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Earthquake Resistant Design of Buildings and Education in Australia

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ABSTRACT

Within typical structural design subjects at Australian Universities the emphasis is on elastic analysis of frames, and ultimate strength design of the critical sections or members. Approximate methods are used to account for non-linear behaviour such as that due to cracking in reinforced concrete frames by altering the absolute and relative stiffness attributed to the columns and beams. This level of understanding of structural behaviour is sufficient to allow the student to conduct an earthquake analysis on a frame using the Equivalent Lateral Force method, although without further education the significance of the structural modification factor might not be understood. If the student is to practice in an area of moderate to high seismicity, as is likely in a global economy, this knowledge would need to be enhanced significantly. To be truly up-to-date in a world context, the emphasis would need to move away from force-based design to displacement-based design, and hence to performance-based design. This will usually require an understanding of the building behaviour in the non-linear range, and capacity design principles will need to be employed to ensure that the required energy dissipation mechanism is, in fact, realised. Within the context of performance-based design, the performance objectives (eg. a given performance level for a given design level earthquake) are assessed by comparing the expected interstorey drifts with the allowable damage in the assumed structural system. The authors have recently established a Masters subject on “Earthquake Resistant Design of Buildings” at the University of Melbourne, and the content of this subject will be discussed within the paper.

Keywords: earthquake resistant design, education, buildings

1. Introduction

There are many benefits that can be obtained by a structural engineer-in-training, or indeed to a practicing structural engineer, by studying the behaviour of structures when subject to earthquake excitation. The deeper understanding of the structure as a dynamic entity, and one whose response in the non-linear range can be largely dictated by a clever designer, gives an appreciation of the assumptions and limitations contained within the usual design procedures. The latest earthquake resistant design approach, the so-called "performance-based approach", relies on not only an ability to analyse the structural behaviour, but also the behaviour of the non-structural elements, the interaction of these with the structure, and, in some cases, the response of the building contents. It also gives the student an appreciation of the knowledge needed to establish a reliability assessment of the performance, of the need for further experimental data, and a healthy skepticism with regard to the results from computer analyses.

In this paper details are given of a new Masters level subject recently established by the authors at the University of Melbourne on "Earthquake Resistant Design of Buildings". Given the large volume of material written on this topic, this is clearly a very ambitious title for a subject with only 36 hours of face-to-face contact with the students. Of necessity, the subject has been pared down to the knowledge considered essential to a structural engineer working in the field, with references given to enable deeper reading in specific areas.

2. Subject Objectives

The art of designing earthquake-resistant buildings is constantly evolving and improving. The students need to be aware of this, and to become active participants in this process. Instead of assuming that knowledge is fixed and that established code methods are sacrosanct, the students are encouraged to regard "established techniques" as useful tools that may be superseded as knowledge progresses. There are many uncertainties in design; both in predicting the demands and the capacities, and these must be appreciated. Instead of relying too heavily on "sophisticated computational tools" and developing a false sense of security in the perceived accuracy of the output, the students are encouraged to think about the behaviour in an intuitive manner resulting from a fundamental understanding of the variables that influence the ground motions at the site, the ensuing response, and the acceptability of the response in terms of forces, displacements, velocities and accelerations.

The core subject objectives can be summarized as follows:

1) To develop a fundamental understanding of the prediction of ground motions and of the dynamic response of the building to these.
2) To learn from damage experienced in past earthquakes and hence consider building configurations and details which are conducive to good performance.
3) To gain an appreciation of existing analysis and design methods, including the assumptions behind these and any limitations associated with them.
4) To be aware of the move towards performance-based design and to appreciate the nexus between damage and displacement demands.

5) To use their fundamental understanding of the dynamic response and energy balance to pursue innovative solutions to earthquake-resistant design such as base-isolation and the use of energy-dissipating devices, and to provide a basis for well-reasoned retrofitting measures.

At present, the coursework Masters students enrolled in the subject come from a range of educational backgrounds. Eventually this subject will also be a core subject within the two-year Masters of Structural Engineering degree that will be offered at the University of Melbourne as part of the new "3+2" degree structure, adding yet another group within the Masters cohort. Due to the diverse educational backgrounds of the students, the subject has been constructed with the assumption that the students have only a basic knowledge of dynamics and no prior exposure to wave mechanisms and seismology.

