

Background information for some of the proposed earthquake design provisions for the 2005 edition of the National Building Code of Canada¹

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Abstract: There are many changes proposed for the Earthquake Design Provisions of the 2005 edition of the National Building Code of Canada (NBCC). Among them are requirements for complete load paths, separation of stiff nonstructural elements, and the introduction of definitions of irregular structures and special design requirements associated with these irregularities. A new requirement for direction of loading is introduced, along with requirements for elements common to more than one lateral load resisting system. The effects of displacements are emphasized throughout the document, and revised provisions for drift limits are proposed. Revisions to the importance factor that integrate it into the proposed revised format for Part 4, Structural design, of the NBCC are given. Background information is presented.

Key words: load path importance factor, irregular structures, direction of loading, special requirements, drift limits.

Résumé : Il y a plusieurs changements proposés aux clauses sur la conception sismique de la version 2005 du Code National du Bâtiment du Canada (CNBC). Parmi ceux-ci se trouvent les exigences d'un chemin de charge complet, la séparation des éléments non-structurels rigides, et l'introduction des définitions des structures irrégulières et des exigences spéciales de conception associées à ces irrégularités. Une exigence nouvelle pour la direction des sollicitations est introduite, ainsi que des exigences pour les éléments communs à plus d'un système de résistance des charges latérales. Les effets des déplacements sont accentués à travers le document et des clauses révisées pour la limitation des mouvements sont proposées. Les révisions du facteur d'importance l'intégrant à l'intérieur du format révisé proposé de la partie 4, Conception structurale, du CNBC sont présentées. De l'information de contexte est présentée pour les sujets ci-haut mentionnés.

Mots clés : facteur d'importance du chemin de charge, structures irrégulières, direction des sollicitations, exigences spéciales, limitations des mouvements.

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Introduction

The proposed revised Earthquake Design Provisions for the proposed 2005 edition of the National Building Code of Canada (NBCC) address building performance in a broad sense and include the following issues: ground motions, site soil effects, analysis, and design. The design requirements can be further divided into load-reduction *R* factors, which are treated separately in a companion paper (Mitchell et al. 2003), and a series of requirements, which are discussed

herein. They are as follows: (i) general requirements; (ii) earthquake importance factor; (iii) building configuration of regular and irregular structures; (iv) direction of loading for analysis and design; (v) special requirements and restrictions; (vi) building displacements, drift limits, and separation of buildings; and (vii) foundation provisions.

General requirements

The general requirements are fundamental building requirements that experience over the years with earthquakes has shown to be important for "good building performance". Among them are the following:

- (1) The structure must have a clearly defined, complete load path.
- (2) The elements in the load path, which are designed and detailed to resist the earthquake load, must be clearly identified as being the seismic force resisting system (SFRS) and must be designed to resist 100% of the earthquake loads. The SFRS acting alone is used to calculate displacements.
- (3) All other elements of the structure will displace with the building to its expected earthquake displacement, which will introduce forces in them such as axial forces,

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shears, and moments. These forces may reach the capacity of the elements, or the element may be displaced into the inelastic range. It is imperative that these elements do not lose their vertical load carrying capacity while undergoing these cyclic displacements. They must be investigated and it must be shown that they either remain elastic in the expected earthquake displaced configuration or are detailed in such a way that they can accommodate cyclic inelastic activity without losing their ability to support gravity loads. The lateral resistance of these elements is not to be counted in the lateral resistance of the structure, as they are often flexible and contribute little to the resistance, often do not meet the necessary requirements for ductile detailing, may not be part of a complete load path, and are usually not detailed to maintain their lateral resistance under cyclic nonlinear loading even if they can maintain their vertical load capacity. Where this is not the case, they can be made part of the SFRS if they meet the requirements and restrictions of the SFRS.

