7th Canadian Conference on Earthquake Engineering / Montreal / 1995
7ième Conférence canadienne sur le génie paraséismique / Montréal / 1995

Performance Based Building Codes for Seismic Design

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ABSTRACT

It is widely believed that a performance-based format for building regulations and codes encourages innovation and the development of new technology. In spite of this recognition, the development and use of performance-based codes has not seen much progress. This is mainly because of the difficulty in specifying a measurable performance that must be achieved to meet a specific objective. When the performance required cannot be quantified, verification of compliance becomes difficult. These and other issues relevant to the development of performance codes for seismic designs are discussed and the strategies that may be employed to address such issues are outlined. It is observed that one practical framework for performance-based seismic requirements could consist of the building regulations related to structural sufficiency, written in qualitative performance terms, and one or more accompanying non-mandatory documents containing methods of verifying compliance based on calculations and/or testing.

INTRODUCTION

The primary purpose of building regulations is to assure the health and safety of the users and the public. The regulations seek to achieve this through a set of requirements contained in codes and standards which form part of the regulations. In Canada, the National Building Code of Canada (NBCC) (ACNBC, 1995) is meant to be a model code of "minimum requirements for public health, fire safety and structural sufficiency". The code also takes into account the requirements of durability and economy. Considerations of comfort, convenience and amenity are at times included, particularly when they have an impact on health and safety.

The requirements in NBCC and in the standards recognized by it are in most part written in a prescriptive manner. Thus, the code essentially specifies a technical solution without fully identifying the particular objective that the requirement is supposed to meet. There is an alternative format of writing the code, one which clearly specifies the objective without dictating a means of achieving it. Codes written in this format are called performance-based codes or objective-based codes.

The need for developing performance-based seismic codes has been identified by a large group of people including, researchers working in the area, building officials, and code writing bodies. In the United States, the Structural Engineers Association of California (SEAOC) Vision

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2000 Committee is working on the development of a framework for performance-based seismic design requirements. The background work related to this effort is being carried out by Applied Technology Council under its project Nos. 33 and 34. More recently the Federal Engineering Management Agency (FEMA) has contracted with the Earthquake Engineering Research Centre (EERC) at the University of California to prepare a report on performance-based requirements for seismic design. As a part of this contract, EERC has developed seven Issue Papers to focus on the various issues related to performance-based seismic design of buildings (Moehle, 1994). The issues contained in these papers were discussed at a User Needs Colloquium held in San Francisco on January 27-28, 1994. The final report of the Colloquium will identify issues, identify gaps in existing knowledge and propose an action plan.

Development of performance-based building regulations is also being pursued at the National Research Council of Canada (NRC). Some of the issues related to performance-based requirements for seismic design are contained in an Internal Report of the NRC. (Humar, 1993).

PRESCRIPTIVE CODES AND PERFORMANCE BASED CODES

Prescriptive Codes

In most cases, building control regulations prescribe specific technical requirements without necessarily identifying the objective that the requirements are meant to achieve. Standards containing the requirements written in this format are said to be "prescriptive" in nature.

Prescriptive codes are, in general, self contained so that reference need not be made to another document for the full understanding of a requirement. Verifying compliance with the regulation is quite straight forward. Prescriptive codes, however, have a serious drawback – they tend to inhibit innovation and the introduction of new technology and materials. Even though they usually have an *equivalency clause*, allowing alternative solutions, its application is difficult in the absence of a stated objective. Furthermore, specified solutions are based on the technology available at the time the regulations are formed. The technology thus gets locked in until a new version of the regulation is issued.

Performance Based Codes

Performance-based codes state the objective of the control regulation and specify measurable performances that the building or its component should achieve in order that the required objective is fulfilled. The means of achieving the required performance is not specified, so that any technical solution that can be demonstrated to meet the specified performance standard is acceptable. Evidently, a means of verifying performance also needs to be specified.

Performance-based codes do not dictate the use of a specific form of construction or a particular material. By providing a valid basis for seeking alternative solutions, they encourage innovation as well as introduction of new technology and materials.