The subject has an international focus, and considers regions with differing levels of seismicity, ranging from low to very high. By the end of the subject the students are expected to be able to:

- Describe the causes of seismicity in the world, both inter-plate and intra-plate. Identify hazards to buildings caused by earthquakes.
- Interpret response spectra presented in different formats, including the Acceleration-Displacement Response Spectrum (ADRS) diagram, and hence to quantify the potential ground motion hazards on the building.
- Demonstrate knowledge of techniques for analysing the response of structures to ground motion, for SDOF and MDOF structures, and linear and non-linear. Show an understanding of the assumptions behind these, and any limitations.
- Employ capacity design principles and the concept of strength hierarchies to ensure that the structure responds to an earthquake in the desirable way. Apply this concept to the design of a range of structural systems for buildings including moment resisting frames of reinforced concrete, steel and composite construction, reinforced concrete structural walls, and concentric or eccentrically braced steel frames. Design details that will ensure sufficient ductility in key plastic regions.
- Appreciate the uncertainties involved in the prediction of both demands and capacities, and demonstrate an understanding of the aims of performance-based design. Quantify acceptable limits on the parameters used to determine the performance of the structure, non-structural components, and building contents.
- Compare the codes and guidelines used in different countries, with emphasis on Eurocode 8, the IBC, FEMA publications and the Canadian code. Appreciate the extent to which they have embraced performance-based methods.
- Undertake seismic design and assessment of building structures using both force-based methods and displacement-based methods (both initial stiffness and secant stiffness approaches) including the Capacity Response Spectrum Method and the Substitute-Structure Method.
- Assess seismic performance of non-structural components and building contents and identify effective measures to mitigate potential damage.
- Use an appreciation of conservation of energy to select appropriate retrofitting strategies.

- Use an appreciation of the interaction between dynamic input and building response to identify situations where base isolation or the use of energy dissipating devices can be effective in new design or in modification of an existing structure.
- Identify the vulnerable features within houses constructed of un-reinforced masonry (including adobe), reinforced masonry and timber. Demonstrate the key steps to ensure good performance.

3. Outline of Subject Content

This subject gives an international perspective to the subject of earthquake resistant design of buildings, encompassing regions with levels of seismicity varying from low to high. It introduces the necessary geological and structural dynamics background to build up an understanding of the forces and displacements that building structures of different types are likely to be subjected to. It gives a historical background to design methods intended to ensure adequate performance of these structures at the serviceability, damage and collapse limit states, leading up to the most recently proposed methods such as the Direct Displacement Based Design method. It includes consideration of structural and non-structural elements and building contents. Particular attention is paid to detailing, not just of the connections, but also with consideration given to the resulting overall behaviour of the building due to strength hierarchies established within the design (the "capacity design method" pioneered by researchers at the University of Canterbury, New Zealand). The building types considered range from single storey timber and masonry (both reinforced and unreinforced, and including adobe) houses to multistory steel, concrete or composite frames. Assessment and retrofitting of existing structures are also addressed.
The lecture topics are listed as follows:

- Introduction: Towards performance based design
- World Seismicity and Earthquake Hazards
- SDOF Response
- Linear Dynamic Analysis of MDOF systems
- Non-linear Dynamic Analysis of MDOF systems
- Capacity Design
- Traditional Code Approaches to Design
- Comparison of Codified Design Methods
- Displacement-based Design
- Applications of Design Methods to structures of different types
- Assessment and Retrofitting of Existing Structures
- Non-structural components and building contents
- Base Isolation
- Energy-dissipating devices
- Residential structures

4. Towards Performance-Based Design

The design of earthquake resistant buildings is not an exact science. It requires a certain artistry that is used to coax the building into behaving in a suitable manner. There are many uncertainties in both the demands being placed on the building and in the capacity of the building to meet these demands. The designer must have a good appreciation of these before embarking on the design. Performance-based design is an excellent vehicle for conveying these uncertainties to the student, whilst still leading towards a rational basis for design. It is introduced early in the lecture series to set the stage for the latest trend towards "improved reliability in the engineering process by more directly relating computed response and expected seismic performance" (from [CEB-FIP, 2003]). Students are shown that the impetus for this change came partly from the large financial losses experienced after moderate to strong earthquakes in Kobe and Northridge. These losses, that were due not only to construction and repair costs but also to downtime of businesses, were greater than previously expected, and were not socio-economically acceptable. Prevention of collapse is no longer seen by many to be a sufficient criterion for design, and the focus has become the control of damage.

