistant Structural Systems

Three types of earthquake resistant structural systems are generally available.

9.1. Moment Resisting Frames:

Moment resisting frames typically comprise floor diaphragms supported on beams which link to continuous columns. The joints between beam and columns are usually considered to be ‘rigid’. The frames are expected to carry the gravity loads through the flexural action of the beams and the propping action of the columns. Lateral loads, imposed within the plane of the frame, are resisted through the development of bending moments in the beams and columns. Framed buildings often employ moment resistant frames in two orthogonal directions, in which case the column elements are common to both frames.

Moment resisting frames are well suited to accommodate high levels of inelastic deformation. When a capacity design approach is employed, it is usual to assign the end zones of the flexural beams to accept the post-elastic deformation expected, and to design the column members such that their dependable strength is in excess of the over-strength capacity of the beam hinges, thereby ensuring they remain within their elastic response range regardless of the intensity of ground shaking. Moment resisting frames are, however, often quite flexible. When they are designed to be fully ductile, special provisions are often needed to prevent the premature onset of damage to non-structural components.

9.2. Shear Walls

The primary function of shear walls is to resist lateral loads although they are often used in conjunction with gravity frames and carry a proportion of gravity loads. Shear walls fulfil their lateral load resisting function by vertical cantilever action. By reference to Figure 7 it can be seen that both the shear force and bending moment generated by the earthquake actions increase down the height of the building. Since shear walls are generally both stiff and can be inherently robust, it is practical to design them to remain nominally elastic under design intensity loadings, particularly in regions of low or moderate seismicity. Under increased loading intensities, post-elastic deformations will develop within the lower portion of the wall (generally considered to extend over a height of twice the wall length above the foundation support system). This can result in difficulties in the provision of adequate foundation system tie-down to prevent uplift. The design of rocking foundations is common with shear walls, although care is required to ensure permanent rotational offsets are avoided following an earthquake. As outlined in Section 8.1, good post-elastic response can be readily achieved within this region of reinforced concrete or masonry shear walls through the provision of adequate confinement of the principal reinforcing steel and the prohibition of lap splices of reinforcing bars.

Shear wall structures are generally quite stiff and, as such inter-storey drift problems are rare and generally easily contained. The shear wall tends to act as a rigid body rotating about a plastic hinge which forms at the base of the wall. Overall structural deformation is thus a function of the wall rotation. Inter-storey drift problems which do occur are limited to the lower few floors. A major shortcoming with shear walls within buildings is that their size provides internal (or external) access barriers which may contravene the architectural requirements. This problem can be alleviated by coupling adjacent more slender shear walls. The coupling beams then become shear links between the two walls and with careful detailing can provide a very effective, ductile control mechanism.

9.3. Braced Frames

Frames which employ diagonal braces as the means of transmitting lateral load are common in low-rise and industrial buildings. The bracing elements are typically inclined axially loaded members which traverse diagonally between floors and column lines. They are very efficient in direct tension and may also be detailed to accept axial compression although suppression of compression buckling requires careful assessment of element slenderness. Two major shortcomings of braced systems are that their inclined diagonal orientation often conflicts with conventional occupancy use patterns (either internally or across windows or external fabric penetrations); and secondly they often require careful detailing to avoid large local torsional eccentricities being introduced at the connections with the diagonal brace being offset from the frame node. A variation on this form of lateral resisting system is the eccentrically braced frame. This system employs a horizontal ‘K’ form of bracing with the central zone of the ‘K’ acting in flexure as the tension/compression legs of the brace drive the beam element into direct flexure.

10. The Importance & Implications of Structural Regularity

10.1. General

Most Standards outline certain provisions relating to both the vertical regularity of the structure and also the plan regularity. These usually apply to the appropriateness of several assumptions implicit in the distribution pattern of the loading or the torsional effects.

10.2. Vertical Regularity

Ideally the capacity of the structure should follow the shear and bending moment pattern of the structure shown in Figure 7. Substantial departures from this ideal typically result in the onset of premature post-elastic deformations often concentrated at over one level. When this occurs, elements within the one level degrade, attract additional (post-elastic) deformation and a soft-storey mechanism develops with collapse often being the inevitable result.

The vertical regularity check is intended to avoid abrupt changes in overall strength or stiffness at any particular level. Where such provisions are not met, then a more detailed analysis will be required to ensure that post-elastic deformation capacity at each level can be met without unacceptable loss of strength or post-elastic deformation demands in excess of their capacity.