A number of difficulties are inherent in the practical application of a performance-based code (Oleszkiewicz, 1992). To be effective, a performance code or standard should state the required performance of the building or component in quantified terms and include a method or methods of assessment and verification. Often the task of specifying a performance requirement to achieve an objective is very difficult or impossible. This may be so because of lack of knowledge, or because of the multiplicity of variables and human factors involved. Verification also becomes difficult when performance requirements cannot be stated in quantified terms.

PRINCIPLES OF A PERFORMANCE-BASED CODE FOR SEISMIC DESIGN

Objectives

The issues outlined in the previous section in relation to performance-based regulation for building design in general also apply to requirements for seismic design. However, the infrequent nature of earthquake events coupled with the severity of the hazard posed by such events and the technical complexities require that additional consideration be given in defining the objectives of design, in setting performance goals to achieve the objectives, and in determining the means by which such goals can be met.

The following objectives, among others, have been suggested for seismic design: (a) life safety; (b) post-earthquake functionality; (c) minimum or no occupancy interruption; (d) specific level of economic loss; and (e) hazardous material containment.

The objective of life safety, which calls for a low risk of the loss of life through collapse, is common with other building regulations. However, a certain amount of damage to the structural and non-structural components is accepted as long as it does not jeopardize life safety. Post-earthquake functionality requires that the damage to structural and non-structural components be minimal and the electrical and mechanical services continue to function so that the buildings may be used for services essential for recovery from the hazard. The objective of containment is applicable to buildings that are used to store hazardous or toxic material which should not be allowed to escape. Objectives of minimizing economic loss and occupancy interruption have been motivated by the experience of large rehabilitation costs and the prolonged depletion of useable building stock in the wake of an earthquake, both of which could lead to severe economic recession in the affected area.

Translation of Objectives to Performance Criteria

In developing a performance-based code for seismic design, the objectives outlined here need to be translated into measurable performance. The performance should ideally be specified as an acceptable integrated probability of the structure exceeding certain limit states during the earthquake events that the structure is likely to experience. Because of the complexity involved in specifying an integrated probability, performance criteria may be limited to specified events or an equivalent substitute such as a static collapse load verification. Once a measurable performance has been specified, at least in theory the code need not specify the method of achieving that performance. However, because of the difficulty in verifying compliance, seismic codes will have to continue to specify the technical solution in one form or another. These should be looked upon as examples of "deemed to satisfy" solutions which do not preclude the use of alternative methods of meeting the performance criteria. As more performance-oriented procedures are developed, these will then replace the "deemed to satisfy" solutions.

Present seismic codes in general specify prescriptive solutions that by implication are supposed to meet one or more of the objectives outlined earlier. The specific performance criteria that these solutions fulfill are not always fully quantified. The seismic design requirement of NBCC are supposed to provide an acceptable level of life safety. The corresponding performance requirement is that the building be designed so as not to collapse under a major earthquake, defined as one with a probability of exceedance over 50 years of not more than 10%. The NBCC attempts to quantify the performance level of post-disaster buildings by requiring that the design forces for such building be 1.5 times those for normal buildings. In most cases, however, the design regulations do not clearly specify a measurable performance requirement, even for the commonly accepted goal of life safety.

The performance levels required to meet the objectives of limited occupancy interruptions, specified economic loss, building conservation, and hazardous material containment have not been defined and need additional study and research.

Methods of Verifying Performance

The difficulties inherent in specifying measurable performance goals of a seismic design and in defining performance-based procedures for meeting these goals have been outlined in the previous section. Performance-based codes are designed to be flexible, allowing a variety of solutions. However, flexibility comes at the price of uncertainty and the risk of varying interpretations. The problem is compounded when the performance requirements are not specified in quantitative terms. To overcome this difficulty, performance-based regulations must almost always recognize other documents that contain verification methods, often written in prescriptive terms, and provide examples of acceptable technical solutions. The approved documents constitute the non-mandatory part of the regulations and therefore do not dictate a solution. This strategy has considerable advantage. First, it provides the much needed certainty to the requirements of the regulations. The non-expert builder or owner, or any one else who does not want to devise an alternative solution, may use the prescriptive specifications of the accompanying documents or the examples of acceptable solutions and be assured of compliance. The innovator, on the other hand, may design his own solution, but with the added benefit of using the approved documents as guides. The mandatory provisions of the regulations must, of necessity, be written in legal terms so that they can be interpreted in courts of law. The accompanying documents, on the other hand, being non-mandatory, may be written in plain language with illustrative examples, figures and diagrams. This makes them much easier to use in practice. Also, the non-mandatory referenced documents can be revised, amended, enhanced or modified with much greater ease. Their provisions can therefore be more responsive to changing technology.