- (4) Often there are stiff elements in a building such as concrete, masonry, brick, or precast walls or panels that are not part of the SFRS. These have the potential for affecting a building's response, interfering with its expected behaviour, and damaging themselves and other building components, including the structure, as the building displaces in an earthquake. A common and classic example is infill walls that are not full height between columns and thus create "short" columns. This has been a common source of damage and collapse in earthquakes. For this reason these panels and walls must be separated by gaps or sliding joints so that they do not interfere with the structure as it displaces, or they must meet the requirements of the SFRS and be made part of it.
- (5) Other effects due to elements other than wall or panel elements, such as frame action of beams and columns not part of the SFRS, that are stiff enough to affect the building response must be accounted for when (i) determining the period of the structure to determine the design forces; (ii) determining the irregularity of a structure; and (iii) designing the SFRS if the non-SFRS elements have an adverse effect on the SFRS, for example, where the beam of a non-SFRS frame is attached at 90° to the end of the column of an SFRS frame, the load and moments in the end column of the SFRS will be affected by the beam of the non-SFRS frame under earthquake actions.

Earthquake importance factor

Previously, importance factors in Part 4 of the 1995 NBCC were dealt with as follows: (i) snow — no importance factor; (ii) wind — load levels based on return period with deflection calculations and cladding loads based on a 1 in 10 year return period, structures of non-post-disaster buildings designed to 1 in 30 year winds, and structures of post-disaster buildings designed to 1 in 100 year winds; and (iii) earthquake — load factors of 1.3 for schools and 1.5 for post-disaster buildings.

The Part 4 Structural Loads Committee of the NBCC felt there were inconsistencies in this approach and expressed concern with the following:

- (1) After the ice storm in Eastern Canada in 1998, school gymnasiums were being used as shelters, with ice loads on the roofs approaching the design loads. This left little margin for expected winter snow loads. The committee felt that increased protection should be applied to this situation, similar to the earthquake importance factor for schools.
- (2) Wind loads were using different return periods to determine loads, but earthquake loads were using load factors to deal with increasing the loads for "important" structures.
- (3) Why is cladding only designed for 1 in 10 year wind forces, since a cladding failure could be a significant threat to life? Also, which wind load should be used for cladding loads on a post-disaster building?
- (4) Why do schools have an importance factor greater than 1.0 for earthquake loads but not for wind or snow loads?

These questions and others prompted the Part 4 Structural Loads Committee to strike a task group to study these issues, and they came back with proposals as follows:

- (1) Define importance categories as low, normal, high, and post-disaster.
- (2) Define building uses and functions for these categories. Schools are high and post-disaster is similar to what is now in the NBCC.
- (3) Low is basically farm buildings or very low occupancy, low-risk, bulk storage sheds such as highway salt sheds.
- (4) Use importance factors rather than different return periods to determine the design loads.
- (5) For ultimate limit states, the factors vary from <1.0 for low-importance buildings to ≥ 1.0 for other importance categories.
- (6) For serviceability limit states, the values for snow and wind are <1.0. For earthquake loads, the factor does not apply. Drift limits in the earthquake load section govern.

The importance factors proposed for the ultimate limit state for earthquake loading are low = 0.8, normal = 1.0, high = 1.3, and post-disaster = 1.5. These are more or less as before but differ from those proposed for wind and snow.

The use of an earthquake importance factor increases the design force level and, in effect, for a given earthquake, should lessen the inelastic demand on a structure (it is often coupled with tighter drift limits to decrease nonstructural damage). It can be thought of as increasing the earthquake resistance and the "safety" of a structure or designing for an earthquake associated with a longer return period. Regardless as to how it is interpreted, the intent is to enhance the safety and performance of important structures. Schools are still classified as high importance, requiring a higher level of protection than a normal structure, just as they were in the 1995 NBCC. The reasons are as follows: (i) they are usually distributed throughout the population centres of an area and can be used for emergency refuge purposes; and (ii) children are smaller than adults and would have more difficulty dealing with a frightening earthquake and resulting damage; for instance, debris in exits would be a greater challenge for children than for adults. Note that the high importance des-

ignation is not intended to apply to universities or colleges, although it could be requested by an owner.

Structural configuration

Observations of earthquake damage to buildings indicate that, in general, “regular” buildings perform better than “irregular” buildings.

Although other codes have defined “irregularities” (New Zealand Building Code (NZBC); Uniform Building Code (UBC 1997); National Emergency Hazard Resolution Program Model Code (NEHRP 1997); and International Building Code (IBC 2000)), the limitations have not been particularly restrictive, and the main consequence has been the necessity to perform a dynamic analysis.