Without an understanding of the history of seismic design the students would not be able to understand the reasons for the move towards performance-based design and an up-front consideration of displacements. Thus, students are introduced to the history; ranging from the mid-20th century simple consideration of 10% of the weight of the building as a distributed lateral load, to the current emphasis on displacement-based approaches. Force-based methods such as the equivalent load method, and the response spectrum method, are covered in depth since they form the basis for many existing codes. This includes detailed consideration of ductility and the response modification factor. Within these codes, displacement capacity, if directly checked at all, is calculated at the end.

The critique given in [Priestley, 2003] of force-based methods, in particular the response spectrum method, with respect to the analysis and design of reinforced concrete frames and walls help to illuminate some of the flaws and limitations contained within these. For example, one of his strongest messages is that the stiffness of reinforced concrete members is directly proportional to the flexural strength even though it has traditionally been assumed to be independent of strength. Hence, although multi-modal analysis requires the initial stiffness of members to be known, it is actually impossible to define this stiffness prior to completion of the design. An introduction to the Direct Displacement-Based Design Method (DDBD) and other displacement-based methods follow on from this critique. In this subject the emphasis is on simple examples that demonstrate the principles employed. The students are also asked to study one of the displacement-based methods discussed in [Sullivan et al, 2004] in detail and to provide a summary and an example that illustrates its use.

In some ways, performance-based design can be viewed as an extension of current practice. Existing codes are performance-based in the sense that limitations to displacements (eg. to interstorey drifts) have usually been enforced at both serviceability and ultimate levels. However, the latest performance-based matrix is more comprehensive in that it considers a range of design levels and of performance levels (see Figure 1 from [CEB-FIP, 2003]). Typically, also, the focus is on displacements rather than forces, as is illustrated well in Figure 2 from [CEB-FIP, 2003] in which six displacement-based performance levels are shown. This gives designers the opportunity to portray expected damage to the building owner in a simple and effective manner. The owners are required to make decisions regarding their building in terms of the objectives they would like it to meet, eg. basic, essential or safety critical. They may, in fact, choose different objectives for structural and non-structural elements.

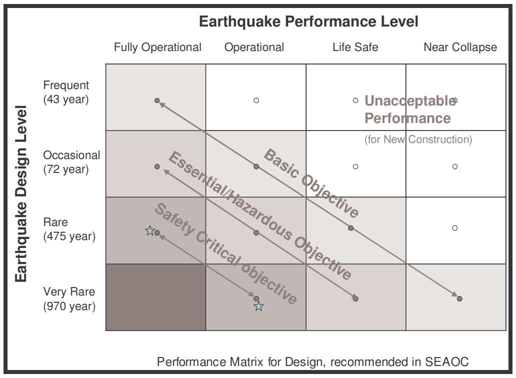

Figure 1

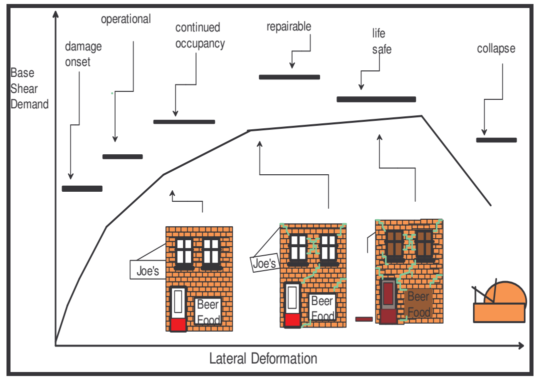

Figure 2

Figure1: Earthquake Performance Level

Figure2: Performance levels and relative damage, (State of Art Report (CEB-FIP) bulletin 25

Performance-based design requires an accurate depiction of the ground motion at a site corresponding to a particular design level, and quantification of the important parameters that define the damage limits. There is considerable uncertainty associated with the achievement of each performance objective; in establishing the spectra or the collection of ground motion records used to define the design level, in calculating the overall and local response of the building at the required design levels, in establishing through careful examination of experimental results the level of damage that corresponds to the calculated response, and in establishing the acceptability criteria to ensure a particular level of performance. A summary of the key uncertainties is given in Table 1.