It is wise to avoid abrupt curtailment of reinforcing steel at one level of a reinforced concrete frame or substantive changes in a column section. It is better to introduce such changes gradually, over several floors, thereby allowing a smooth transition between sections to develop. Obviously it is undesirable to curtail shear walls above their base as this also induces a very real potential for soft-storey development.

10.3. Horizontal Regularity.

The random, three dimensional motions generated by earthquakes is usually simplified into two transverse orthogonal components with the vertical response typically being ignored. The transverse dynamic response may also introduce twisting and torsional effects into the response, either directly as a function of the input ground motion, or because of variations in the spatial distribution of seismic mass, or because of the structure being irregular in plan.

Measures employed to counter these effects typically involve distributing the lateral load resisting systems about the building plan and attempting to limit the plan profile to being reasonably regular and compact. Most modern earthquake loading standards require the designer to assess the Centre of Rigidity (CoR) of the structural system, and the centre of mass (CoM) of the uniformly distributed seismic mass. The eccentricity is typically increased by 10% of the building width to allow for unexpected variations in torsional effects with the magnitude of the resulting torsional action (being the product of mass and linear eccentricity between CoR and CoM) increasing accordingly. Such approximations tend to be based upon the response of the structure within the elastic response domain and may provide little security against collapse once the deformations have progressed into the inelastic domain. Paulay [13] has recently proposed an elegant means of directly addressing post-elastic torsional effects. He postulates that the post elastic torsional demand can be met, satisfied and indeed controlled by rigorous detailing of lateral load resisting elements so as to ensure their displacement ductility demands are met. Provided this is achieved the effects of torsion are readily accommodated.

The preferred method of minimising torsional effects is to select floor plans which are regular and reasonably compact. Wide separation of horizontal lateral load resisting systems is encouraged. Plan forms with re-entrant corners such as 'L' and 'T' plan layouts should be avoided, or, where these plan forms are dictated by other constraints, seismic separation joints should be introduced between rectangular blocks. Such joints must be designed to accept the post-elastic dynamic response of the building parts, which may be responding with disparate phases. Contact and hammering between blocks is to be avoided.

10.4. Floor Diaphragms

The floor system, in additional to supporting the live loads induced by the building contents, can also be designed as a floor diaphragm which links the lateral load resisting systems at each level. Other horizontal loading mechanisms such as horizontal trusses or deep beams can be used where the floor system is interrupted by penetrations or openings. The diaphragm action of floors is often taken for granted during design. It is important that designers allow for the concentrations of horizontal stress within the floor diaphragm around openings and penetrations through the provision of diagonal corner steel within the flooring. Care should also be taken to ensure that the interconnection between the floor diaphragm and the vertical lateral load resisting system is sufficiently robust to transmit the required shear between elements. Precast flooring systems using slender cast insitu toppings can be quite vulnerable in such circumstances.

11. Methods of Analysis

Earthquake engineering design techniques have advanced greatly with the advent of modern computing techniques. The prudent designer, however, is wise not to lose sight of the primary objective of earthquake design (ie collapse avoidance) and to remember the level of uncertainty present in several of the key input parameters. Little may therefore be achieved by using highly sophisticated analysis techniques when neither the input ground motion nor the post-elastic response of the structure are well understood. The selection of regular building configurations and the application of sound detailing principles are more likely to provide the required level of security against collapse than detailed refinement of the analysis techniques.

11.1. Integrated Time History Analysis

Integrated time history analysis techniques involve the stepwise solution in the time domain of the multi-degree-of-freedom equations of motion which represent the actual response of a building. It is the most sophisticated level of analysis available to the earthquake engineer. Its solution is a direct function of the earthquake ground motion selected as the input parameter for the specific building. Such records are seldom available directly for a given site and either synthetic ground motion or modified real free-field records are generally used. The modelled representation of the structure itself is required to realistically represent both the elastic and post-elastic response characteristics of the building. Since this detail of information is seldom available when commencing the design process, this analysis technique is usually limited in its application to checking the suitability of assumptions made during the design of important structures (i.e. the onset sequence and deformation demands of inelastic plastic hinge zones) rather than a method of assigning lateral forces themselves.

11.2. Multi-modal Analysis

Multi-modal analysis is an elastic dynamic response analysis technique which involves first the determination of the structural response of each mode of vibration of the building followed by the combination of the resulting forces for each significant response mode.