The Canadian National Committee on Earthquake Engineering (CANCEE) feels that this is an important issue, which, although addressed in the 1995 NBCC commentary to Part 4, has never been in the code itself. With the major changes being proposed, CANCEE feels now is the time to introduce definitions for regular and irregular buildings along with restrictions on analysis methods, building use, and design.

Structural irregularities are defined as follows and correspond closely to the definitions in the IBC and the UBC:

- (1) *Vertical stiffness irregularity* is considered to exist when the lateral stiffness of the SFRS in a storey is less than 70% of the stiffness of any adjacent storey, or less than 80% of the average stiffness of the three storeys above or below.
- (2) *Weight (mass) irregularity* is considered to exist where the weight of any storey is more than 150% of the weight of an adjacent storey. A roof that is lighter than the floor below need not be considered.
- (3) *Vertical geometric irregularity* is considered to exist where the horizontal dimension of the SFRS in any storey is more than 130% of that in an adjacent storey.
- (4) *In-plane discontinuity* in vertical, lateral force resisting elements is considered to exist when there is an in-plane offset of a lateral load resisting element of the SFRS or a reduction in lateral stiffness of the resisting element in the storey below.
- (5) *Out-of-plane offsets* is considered to exist when there are discontinuities in a lateral force path, such as out-of-plane offsets of the vertical elements of the SFRS.
- (6) *Discontinuity of capacity (weak storey)* is considered to exist when the storey shear strength in a storey is less than that in the storey above. The storey shear strength is the total strength of all seismic-resisting elements of the SFRS sharing the storey shear for the direction under consideration.
- (7) *Torsional sensitivity*, to be considered when diaphragms are not flexible, is considered to exist when the maximum displacement on a diaphragm in the direction of loading is 1.7 times the average displacement of the diaphragm in the direction of loading.
- (8) *Non-orthogonal systems* is considered to exist when the SFRS is not oriented or does not act along a set of orthogonal axes.

These irregularities are known to have a detrimental effect on building behaviour, some being worse than others. For instance, stiffness or weight irregularities and torsionally stiff irregular buildings can be dealt with by using a dynamic analysis. This goes a long way in overcoming the shortcomings of applying a static load distribution that is based on a “first mode” shape for uniform buildings.

Torsionally flexible buildings can be dealt with by prescribing an accidental torsional moment load case, which is quite punitive.

In-plane or out-of-plane offsets of the lateral load resisting system, particularly for wall structures, are a more serious problem, however. A dynamic three-dimensional analysis may improve the force distribution, but that alone does not help with issues of potential overload of the supporting structures, large force transfers in and out of the elements at the discontinuities, and large force transfers through the diaphragms. Simply making the numbers “work” will not provide a “good” building, and the proposed provisions ban the use of offsets or discontinuities of walls in tall buildings in high seismic zones.

Weak storeys are also very serious, and the proposed provisions ban them in most seismic zones.

In summary, these irregularities are used to trigger restrictions and special requirements elsewhere in the provision based on (i) the natural period or height of the building (i.e., are higher modes important?), (ii) whether the building is in a “high” or “low” seismic zone, and (iii) the importance category of the building.

The special requirements may include the following: (i) the irregularity is not allowed, (ii) dynamic analysis must be performed, (iii) special “capacity design” procedures must be used on certain elements, and (iv) design forces must be increased. These are described in more detail elsewhere in this paper.

Special requirements and restrictions

There are special requirements and restrictions throughout the proposed provisions. The intent of these is to try to improve the expected performance of a structure by using better analytical tools for some buildings and mitigating or eliminating the known problems associated with poor structural configurations.