PROPOSED FRAMEWORK FOR PERFORMANCE-BASED SEISMIC CODE

General Format

It is apparent from the discussion in the previous sections that a number of complex issues need to be resolved before fully performance-based requirements are developed for seismic design. One possible strategy is to wait until all the issues are resolved. A more effective alternative is to make a beginning toward adopting performance-based requirements written in the format of a mandatory part supplemented by approved documents containing methods of verification and examples of acceptable solutions. It is also logical that at first all of the approved documents would be based on the existing provisions of the Code and the referenced standards. In the long term, advantage may be taken of the fact that approved documents do not constitute a mandatory part of the code and need not therefore be worded in legal terms. Evidently, approved documents covering a range of design options from the equivalent lateral load method to non-linear dynamic

TABLE 1: Proposed Components of a Performance-Based Seismic Code

Objective	Suitable Type of Analysis	Needed Performance and Required Performance Verification
(1) Minimum safety level	*Standard buildings:* Equivalent static for specified return period	- Full requirements of equivalent static method - Verify static collapse load
	Non-standard buildings: Response spectrum analysis with static force-reduction factors	- Specify non-standard building features that demand this method - Verify static collapse load
(2) Increased safety level	As above	- Specify type of buildings that need this treatment - Specify increased safety level in form of a load multiplier (e.g.I) - Verify available member ductility - Verify static collapse load
(3) Functionality (hazardous material containment, operational readiness)	Linear or non-linear dynamic analysis using response spectrum or time history	- Specify degree of functionality - Convert to corresponding deflection and/or acceleration limits for structure and content - Verify available member ductility of structural and non-structural members - Verify static or dynamic collapse load
(4) Minimum Economic Loss	Equivalent static or dynamic analysis (response spectrum or time history)	- Specify acceptable economic loss - Convert to damage criterion (e.g. ductility) - Apply equiv. static or dynamic analysis to verify damage criterion - Verify static or dynamic collapse load

analysis should be developed.

While the specific items that must be included in approved documents related to performance-based seismic code will no doubt be subject to wide ranging debate and discussion and will need modification and expansion, the proposed framework presented in Table 1 is seen as a first step in identifying some major issues and to initiate the process of preparing proposals for eventual consideration by relevant code committees. It is believed that the proposed framework will facilitate the move to a format in which only the performance requirements are stated in the code.

Table 2a: Type of Base Motions for Seismic Analysis

Type	Description
a)	Zonal acceleration and velocity or site-specific values (1990 and 1995 NBC)
b)	Response spectrum derived from parameters in a) (1990 and 1995 NBC)
c)	Uniform hazard spectrum (under development, possibly 2000 NBC)
d)	Time history ground motion that satisfies spectrum bounds of b) or c) (available methods)

Table 2b: Effect of Soils

Type of Base Motion (from Table 2a)	Possible Incorporation of Soil Effects
a)	Similar to 1995 NBC
b)	Similar to 1995 NBC or 1-D analysis using non-linear soil properties
c)	Frequency-dependent soil factors (to be determined)
d)	As for c) or 1-D or 2-D analysis with non-linear soil properties and possible soil-structure interaction effects

For the objective of *Minimum Safety Level*, the outline in Table 1 can be seen as an evolutionary process in that the current seismic provisions in the 1995 NBCC are restated in an objective-based format. An added proposed feature is the verification of the static collapse load since this is within the philosophy of performance verification of minimum safety against collapse; however, the details of such procedure would still need to be developed. *Functionality*, including containment of hazardous materials, requires that specific attention be paid to the deformational criteria of components and machinery in order to assure functionality, and this can likely be achieved only by appropriate dynamic analyses. The objective of *Minimizing Economic Loss* to a specified level is seen as an optional one. Considerable development of procedures would be needed to achieve this objective. In any case, the minimum life safety requirements would also need to be satisfied.