Table 1 Uncertainties in Seismic Design

Demands on the structure and its components	**Capacity of the structure and its components**
Engineering Seismology	Strength capacity of a component (eg. flexural strength complicated by slab contributions, connection details, presence or shear or axial force)
Characteristics of the earthquake shaking at the site in question	Strength capacity of components at large deformations (load history dependent, possibly rate dependent)
Characteristics of the structural system	Prediction of deformation capacity of components
Modelling of the structural system	Relationship bet. component strengths and overall structural strength.
Analysis and interpretation of the demand data	Relationship bet. component deformations and overall structural deformations.

There are key questions that need to be asked.

How well can we define the ground motion hazard, and in what way is it best to present this so that a rational displacement-based approach is facilitated?

Earthquake ground shaking which puts the structure at risk can be characterised effectively by the combination of acceleration, velocity and displacement. However, provisions in most earthquake loading standards are mostly expressed in terms of the peak responding accelerations of elastic single-degree-of-freedom systems without making references to the other elements of motion. Commentaries and handbooks written in support of these provisions tend to be putting all the emphasis on the strength demand of the structural elements (for example, the base shear demand). When the inter-relationships between the three elements of motion are not well understood, the physical processes of seismic response can be difficult to interpret and the behavioural trends difficult to comprehend.

Meanwhile, engineers generally have a poor understanding of the seismic demand behaviour of the earthquake in terms of displacement. The successful implementation of the displacement-based (DB) design methodology has been compromised as a result (given that the comparison of the seismic displacement demand with the displacement capacity of the structure is central to the DB method).

The seismic demand module in the *ERDB* subject has been designed to teach the fundamentals of earthquake ground shaking and the response behaviour of simple structural models, with equal emphasis put on acceleration, velocity and displacement. Thus, the conventional force-based and the alternative displacement-based formats of quantifying seismic demand are delivered as an integral concept and not introduced sequentially. Three key topics in the syllabus which are focused on this ambitious educational objective are outlined as follows:

(i) Modelling of the elastic seismic demand.
(ii) Modelling of the inelastic seismic demand.
(iii) Multi-disciplinary facets of seismic demand modelling.

What methods can be used to analyse the building response and what are the limitations of these?

In Table 2 (after [Filippou and Fenves, 2004]), a list of types of analysis for seismic design is presented in order of increasing rigour and increasing requirements for modeling and complexity within the analysis. These methods are all covered in this subject, some in more detail than others. Students are given a fundamental background

Table 2 - Structural Analysis Procedures for Earthquake-Resistant Design

Category	**Analysis Procedure**	**Force-deformation Relationship**	**Displacements**	**Earthquake Load**	**Analysis Method**
Equilibrium	Plastic Analysis Procedure	Rigid-Plastic	Small	Equivalent Lateral Load	Equilibrium Analysis
Linear	Linear Static Procedure	Linear	Small	Equivalent Lateral Load	Linear Static Analysis
	Linear Dynamic Procedure 1	Linear	Small	Response Spectrum	Response spectrum analysis
	Linear Dynamic Procedure II	Linear	Small	Ground motion history	Linear response history analysis
Non-linear	Nonlinear Static Procedure	Nonlinear	Small or Large	Equivalent lateral load	Nonlinear static analysis
	Nonlinear Dynamic Procedure	Nonlinear	Small or Large	Ground motion history	Nonlinear response history analysis

in the dynamic analysis of multi-degree-of-freedom systems with an appreciation of the influence of modes of higher order than the fundamental. Of necessity, the hand calculations are based on the assumption of linear behaviour. Computer analyses are required for all but the very simplest non-linear systems. The use of computer packages has not been incorporated directly into the subject, although a non-linear time history program, RUAUMOKO [Carr, 2003], is demonstrated as part of the subject. However, the results of linear and non-linear computer analyses are given from various papers and from [Chopra, 2007], since displacement-based design does usually require calculation of the non-linear response. These are used for the following purposes:

