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Comparison of Design Base Shear Specifications in Canadian and U.S. Building Codes

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ABSTRACT

Numerous changes have been made in the seismic loading provisions of the National Building Code of Canada (NBCC) during the past several decades; the anticipation of further major changes call for an evaluation of the level of protection provided to buildings designed according to that code. This paper reports on the first stage of such a study, namely the comparison of base shears for buildings designed according to NBCC 1990 and the 1991 edition of the Uniform Building Code (UBC). Comparisons are made of seismic zoning maps, force reduction factors as well as overall base shear. The results indicate that there is a reasonable match of design base shear for structural systems having a high ductility capacity but that there are significant differences for a number of other systems.

INTRODUCTION

Numerous changes have taken place in the seismic loading provisions of the NBCC since such provisions were first included in the main text of NBCC in 1953. Uzumeri et al. (1978) have described the developments in NBCC seismic loading provisions up to the 1977 edition; a number of further changes have taken place since 1977. Heidebrecht, Basham and Finn (1995) outline the significant changes and also describe the need for an evaluation of the level of protection provided to buildings designed according to those provisions.

A research project to evaluate this level of protection has been initiated at McMaster University; the first stage, namely a comparison of design base shear specifications in NBCC 1990 and the 1991 UBC, is the subject of this paper. This kind of study helps to assess how structures designed to meet Canadian standards compare with those designed in a country which has good building design and construction practices and a high expectation of good performance when buildings are subject to strong seismic ground motions. UBC 1991 is the appropriate standard of comparison since it is the most recent edition of the most widely used seismic code in the U.S. While the comparison is made with NBCC 1990, it will generally be applicable to NBCC 1995, since very few substantive changes have been made in the seismic loading provisions of NBCC 1995. The objective of this paper is to identify key areas of similarity and difference.

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NBCC 1990 AND UBC 1991 BASE SHEAR SPECIFICATIONS

In NBCC 1990, the lateral seismic force (base shear) V is given by

$$V = (V_e / R) U \tag{1}$$

in which U = 0.6 is a calibration factor, R = a force modification factor (values range from 1 to 4), and V_e = elastic lateral seismic force, which is given by

$$V_e = v \; S \; I \; F \; W \tag{2}$$

in which v = zonal velocity ratio, S = seismic response factor (a function of period T and the combination of seismic zones Z_a and Z_v), I = importance factor (1 for buildings of normal importance), F = foundation factor (1 for buildings on rock or stiff soil), and W = dead load.

Since this comparison is for buildings of normal importance situated on rock or stiff soil, the resulting base shear coefficient is given by

$$[V/W]_{U\text{-}NBCC} = (v \; S) U / R \tag{3}$$

The seismic response factor S is shown in Fig. 1. Since NBCC 1990 specifies a load factor of 1 for earthquake loads, the base shear coefficient in Eq. 3 is that associated with the ultimate limit state. The subscript "U-NBCC" refers to "Ultimate - NBCC", for purposes of subsequent comparisons with the UBC base shear coefficient.

In UBC 1991, the total seismic design lateral force is given by

$$V = (Z \; I \; C) W / R_w \tag{4}$$

in which Z = seismic zone factor, I = importance factor (1 for buildings of normal importance), R_w = numerical coefficient (equivalent to force reduction factor; values range from 4 to 12), and C = $1.25/T^{2/3}$ (≤ 2.75) for buildings on rock or stiff soil. The coefficient C corresponds to the seismic response factor in NBCC 1990 and is also shown in Fig. 1. While the two factors are not strictly comparable, it can be seen that the shape of the coefficient C is reasonably similar to S for the case of $Z_a = Z_v$.

The UBC expression for V in Eq. 4 must be multiplied by a load factor to get the ultimate limit state base shear. In a study of correlations between various U.S. codes, Freeman (1990) notes that a load factor of 1.5 is appropriate to place UBC forces on a strength design (i.e. ultimate limit state basis). The resulting base shear coefficient for buildings of normal importance is then given by

$$[V/W]_{U\text{-}UBC} = 1.875 \, Z / (R_w \; T^{2/3}) \tag{5}$$

in which the subscript U-UBC refers to "Ultimate - UBC" .

