Designing for earthquake induced loading

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Introduction

Past Australian building practice involved little, if any, provision for resistance to seismic loadings. Accordingly, the relatively minor earthquake at Newcastle in December 1989 (Richter Magnitude 5.6) resulted in a disproportionate level of damage and economic loss to the community. In fact, no part of Australia can be guaranteed immune from such an event and similar levels of damage may reasonably be expected in any built-up area.

Levels of earthquake resistance supplied in future structures, as well as the refurbishment and/or retrofitting of existing structures, will be determined ultimately by the price society is prepared to pay: clearly a balance must be struck for it is not realistic, nor possible, to actually design for all eventualities.

This paper discusses the place and relevance of earthquake loadings in the design cycle, various design criteria including that recommended as appropriate for Australia: before outlining the analysis options open to the earthquake engineer.

Earthquake loading and the design process

In areas of the world recognised as earthquake-prone, and having a well-monitored history of damaging seismic events, it is essential for a preliminary structural design to be based on some combination of dead, live and earthquake loadings. In these circumstances resistance to earthquake loading will dictate choice of structural configuration. An important feature of such structural configurations will be the existence of skeletons by which some measure of integrity is guaranteed as the structure responds to the rather haphazard series of impulses typical of strong ground motions.

In the design process it should be borne in mind at all times that the design loadings for future earthquakes, however derived, will always be subject to a degree of uncertainty.

Because of the low level of seismicity in Australia, preliminary structural designs will almost always be dominated by a combination of dead, live and wind loading, with earthquake loading being applied to check if design refinements are required. Such refinements may include alternatives to structural configuration, modification of structural elements and improved detailing (such as a more appropriate distribution of flexural and shear reinforcement if the structure is reinforced concrete). The aim is to provide a structure that is resilient to earthquake attack. If available records of ground acceleration versus time (ie, time histories) for a particular region, or locality, can be processed to provide appropriate response spectra, these spectra may then be used either to assess the earthquake loading that a particular structure might attract, or they may be used as the basis for a complete structural analysis under earthquake loading. Another possibility is that these local records might have been gathered with a view to analysing a particularly important structure (such as a nuclear power plant), and the designer would proceed to carry out real time dynamic analyses of the structure.

However, for most buildings and engineered structures estimates of design earthquake loadings may be obtained by following a series of simple steps, as outlined in a code. The loading provisions in earthquake codes around the world follow similar principles and provide a means of realistically assessing an equivalent set of static loads to be applied to a structure in order to represent an `average' future earthquake.

If the structure under consideration has features, such as unusual distributions of mass and/or stiffness, which call into question the validity of the simplified code approach the designer is faced with considerable difficulty in realistically defining an appropriate earthquake loading. (It should be noted that, if loadings can be defined, appropriate techniques for structural analysis are readily available, for the most part). Notwithstanding the obvious difficulty of reliably predicting future earthquake events on the basis of a knowledge of past events, the present lack of adequate records makes this task almost impossible in Australia. The gathering of a statistically significant number of appropriate records of strong ground motions for any given region will take many years.

In practice every effort should be made to utilise whatever information and experience is available to derive suitable response spectra for structures for which the simplified code approach is inapplicable. Irrespective of these efforts, as a very minimum, the designer must carefully consider designing details that ensure a reasonable degree of structural resilience is provided in buildings and other engineered structures. This presupposes that adequate load paths exist by which seismic loads may pass through the structure. This exercise, in itself, is important, especially where geometric complexity exists.

Design criteria and analysis options

Design criteria

In areas of the world recognised as being prone to major earthquakes the engineer is faced with the dilemma of being required to design for an event, the magnitude of which has only a small chance of occurring during the life of the facility. If the designer adopts conservative performance criteria for the facility the client (often society) is faced with costs which may be out of proportion to the risks involved. On the other hand, to ignore the possibility of a major earthquake could be construed as negligent in these circumstances.

To overcome this problem a dual design philosophy has been developed, by which procedure :

1. A moderate earthquake, such as may reasonably be expected at the site, is used as a basis for the seismic design. The facility should be proportioned to resist such an earthquake without significant damage. This `damageability' limit state should ensure safety, limited non-structural damage and the continued performance of facilities and services, particularly those with important post-earthquake functions. The list includes hospitals, police, fire and civil defence facilities, water supply, telecommunications, electricity generation and distribution systems, etc. Almost as important is the maintenance of road and rail communications, particularly for food distribution (including warehouses and their contents). Similarly, the protection of industrial complexes, in their own right, as well as the protection of individual items of equipment in other buildings and facilities, is a necessary consequence of adoption of this limit state.

2. The most severe, credible earthquake that may be expected to occur at the site is used to test safety. In this ultimate limit state, significant structural and non-structural damage is expected but, neither collapse nor loss of life should occur.

In Australia, given the levels of seismicity expected, a structure designed for the ultimate limit state (avoiding collapse) will also usually satisfy the damageability limit state. However, in highly seismically active areas, the structure must be designed for both limit states. This is because the loads induced under damageability limit state earthquake will often exceed the elastic limits of the structure. This would rarely be the case in Australia.

It is the dual design philosophy which really forms the basis for the future practice of earthquake engineering in Australia.