- To instill an appreciation of the effect of simplification in modeling of the structure.
- To compare the linear the results of linear time history analyses with the response spectrum method.
- To indicate that the choice of the suite of ground motion records (both number and type) selected when analyzing a structure using non-linear time-history analysis can have a large influence on the results
- To show that the push-over analysis can give a good representation of the behaviour although it does not incorporate cyclic deterioration.
- To show the effect of varying the relative strength hierarchies of the members within the structure (this leads into capacity design)

What parameters should be used to establish acceptability criteria for the building?

In a performance-based approach, performance levels are keyed to acceptable values of measured structural response parameters such as drift and ductility (monotonic and cumulative), structural damage indices, interstorey drift indices and rate of deformations such as floor velocities and accelerations. The designer must be able to predict the level of these parameters for a given design level of earthquake (the demands) and to compare them with “acceptable” levels (the capacities).

The parameters mentioned above are obviously useful, but the students are asked to consider other matters such as

- Whether the structure could be made somewhat insensitive to earthquake shaking (eg. use base isolation).
- Whether new materials and technologies could be used for new and retrofit construction (eg. passive and active energy dissipating devices).
- Whether the building itself is designed to be self-centering after an earthquake.

How is the level of damage corresponding to a particular response able to be established?

For a parameter such as drift it is possible to establish the amount of damage corresponding to a given level of this parameter by using the results of carefully devised testing of components or subassemblages. Clearly, different amounts of drift can be tolerated by structural systems made of different materials, or of the same type of material but with different levels of detailing. In FEMA-356 [ASCE, 2000], for example, the acceptance criteria are given at the component level for parameters relevant to most of the important components of structural systems made of steel, reinforced concrete, wood and masonry. There is a great need for further testing, especially of newly devised systems, and the students are made aware of this.

Buildings will usually be designed to behave in an inelastic manner during a rare or very rare earthquake event. The use of capacity design principles is shown to be essential to ensure that the building will remain stable and reliable in a very large earthquake. Students must be familiar with the basic concepts of capacity design and to have sufficient knowledge of the behaviour of structural elements and connections to be able to create a ductile design. But they must go further than this. Some examples are given to challenge the students. For example

- Partial height masonry infill might be seen as a non-structural element, but how does this effect the response of the building frame? Is the analysis of the bare frame sufficient?
- Should secondary frames be designed to accommodate the same drifts as the primary ones?
- What limitations should be placed on the use of slab-column frames in areas of high seismicity?
- Does full-height masonry infill within a frame improve the structural behaviour relative to the bare frame?

5. Conclusions and Future Improvements

The subject objectives and content have been defined. The emphasis is on the students gaining an intuitive understanding of behaviour based on sound physics principles, and the results of computer analyses are shown to be only as good as the assumptions on which they are based. Past design philosophies and analysis methods are presented in the context of a shift in the profession towards performance-based design. The basic tenets of performance-based design are presented early on in the lecture series and the remaining lectures are devised to give the students the tools and knowledge to build up to this approach to design. Students are made aware that research is still needed to develop more reliable analytical procedures that permit performance evaluation at all levels of performance of a wide variety of soil-foundation-structure systems and their components, of non-structural systems and of building contents. Also further work is needed to establish criteria and formats for comprehensive databases used in the performance-based earthquake engineering evaluation process, eg., ground motions, experimental data, fragility curves, etc.

Seismic-resistant design is not seen as a static process, but one that is constantly evolving. The next stage may be towards a reliability-based performance assessment (a full probabilistic approach to performance assessment) in which all uncertainties in the earthquake intensity, the engineering computations and the acceptance criteria would be taken into account. Also, there are moves in the research environment towards expressing performance in terms of continuous variables such as percent replacement costs, length of downtime and casualty rate (sometimes called “Decision Variables”). As the uncertainties in design, and the relation between damage and the decision variables, are better defined, these design and assessment procedures will become more of a reality. Also, there is room for improvement in the incorporation of sustainability principles into the design process. Sustainability is often treated as a bit of a poor cousin when compared with economic considerations!

6. Acknowledgements

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