SEISMIC ZONING

The NBCC 1990 seismic zoning maps display peak horizontal acceleration "a" and peak horizontal velocity "v" calculated at a probability of exceedance of 10% in 50 years. The methodology for these calculations is explained in Basham et al. (1982) and the application of these maps in the NBCC seismic loading provisions is described in Heidebrecht et al. (1983). These maps define zonal values of "a" and "v" for six zones Z_a and Z_v with maximum zonal values of 0.40g and 0.40 m/s respectively.

The map of seismic zone factors (Z) used in UBC 1991 is based on the seismic hazard map prepared by Algermissen and Perkins (1976). That map provides peak ground acceleration (PGA) on rock at a probability of exceedance of 10% in 50 years; the methodology for obtaining those values relied heavily on historical seismicity. The UBC 1991 zone factors map corresponds approximately to the Algermissen and Perkins map values of PGA modified by a variety of scientific and non-scientific considerations (Bertero 1991)

For the purpose of this study, it is necessary to develop or assume some equivalences of seismic hazard between the NBCC 1990 and the UBC 1991 maps. Since seismic hazard in NBCC 1990 is based on "v", which correlates well with the response and behaviour of structures with periods of 0.2s and longer and because the seismic zoning maps in NBCC 1990 and UBC 1991 have been developed on completely different bases, it is not straightforward to develop equivalences between these two maps. The approach used in this study is to consider possible equivalences between locations in southwestern British Columbia (Vancouver and Victoria) and a nearby U.S. city (Seattle). Consider the following arguments:

a) With respect to seismo-tectonic aspects, the source zone models being used in the current revision of Canadian seismic hazard (Adams et al. 1994) recognize that the major contribution to seismic hazard in this geographical area is the deep seismicity in the Georgia Strait - Puget Sound region. The resulting distribution of seismic hazard along a roughly north-south profile shows hazard increasing as one moves south from Vancouver towards Victoria and Seattle. On this basis, Victoria would be more comparable to Seattle than would Vancouver.

b) Seattle is in UBC Zone 3, with a seismic zone factor Z of 0.30. Since the UBC map is based on the 1976 Algermissen and Perkins map of PGA on rock (at a 10% in 50 year probability of exceedance), the Seattle rock PGA can be considered to be approximately 0.30g. Maps of EPV (effective peak velocity) and EPA (effective peak acceleration) prepared subsequently for the NEHRP Provisions show that the Seattle value of EPV in units of m/s is approximately equal, in numerical terms, to EPA in g. Consequently, the estimated value of PGV for Seattle would be approximately 0.30 m/s, which is the same as the zonal value of "v" for Victoria in the NBCC 1990 zoning map.

c) If one were to assume that Vancouver and Seattle are equivalent in terms of seismic hazard, then the logical deduction would be that Victoria would have a hazard level equal to or higher than that of San Francisco, i.e. because PGV in Victoria is 50% higher than PGV in Vancouver whereas the seismic zone factor in San Francisco (UBC zone 4) is only one-third more than that in Seattle. This logical deduction is not consistent with the general recognition that the seismicity in this particular geographical area is less than that of the California coast, including San Francisco.

On the basis of the above arguments, it is asserted that seismic hazard for medium to long period structures in Victoria ($Z_v = 5$ and $v = 0.30$) is equivalent to that in Seattle, which is located in UBC zone 3 with a seismic zone factor of 0.30.

REDUCTION FACTORS

R (NBCC 1990) and R_w (UBC 1991) are both force reduction factors which reflect the fact that the required strength for lateral load resisting systems can be reduced from the elastic demand on the basis of the ductility capacity of the system. However, the numerical values of the two factors are considerably different. The factor R is approximately equal to the estimated maximum system ductilty factor (e.g. for top deflection) and is therefore used directly in NBCC 1990 to reduce the elastic base shear V_e, with the final result modified by the calibration factor U. Consequently, values of R range from 1.0 for non-ductile systems (e.g. unreinforced masonry) to 4.0 for systems with the largest capacity to dissipate energy through ductility (e.g. ductile moment-resisting space frames).