Seismic Design Base Motion and Soil Effects

The action that is associated with seismic effects on structures is the dynamic motion of the ground. The ground motion, together with a probabilistic return period representing seismic hazard, is specified in the seismic zoning maps along with the related ground motion parameters, and is usually associated with rock or ***firm ground***. These ground motions are summarized in Table 2a. In addition, the ground motion corresponding to that of bedrock of the earth's crust is amplified and modified by the presence of soils having varying geometric features and material properties. In the 1995 NBC such soil effects are expressed in terms of the foundation factor F, used as a multiplier in the base shear calculation. This factor, or possible improved versions, can be retained for the equivalent static method. For dynamic analyses, however, more detailed soil amplification studies are indicated. Possible ways of linking these soil effects with various ground motion parameters are presented in Table 2b.

Approved Methods of Verification

Equivalent Lateral Load Method The primary method for verifying compliance with the objectives of a seismic design code should, for regular buildings, include the equivalent static lateral load method. In the method currently specified by NBCC, the building structure is required to be designed for a set of static lateral forces induced by the design earthquake. This method, possibly slightly modified, would be referenced in a performance-based code.

Dynamic Analysis The equivalent lateral load method is not applicable to buildings with significant irregularities in plan or in elevation, or in the distribution of stiffness or mass, and to buildings with major setbacks and discontinuities. A dynamic analysis is specified by the NBCC in all such cases, and this would be similar in a performance-based code.

Recent efforts have led to the development of several innovative methods of safeguarding the buildings against the effects of earthquakes. These innovations include the techniques of base isolation, controlled friction damping devices, and methods of active control. A performance-based code format will permit the use of such innovative techniques provided they satisfy the general performance requirements of the Code. Until such requirements are quantified, it is desirable that acceptable verification methods be provided in the accompanying documents to prove equivalence. The performance of innovative designs can best be predicted by an appropriate procedure of dynamic analysis. Both the response spectrum modal superposition method as well as a step-by-step non-linear analysis should be available. A non-linear analysis requires the definition of one or more ground acceleration time histories, and a careful modeling of the structural behaviour in the inelastic range. The latter poses considerable challenge because of the complexity of the inelastic material behaviour. Several such solution methods have, however, been employed in the seismic design of regular and irregular buildings and those with innovative antiseismic devices.

REQUIRED DEVELOPMENTS FOR A PERFORMANCE-BASED SEISMIC CODE

The following are seen as some important issues that need to be pursued and resolved in order to achieve a fully operational performance-based seismic code.

1. Define an acceptable method to verify static collapse load as a measure of adequate seismic safety.

2. Develop methods of correlating the material, element and system limit states with the desired performance.

3. Document an acceptable response spectrum and time-history analysis.

4. Find relationship between degree of functionality and deflection/acceleration criteria for structural members and content; similarly for containment of hazardous materials.

5. Find relationship between acceptable economic loss and damage criteria.

6. Develop suitable soil factors and establish the reliability of soil response analysis methods.

It is clear that these issues will not be fully resolved before a performance-based code is introduced. Alternative means will then have to be found in reaching the same objectives.

SUMMARY AND CONCLUSION

The main features for a proposed performance-based seismic code are described, namely a statement of the objective, acceptable methods of achieving the objective, and verification of performance. Examples of objectives include level of life safety, functionality after an earthquake, minimizing economic losses, and the prevention of the escape of hazardous materials. Depending on the type and importance of structure, acceptable methods of analysis to verify performance would include the current NBC equivalent static load method, the response spectrum method and time-history non-linear analysis.

It is concluded that suitable performance requirements and verification methods will need to be developed; until these become available, ***deemed-to-satisfy*** approaches will have to be used.

DISCLAIMER

The opinions expressed are those of the authors and do not necessarily reflect the views of the Canadian Commission on Building and Fire Codes, responsible for the National Building Code of Canada.

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