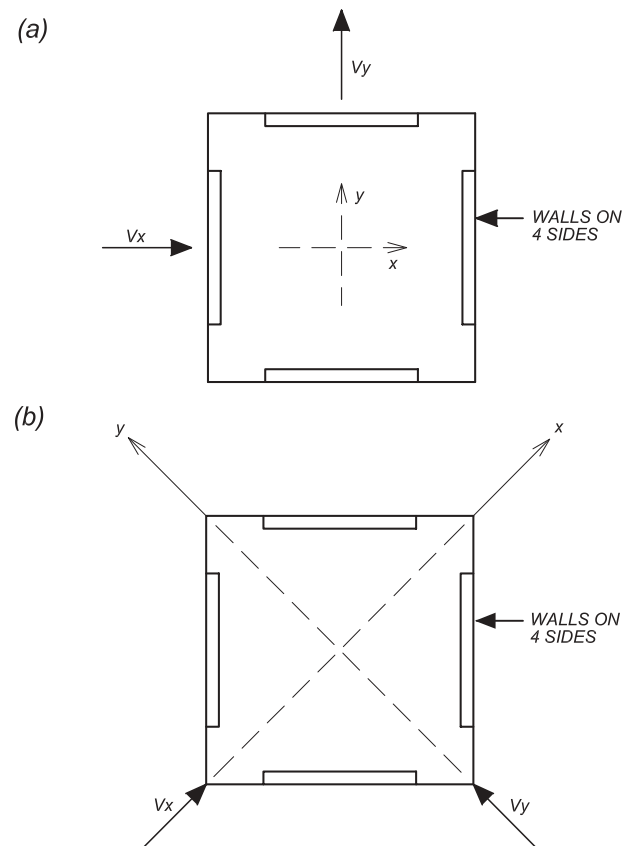
Some of the requirements and restrictions are as follows:

- (1) Stiff elements such as concrete, masonry, brick, or pre-cast walls or panels not part of the SFRS must be separated from the SFRS so as not to impair its expected behaviour.
- (2) The “equivalent static force method” has been the primary method of analysis for years. It is well known that it is a reasonable approximation for regular buildings dominated by their first mode of vibration. It is not as good an approximation, however, for irregular or long-period buildings. The provisions now require the primary analytical method to be the “dynamic analysis” method, except that the “static method” may be used for (i) buildings in very low seismic zones, (ii) regular structures less than 60 m in height and with fundamental lateral periods less than 2.0 s, and (iii) irregular structures (except “tor-

sionally sensitive ones”) less than 20 m in height with fundamental lateral periods less than 0.5 s.

- (3) Previously, the NBCC assumed that earthquake loads could act in any horizontal direction, but analysis about the building’s “principal axes” was considered to be adequate. The NBCC commentaries then went on to talk about “analysis about each of these orthogonal axes” but the term principal axes is not used in the commentaries, although it seems to be implied. Most designers probably have some idea of what it might mean (i.e., if the building is pushed through the shear centre along a principal axis, then it deflects only along that direction and not perpendicular to it), but it is an ambiguous concept at best, hard to determine in general, and might be meaningless in a building with setbacks or with frames and walls at arbitrary orientations. Many designers simply pick, using judgement, a set of axes that appears to reflect the predominant orientation of the lateral elements and analyze the building about these axes. In an attempt to clarify this issue, a new set of requirements is proposed here and is illustrated in Fig. 1. It can be seen that the choice of axes can have a significant effect on forces in members. Basically (i) where components of the SFRS are oriented along a set of orthogonal axes, independent analysis about each of these axes shall be performed; (ii) where the components of the SFRS are not oriented along a set of orthogonal axes, and the structure is in a low seismic zone, then independent analysis about any two orthogonal axes is permitted; and (iii) where the components of the SFRS are not oriented along a set of orthogonal axes and the structure is in a medium or high seismic zone, then the analysis of the structure can be done independently about any two orthogonal axes for 100% of the prescribed earthquake loads in one direction concurrently with 30% of the prescribed earthquake loads acting in the perpendicular direction. This is meant to approximate the worst force distribution that can occur in the structure, and Fig. 1 illustrates this using a one-storey symmetrical structure with four equal walls; the loads applied are $V_x = V_y = V$, and no torsion is accounted for. Figure 1a illustrates loads applied to axes parallel to an orthogonal SFRS; the design shears are $0.5V$ and are not affected by the 100 + 30% rule. Figure 1b shows the loads applied at 45° to the orthogonal SFRS without the 100 + 30% rule. The wall design shears are $0.35V$, which is clearly too low; however, use of the 100 + 30% rule gives wall design shears of $0.46V$, which is approximately equal to those for the “orthogonal” case in Fig. 1a.
- (4) Buildings with an SFRS with a weak storey are not permitted except for very low seismic zones, and then the design forces must be 1.5 times the elastic response with no ductility or overstrength force reductions.
- (5) Post-disaster buildings must be designed with an $R_d = 2.0$ or greater, where R_d is essentially an R factor and is described in a separate paper (Mitchell et al. 2003). Post-disaster buildings cannot have a weak storey; and, in medium to high seismic zones, cannot have the following types of irregularities: vertical stiffness, vertical geometric, in-plane discontinuity, out-of-plane offsets, and torsional sensitivity.