For such assessments it is usually convenient to consider the structural mass to be concentrated at each floor level which results in one degree of freedom for each floor provided torsional effects are ignored. When the building is torsionally susceptible, lateral and torsional response will need to be considered thus doubling the number of possible response modes. The procedure involves determining both the response period and mode shape, the determination of the lateral shear coefficient for each response mode (from the design spectra using the modal period) and the distribution of the resulting base shear according to the response shape at each floor. The contribution of each response mode is then combined with an allowance being made for the time variance between different response modes. Thus a square-root-sum-of-squares (SRSS) method of combining lateral forces is generally used, although other combination methods such as the complete quadratic combination (CQC) method may be required where the response modes are close together. A static analysis using the resulting equivalent forces is usually used as the basis for determining the forces and displacements of the overall structure.

While this technique takes into account allowance for the true response characteristics of the building (i.e. does not assume only first mode response) it should be remembered that it is still assessing the structural response while it remains elastic. Collapse avoidance, with the implied onset of controlled damage (i.e. post-elastic deformations), requires many assumptions to be made to arrive at the inelastic response. In addition many of the structural member properties needed for the analysis are unknown until after a preliminary analysis has been undertaken. Thus the sophistication of the model often adds little to the final design.

11.3. *Equivalent Static Analysis*

The equivalent static analysis procedure is also essentially an elastic design technique, although some consideration of the post-elastic response enters into the selection of the determination of the lateral force coefficient (item 2 below). It is, however, simple to apply than the multi-model response method, with the implicit simplifying assumptions being arguably more consistent with other assumptions implicit elsewhere in the design procedure.

The equivalent static analysis procedure involves the following steps:

1. Estimate the first mode response period of the building from the design spectra.
2. Use the specific design response spectra to determine that the lateral base shear of the complete building is consistent with the level of post-elastic (ductility) response assumed.
3. Distribute the base shear between the various lumped mass levels usually based on an inverted triangular shear distribution of 90% of the base shear commonly, with 10% of the base shear being imposed at the top level to allow for higher mode effects.
4. Analyse the resulting structure under the assumed distribution of lateral forces and determine the member actions and loads.
5. Determine the overall structural response, particularly regarding the inter-storey drifts assessed for the elastically responding structure. (For the assessment of the post-elastic deformation, design standards typically magnify the elastic deformed shape by the structural ductility to determine the overall maximum deformation – typically at roof level. The introduction of a non-linear response profile to allow for local rotation at plastic hinge zones is often required when determining the inter-storey drifts.)

12. Trends and Future Directions

Considerable technical effort is being expended on refining the models used to determine earthquake hazards throughout the world. Although this is one area of uncertainty, modern structural design practices, particularly the application of capacity design techniques, are robust enough to overcome such deficiencies. It is the author’s view that this effort may perhaps be better directed towards refining understanding of the post-elastic demand capacities of different structural systems and to devising techniques where the performance of new or innovative solutions can be realistically assessed.

The international trend towards prescribing building performance expectations has gone some way towards raising public awareness as to what performance is expected from buildings within their community. This enables some rational cost/benefit decisions to be made regarding insurance and business continuance planning. However, the engineering fraternity is somewhat tardy in tackling the thorny issue of realistic whole-building performance under rare events such as earthquake attack. The concept of various intermediate performance levels is being presented in modern design specifications [8] where four levels of performance are stipulated which range from survival through continued occupancy to no-damage. This may be anticipated as being the target for future standards and more work is required to ensure the performance targets are matched by the design procedures employed.

Displacement based design appears to offer some solutions in this endeavour. Here the engineering convenience of translating the earthquake motion into forces in order to execute the design is avoided. Instead the acceptable deformation limits which limit damage are addressed directly, with the collapse avoidance prerequisite achieved by using capacity design techniques [14]. The elegance of displacement based design is its directness in addressing the deformation control aspects necessary for performance based design, and it is expected to see the introduction of this technique into modern standards over the next five years. The changes in design methodology and the necessity for material standards to provide guidance on damping values for different structural system can each be seen as challenges to be addressed.

13. Conclusions

Modern buildings can be designed to be safe under extreme earthquake attack with collapse being avoided. Current earthquake design practices achieve this by dictating the post-elastic response of the building, locating and detailing zones within the structure where high post-elastic deformations are acceptable, rigorously detailing these zones so they can dependably resist the imposed actions while other, less desirable, post-elastic mechanisms are suppressed. Simple procedures for achieving these objectives is included in the paper and their implications on material property (particularly their over-strength ratios) are outlined.

The importance of achieving a regular building plan layout, with a well distributed lateral load resisting system and each with a uniform structural elevation is highlighted. The value of placing design emphasis on achieving the required post-elastic deformation control through careful detailing is highlighted, as is the futility of highly sophisticated, complex analysis when it is based on inherently unreliable loading models.

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