Inferences concerning the basis for the numerical value of R_w are less straightforward, since this factor was developed by concensus and judgement rather than from an analytical or theoretical process (Freeman 1990). Since the UBC base shear formula, Eq. 4, does not include an expression for elastic base shear, the relationship between R_w and elastic demand cannot be determined so easily. Freeman suggests that R_w can be considered as the multiple of two sub-factors R_C and R_D, in which R_C represents the contribution to increase capacity and R_D the contribution to decrease demand (which would be equivalent to R in NBCC 1990). While the relative values of these contributions will vary with type of structure, Freeman reaches the conclusion that elastic demand can be approximately expressed by (3/8) Z / C. This implies that R_D (or R) $= 3\, R_w / 8$.

The approach taken in this study is to compare R and R_w for various types of structural systems and draw inferences on the basis of expected similarities in performance. Since the definitions of structural systems (UBC) and lateral load resisting systems (NBCC) are not exactly the same, it is necessary to make some interpretations in determining equivalent systems. Following consultation with a practicing engineer who is familiar with both codes (DeVall 1994), Table 1 shows UBC 1991equivalents to a selection of the lateral load resisting systems defined in Table 4.1.9.B of NBCC 1990, with corresponding R and R_w values as well as ratios of R_w/R.

This table shows that the R_w/R ratio varies from 2.0 to 5.3. When the R factors were first introduced in the 1990 edition of NBCC, calibration with the previous format was based on the most ductile systems, i.e. those having the highest R values (4.0). Consequently, it would be consistent to consider NBCC/UBC equivalences for the same systems, which have an R_w/R ratio of 3.0. This is reasonably similar to that deduced from the Freeman study, i.e. $R_w/R = 8/3 = 2.67$. Therefore, for general purpose of an overall comparison of base shear coefficients, the ratio $R_w/R = 3$ will be used.

However, since the R_w/R ratio varies considerably, it is instructive to examine more closely the systems which have ratios considerable different from 3. Ratios which are considerably less than 3 imply that UBC provides a lower reduction (than NBCC) relative to that of the most ductile systems. The notable systems in Table 1 are Case 4, steel moment-resisting space frames (MRSF) with nominal ductility ($R_w/R = 2.0$) and Case 8 R.C. ductile flexural walls ($R_w/R = 2.3$).

For Case 4, i.e. steel MRSF systems with nominal ductility, the R_w/R ratio of 2.0 is substantially less than that for the corresponding system in reinforced concrete (3.5 for Case 9), primarily because R = 3 for the steel sytem and R = 2 for the concrete system. This comparison suggests that both the absolute and relative values of these two systems (Cases 4 and 9) should be reevaluated. The apparent anomaly of Case 8 is easier to explain. The excellent performance of ductile flexural walls during strong seismic shaking was the basis for a relative increase in R when the R values were established in NBCC 1990; consequently, it is not surprising that the UBC base shears are, relatively, higher for such systems.

Table 1 Equivalences between NBCC 1990 and UBC 1991 for selected structural systems

Description of Lateral Load Resisting System	**NBCC 1990**		**UBC 1991**		**Ratio R_w/R**
	Case[a]	**R**	**Sys[b]**	**R_w**	
steel - ductile moment-resisting space frame	1	4	C.1.a.	12	3.0
steel - ductile eccentrically braced frame	2	3.5	B.1.	10	2.9
steel - ductile braced frame	3	3	B.4.a.	8	2.7
steel - moment-resisting space frame with nominal ductility	4	3	C.3.a.	6	2.0
steel - braced frame with nominal ductility	5	2	A.4.a. B.4.a.	6 8	3.0 4.0
R.C. - ductile moment resisting space frame	7	4	C.1.b.	12	3.0
R.C. - ductile flexural wall	8	3.5	B.3.a.	8	2.3
R.C. - moment-resisting frame with nominal ductility	9	2	C.2.	7	3.5
R.C. - R.C. wall with nominal ductility	10	2	A.2.a. B.3.a.	6 8	3.0 4.0
reinforced masonry	16	1.5	A.2.b. B.3.b.	6 8	4.0 5.3