Fig. 1. Direction of loading: (a) loads parallel to an orthogonal SFRS; and (b) loads at 45° to an orthogonal SFRS.



- (6) Cutoff walls are a concern in earthquake zones. In high seismic zones, walls forming part of the SFRS must be continuous from the top to the foundation and must not have irregularities consisting of in-plane discontinuity or out-of-plane offsets, except that for buildings less than 20 m in height and with fundamental lateral periods less than 0.5s, such irregularities are permitted if the earthquake design forces and deflections determined from the provisions are increased by 50%.
- (7) Cutoff walls coming down the building will try to resist lateral load as the structure deflects and can impose large vertical loads in the supporting elements. In medium to high seismic zones, these supporting elements must be designed to resist the loads imposed on them as the walls above the discontinuity deflect until the expected lateral earthquake deflection of the structure is reached. This is similar to existing requirements in the NBCC.
- (8) Elements that are common to two SFRSs may be subject to concurrent yielding in these systems, as the earthquake always has components in two orthogonal directions and, as we design for reduced loads using R values, it is quite likely that both systems are yielding. An example of this would be a column common to two intersecting frames, particularly an end column. It is therefore required to use capacity design principals and, where earthquake actions can produce forces in a column or wall due to lateral loading along both orthogonal axes, account must be taken of the effects of potential

concurrent yielding of other elements framing into the column or wall from all directions at the level under consideration and as appropriate at other levels. This requirement is separate from the “direction of loading” requirement and can occur in systems where the component elements of the SFRS lie and act along principal orthogonal axes.

- (9) Yielding of diaphragms in a typical structure is considered to be an undesirable method of energy dissipation. Diaphragms must be designed so that they do not yield. Where diaphragms must transfer forces between lateral load resisting elements, the actual strength of the elements must be used to determine the forces.

Deflection and drift limits

Earthquakes can inflict severe damage to the built environment. They also tend to be rare events compared to “design” wind or snow loads. In the past, codes have recognized this and concentrated on life safety as a goal and not necessarily damage prevention. Several recent earthquakes (Mexico 1985, Loma Prieta 1989, Northridge 1994, and Kobe 1995) have shown, however, that although well-designed buildings have performed well from a life-safety standpoint, the damage has resulted in high repair costs, displacement of people from buildings, and costly business interruptions. The social and economic costs have been very high and have strained community resources. A philosophy is evolving that these costs are too high, even if the events are rare, and that earthquake codes should move in the direction of mitigating damage as well as protecting life safety.

Since large displacements and drifts due to earthquakes contribute to (i) damage to the nonstructural components, (ii) damage to the nonlateral load-carrying elements, and (iii) P-Delta effects, the provisions in the NBCC have moved in the direction of tightening up of the drift limits from previous versions. The provisions follow the suggestions in the SEAOC Vision 2000 (1995) document, which discusses building functional requirements, recommends drift limits appropriate to those functional requirements, and links the drift limits to various earthquake return periods. This is illustrated in Figs. 2 and 3, which have been reproduced with some modification from SEAOC Vision 2000. One difference between the SEAOC Vision 2000 document and the proposed provisions is the difference in the definition of a “very rare” event. SEAOC Vision 2000 uses a 1 in 1000 year return period, whereas the proposed NBCC provision uses a 1 in 2500 year return period, which is compatible with the NEHRP (1997) documents. For comparison, an NBCC “post-disaster” designation is compatible with the SEAOC Vision 2000 definition of “operational.” The more rigorous functional requirement of “fully operational” is more associated with functions such as nuclear reactors.

Implicit in the SEAOC Vision 2000 (1995) document and the proposed provisions is the expectation that for the very rare earthquake event (i.e., 1 in 2500 year return period in the proposed revisions) the building could be in a state of “near collapse,” but not collapsed. The proposed provisions set the near-collapse drift limit at 0.025.