Analysis options

Essentially, an earthquake engineer is faced with three possible methods of analysis/design for earthquake loading on a structure. In all methods the dual design criteria discussed above may be applied. The three analysis/design options available are:

(a) to perform a real time dynamic analysis of the structure,

(b) to perform a response spectrum analysis of the structure and/or

(c) to use the SAA Earthquake Code, currently AS2121 (1979).

Both of the procedures (a) and (b) involve analysis probably using a finite element computer model of the structure. (It is likely that a suitable model will have been developed in the conventional design process when considering dead, live and wind loadings).

Real time dynamic analysis

This method involves subjecting an appropriate finite element computer model of the building, or structural system to a given, previously recorded, earthquake record and examining its response in real time. Response peaks are generally of most interest. There are certain special circumstances where this procedure is useful but, for general aseismic design, it is of little value as the actual earthquake that the built structure may have to resist cannot be guaranteed to have sufficiently similar characteristics to the design earthquake. In particular, the intensity, duration and frequency content of the earthquake may be unsuitable especially if, as often happens, the record comes from another country or continent. Moreover, the method is expensive and time-consuming so that only for special structures can its use be justified. If, in addition, inelastic response calculations are involved another level of complexity (and uncertainty) is introduced. Response then becomes dependent, often heavily so, on the nonlinear models chosen and this dependency is in addition to that inherent in choosing to use one particular record.

Response spectrum approach

This procedure involves the development of an appropriate table, or sequence of peak response values, for use with a finite element computer model of the structure. This sequence, or spectrum, is developed by analysis and statistical manipulation of a series of existing earthquake records. The procedure to develop a response spectrum is outlined below:

(a) A single degree of freedom system with a particular mass, stiffness and damping is selected. The associated natural period is calculated.

(b) A particular digitised earthquake record is selected and this is used as the input ground motion to the single degree of freedom system. A real time analysis is performed to provide a solution for the variation of acceleration, velocity and displacement of the single degree of freedom system with time.

(c) The maximum acceleration (or velocity or displacement) is selected and this, and the natural period of the system, are plotted as the ordinate and abscissa, respectively, of a response spectrum graph.

(d) The period of the system is altered. The real time analysis is repeated with the same earthquake input and the maximum acceleration (or velocity or displacement) is again identified. Plotting of the new value of period and the new maximum acceleration provides a second point on the response spectrum.

(e) The process is continued across a range of periods thus providing a response spectrum curve associated with a particular earthquake and a particular level of damping.

(f) The process may then be repeated for different levels of damping (usually zero to 10% of critical damping) to produce a family of response spectra associated with a particular earthquake.

(g) The complete procedure may then be repeated for another `appropriate' earthquake thus producing another series of curves.

(h) By averaging, smoothing and statistically manipulating the set of curves associated with a particular level of damping a `design' response spectrum may be obtained.

Care must be taken as to which earthquake records are incorporated in a `design' response spectrum as earthquakes in various parts of the world have been found to have markedly different characteristics.

The actual response spectrum analysis technique for a structure involves the use of an appropriate finite element model of the structure in conjunction with a selected `design' response spectrum. The essence of the analytical procedure is as follows:

(a) The first few natural frequencies and modes of the finite element model of the structure are calculated. Usually it is only the first few lowest modes that are of interest.

(b) At each of the frequencies (or modes) the corresponding value of peak acceleration is determined from the response spectrum.

(c) Each of these accelerations is then applied to the model. Since the response spectra gives only the maximum response, the maximum forces associated with each mode are obtained.

(d) The total response is then obtained by superimposing the modal responses. (Note that the actual time variation of the design earthquake motion is unknown, and therefore it is impossible to compute the time variation of response either for a modal component, or for the total).

(e) A conservative upper bound for the response may be obtained by performing either a root of the sum of the squares root mean square, (SRSS) of the model maxima or a complete quadratic combination (CQC). The latter procedure is recommended, particularly if the natural frequencies of some of the modes under consideration are similar.

Quasi-static Code approach

The current Australian Earthquake Code, in common with almost all other Earthquake Codes around the world, uses an equivalent static lateral loading applied to a structure to represent earthquake loadings. In the case of buildings a quantity usually referred to as the `total base shear' is calculated from the product of the weight of the building and a coefficient. This coefficient takes into account the location and importance of the structure, its ductility or energy absorption capacity, its dynamic characteristics and the local soil conditions and their effect on structural responses.

Once the total base shear has been calculated it is distributed up the structure as a series of horizontal loads at each floor level and the structure is analysed with these equivalent horizontal loads applied.

Usually, the total base shear is applied non-concurrently in the direction of each of the main axes of the building. Horizontal torsion, arising from the non-coincidence of the shear centre and the centre of mass of any particular floor must also be considered along with the amplification of torsion that may occur.

It should be noted that for structures with non-uniform vertical distributions of mass and stiffness, earthquake codes are not applicable and can, at best, provide guidance only.

Concluding remarks

The engineering profession in Australia is soon going to have to consider earthquake induced loadings during the design process. These may be treated simply as another environmental loading, similar to wind loading.

However, as professionals with both commercial and community responsibilities, we can no longer plead ignorance of the effect of earthquakes in and around the country.