[a]cases as defined in Table 4.1.9.B of NBCC 1990
[b]systems as defined in Table 23-O of UBC 1991

Ratios of R_w/R which are considerably higher than 3 imply that, for those systems, UBC provides a higher reduction (than NBCC) relative to that assigned to the most ductile systems. The notable example of such systems is reinforced masonry (R_w/R ranges from 4.0 to 5.3). Again, when the R factors were established in NBCC 1990, a deliberate decision was made to reduce the reduction factors for both reinforced and unreinforced masonry; it is expected therefore that these factors will be lower than the corresponding implicit factors in UBC 1991.

BASE SHEAR COMPARISONS

Figure 2 shows comparisons of base shear coefficients in western Canadian and U.S. cities for ductile systems in which the two codes are considered to be equivalent in terms of reduction factors, i.e. $R_w/R = 3$. In view of the earlier discussion concluding that Victoria and Seattle have equivalent hazard in the medium to long period region, it is interesting to note that Victoria base shears are approximately 25% higher than Seattle base shears when $T \geq 0.5$s. It would be premature to conclude either that structures in Victoria are being overdesigned or that those structures have a higher level of protection than comparable structures in Seattle. Rather, it should be noted that the seismic hazard equivalence described earlier in this paper is very approximate and a refined analysis of equivalence would be necessary to be sure that differences of 25% are significant. As an example of a possible refinement, the current revision of seismic hazard in Canada (Adams et al. 1994) shows that the spectral acceleration at T = 0.5s in Victoria is only about 25% higher than that in Vancouver, implying that the equivalent ratio of PGV between the two cities is also about 1.25. This is in contrast to the NBCC 1990 ratio of approximately 1.5. If it is assumed that the level of protection (i.e. design base shear) is about right in Vancouver, then these new results would imply that the design base shear for Victoria should be reduced by about 20%. If such a reduction were put in place, then the medium to long period design base shears in Victoria would only be slightly larger than those in Seattle.

The Victoria base shear coefficient has a short period plateau which is about 80% higher than the corresponding plateau for Seattle. The primary reason for the additional increase is that $Z_a > Z_v$ in Victoria, whereas the C factor in UBC corresponds to $Z_a = Z_v$ (see Fig. 1). It should be noted that the zonal boundary between $Z_a = 5$ and $Z_a = 6$ passes through the Victoria urban region so that this large value for the short period plateau would only apply in part of the region.

Figure 2 also shows that base shears in Vancouver are slightly below those in Seattle for short to medium period structures, which would be expected from the earlier discussion of seismic hazard comparisons. However, for structures with periods longer than about 1 s, Vancouver and Seattle base shears are almost identical. The implication is that the design of long period structures in Vancouver is more conservative, primarily because the seismic response factor S varies in proportion to $1/\sqrt{T}$ in that period region whereas the UBC 1991 C factor varies in proprtion to $1/T^{2/3}$.

Given the large variation in the ranges of R_w/R shown in Table 1, Fig. 3 shows the ratios of NBCC to UBC base shear coefficients for four different values of R_w/R, assuming the seismic hazard equivalence (i.e. v = Z) postulated earlier in this paper, for the NBCC zonal combination $Z_a = Z_v$. This figure shows that the ratio is approximately flat with respect to period, although it increases by about 25% from T = 0.5 s to T = 2 s. The extreme ratios (2.2 to 2.8 for $R_w/R = 5.3$ and 0.8 to 1.1 for $R_w/R = 2$) show the large variation in base shear coefficients which can occur for designs in regions of equivalent seismic hazard. Interestingly, except for short period structures having a low R_w/R ratio, the NBCC base shear coefficients are larger than the corresponding UBC coefficients. However, the earlier discussion concerning the approximate nature of the seismic hazard equivalence should be kept in mind when considering the implications of this information. The variation in R_w/R has the major impact in this kind of comparison. The implication is that the rationale for the values of all reduction factors should be evaluated carefully.