Briefly, the proposed provisions require the following:

- (1) Design deflections are those expected in the 1 in 2500 year return period event and are calculated by including torsion effects in the analysis and multiplying by $R_d R_o / I$, where R_d and R_o are essentially R factors and are described in a separate paper (Mitchell et al. 2003) and I is the importance factor.
- (2) The drift limits are based on h , the floor to floor height, and are $0.01h$ for post-disaster buildings, $0.02h$ for high-importance buildings, and $0.025h$ for other buildings.

Note that although these two requirements appear to be the same or more liberal than those in the 1995 NBCC, they are actually more restrictive because they apply to displacements based on a 1 in 2500 year return period event, whereas the 1995 NBCC uses a 1 in 472 year return period event.

These design deflections are also used to calculate P-Delta effects as discussed in the 1995 NBCC supplement to Part 4 and to check the performance of the nonlateral load-resisting elements.

A simplistic study of the shape of the response spectrum at different return periods for various cities implies that satisfying these drift limits in effect satisfies the suggested drift limits for various return periods for various uses and performance levels as suggested in SEAOC Vision 2000 (1995). For instance, examples of plots of spectral acceleration values versus return period for periods of 0.2, 0.5, 1.0, and 2.0 s are shown in Figs. 4 and 5. Figure 4 is for Vancouver and is representative of a “western” spectral shape, and Fig. 5 is for Montréal and is representative of an “eastern” spectral shape. These shapes are reproduced from studies performed by Adams and Halchuk² in the process of developing the seismic recommendations for the new proposed NBCC provisions. If the following assumptions are made, then it can be shown using the values in Figs. 4 and 5 that for shorter return periods the drift limits for various functional requirements as set out in Fig. 3 are, in general, met: (i) force levels for a given building are proportional to the spectral value for the building at its natural period; (ii) displacements are proportional to the force level; and (iii) the near-collapse drift limit is $0.025h$ for “normal” buildings for the 1 in 2500 year return period, and the post-disaster drift limit is $0.01h$ for the 1 in 2500 year return period.

For example, using Fig. 4, the spectral accelerations for Vancouver for return periods of 2500, 500, and 75 years are approximately 0.65g, 0.35g, and 0.12g, respectively, for a building with a 0.5 s period.

Assuming an $I = 1.0$ building and using assumptions *i–iii* noted previously gives the following: (i) for a 2500 year return period the maximum drift is $(0.65/0.65) \times 0.025 = 0.025$; (ii) for a 500 year return period the maximum drift is approximately $(0.35/0.65) \times 0.025 = 0.0135$; and (iii) for a 75 year return period the maximum drift is approximately $(0.12/0.65) \times 0.025 = 0.0046$.

This illustrates that the drift limits meet the criteria suggested in Figs. 2 and 3. In general, these calculations for other cities and other building periods produce similar results. Due to different seismicity between Eastern and Western Canada, the drift limits for shorter return periods are generally better satisfied in the east than in the west.

²J. Adams and S. Halchuk. Unpublished data.

Fig. 2. Damage status, performance levels, and drift limits; reproduced in slightly modified form from SEAOC Vision 2000 (1995).