DISCUSSION AND CONCLUSIONS

The results of this investigation indicate that there is a reasonable match of design base shear as determined by the NBCC 1991 and UBC 1990 codes for structural systems having a high ductility capacity. However, differences in the relative values of the reduction factor result in significantly different levels of base shear for a number of other systems. The seismologically based seismic hazard equivalence (i.e. v = Z) is approximate but quite reasonable; refinements in the methodology for determining equivalence are needed if distinctions smaller than about 25% are to be made. It should be noted that a comparison of design base shears is relatively simplistic and that other factors in the design process, particularly actual design member sizes and detailing, have a major impact on the level of protection of structures. More detailed studies involving response and damage analyses are needed to obtain a more comprehensive comparison of the levels of protection afforded by different code provisions.

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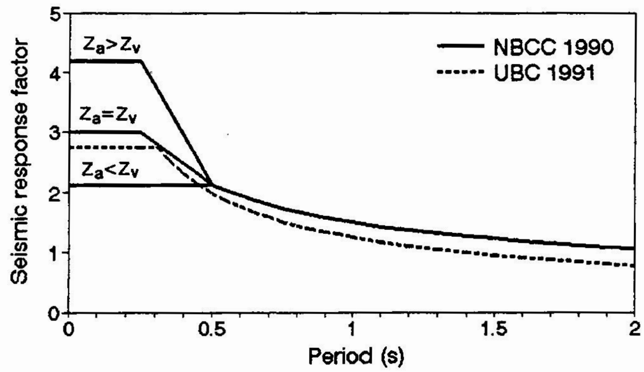

Figure 1. Seismic response factors for NBCC 1990 (S) and UBC 1991 (C)

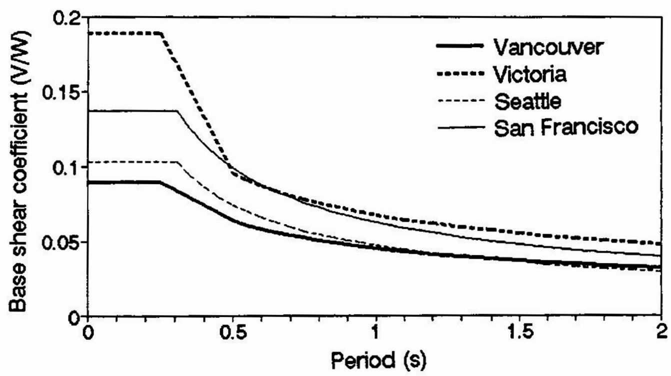

Figure 2. Base shear coefficients for Vancouver, Victoria, Seattle and San Francisco ($R_w/R = 3$; $R_w=12$, $R=4$)

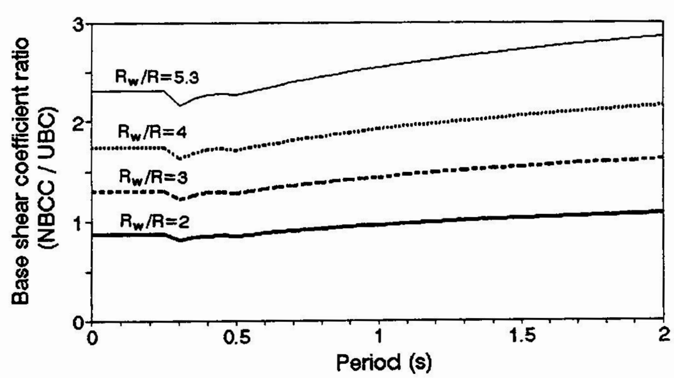

Figure 3. NBCC/UBC base shear coefficient ratios for varying R_w/R ratios ($v = Z$ and $Z_a = Z_v$)