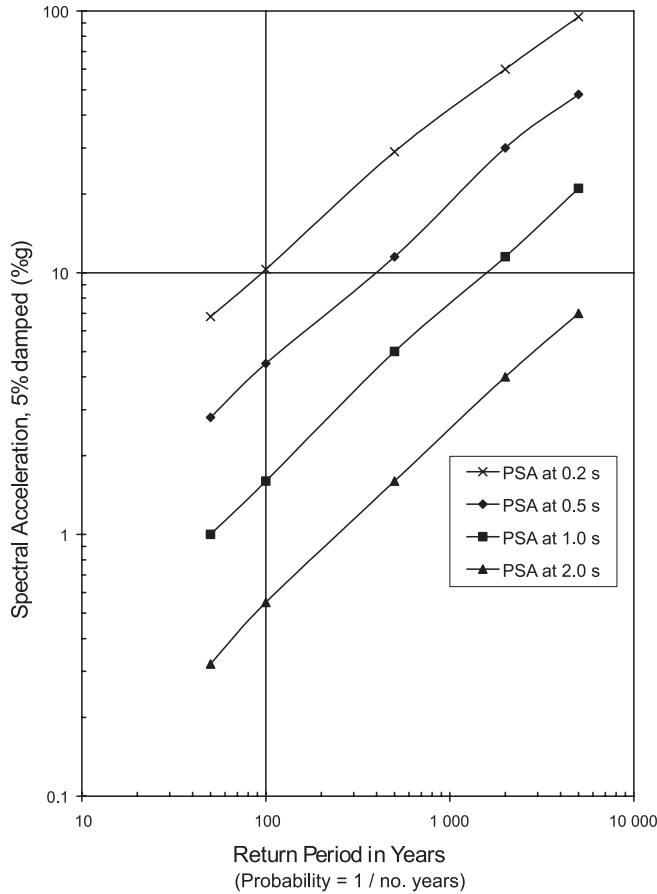
Damage Range & Damage Index	Damage States and Performance Level Thresholds	Drift Limits
Negligible	FULLY OPERATIONAL ↑ ↓	No damage, continuous service.
	Continuous service, facility operates and functions after earthquake. Negligible structural and nonstructural damage	≤0.2%
Light	OPERATIONAL ↑ ↓	Most operations and functions can resume immediately. Repair is required to restore some nonessential services. Damage is light.
	Structure is safe for occupancy immediately after earthquake. Essential operations are protected, nonessential operations are disrupted.	≤0.5%
Moderate	LIFE SAFE ↑ ↓	Damage is moderate. Selected building systems, features or contents may be protected from damage.
	Life safety is generally protected. Structure is damaged but remains stable. Falling hazards remain secure.	≤1.5%
Severe	NEAR COLLAPSE ↑ ↓	Structural collapse prevented. Nonstructural elements may fall.
	Structural damage is severe but collapse is prevented. Nonstructural elements fall.	≤2.5%
Complete	COLLAPSE ↑ ↓	Portions of primary structural system collapse.
	Complete structural collapse	>2.5%

Fig. 3. Recommended performance objectives for buildings; reproduced in slightly modified form from SEAOC Vision 2000 (1995).

EARTHQUAKE DESIGN LEVEL (Return Period)	Drift Limit	FULLY OPERATIONAL	OPERATIONAL	LIFE SAFE	NEAR COLLAPSE	PROBABILITY OF EXCEEDANCE
		(0.2%)	(0.5%)	(1.5%)	(2.5%)	
Frequent (43 years)	■	0	0	0	0	50% in 30 years
Occasional (72 years)	◆	■	0	0	0	50% in 50 years
Rare (475 years)	*	◆	■	0	0	10% in 50 years
Very Rare (970 years)		*	◆	■		5% in 50 years

- Legend:
- Basic Objective - Proposed NBCC Normal Importance
 - ◆ Essential Service Objective - Proposed NBCC High Importance
 - * Safety Critical Objective - No Proposed NBCC Category
 - Unacceptable Performance for New Construction

Fig. 4. Vancouver hazard values: peak spectral accelerations (PSA) for various earthquake return periods and building periods of 2.0, 1.0, 0.5, and 0.2 s.



These drift limits and expected performance levels also seem reasonably compatible with a table of drift limits and expected performance given by Galambos and Ellingwood (1985), which is summarized in Table 1.

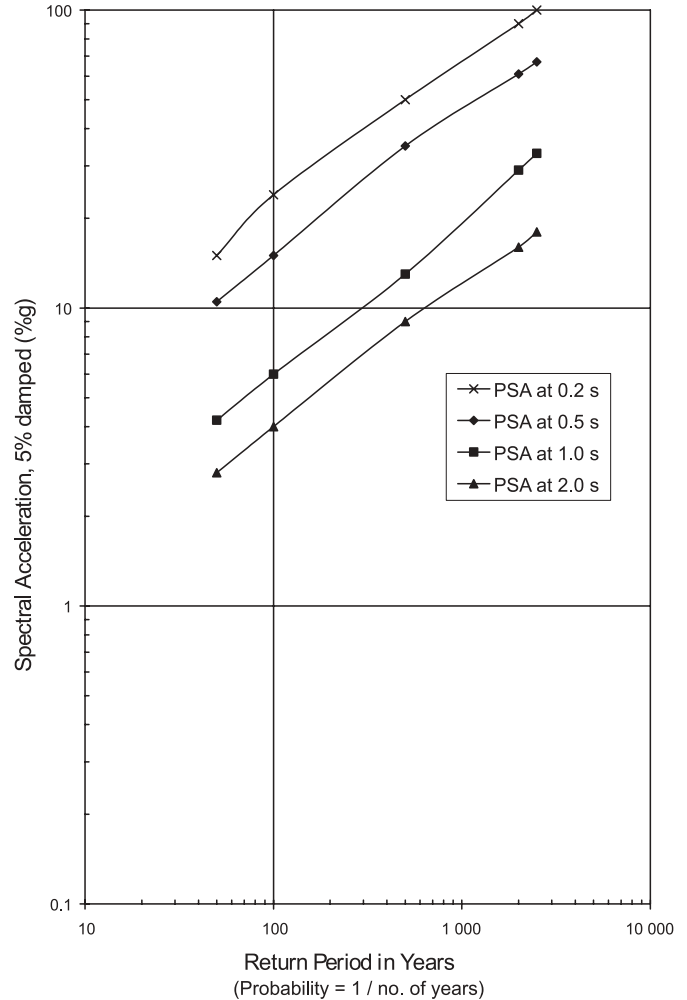
Note that satisfying these drift requirements for various earthquake return periods does not necessarily mean the structure will not yield at shorter return period events. Yielding in the structure is also a function of what *R* value has been chosen for designs and, for high *R* values, structural yielding may occur at short return period events. Buildings designed with high *R* values, however, should be able to accommodate some small inelastic action without many consequences.

The building separation requirements have been revised to “the square root of the sum of the squares” of the individual displacements from the absolute sum of the displacements.

Foundation provisions

In general, foundations are buried in the earth and it is difficult to identify and repair any damage. It is therefore important to try to prevent damage to the foundations. Additional concerns have to do with loads imposed in the ground itself and with the ability of the ground to resist these loads, and there is a general overall uncertainty as to just exactly what does happen to foundations as the ground moves, par-

Fig. 5. Montréal hazard values: peak spectral accelerations for various earthquake return periods and building periods of 2.0, 1.0, 0.5, and 0.2 s.



ticularly with respect to piles. Based on the concerns indicated in this paper, the proposed provisions expand on those in the 1995 NBCC and include the following requirements:

- (1) Foundations must be designed to resist the lateral load capacity of the lateral force resisting system. This will minimize the possibility of the foundation system yielding.
- (2) Foundations must be capable of transferring the earthquake loads between the building and the ground without yielding or exceeding the soil resistance capacity; this is to prevent degradation of the supporting soils.
- (3) Except for very low seismic zones, pile caps must be tied together in two directions. Very often piles are used in soils that are soft or loose, and these soils are susceptible to moving and displacing under earthquake motions. This requirement is intended to inhibit spreading of the piles and subsequent damage to the columns and piles.
- (4) In high seismic zones, footings on very soft soils must also be tied together for reasons similar to those noted in requirement 3. As there is a great deal of uncertainty in the interaction of piles with the surrounding soil in

Table 1. Serviceability problems at various deflection drift indices reproduced in slightly modified form from Galambos and Ellingwood (1985).

Deflection or drift index	Typical behaviour
Not visible	
$h/1000$	Cracking of brickwork
$h/500$	Cracking of partition wall
Visible	
$h/300$	General architectural damage; cracking in reinforced walls; damage to ceiling and flooring; cladding leakage
$h/300$ to $h/200$	Visually annoying; damage to lightweight partitions, display windows
$h/200$ to $h/100$	Damage to finishes; impaired operation of moveable components, i.e., doors, windows, and sliding partitions

Note: This table implies that function becomes impaired at 0.5–1.0% drift. h , storey height.

high seismic zones, it is proposed that the piles be detailed to accommodate cyclic inelastic behaviour when the moments induced in the pile by earthquake motions are greater than 75% of the moment resistance of the pile.

- (5) Loose, saturated soils are prone to liquefaction, which can have serious detrimental effects on a building structure and its foundations. Very large settlements or lateral displacements can take place, which can be very damaging. The proposed provisions require that sites be reviewed for their potential for liquefaction and that the consequences of liquefaction be accounted for in the design.

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