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Comparison of the Seismic Code Provisions of the National Building Code of Canada and the Building Standard Law of Japan

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ABSTRACT

This paper presents a comparative study between the 2015 National Building Code of Canada (NBC) and the 1981 Building Standard Law of Japan (BSLJ). First, a brief description of the evolution and backgrounds of each regulation is given. A discussion of the two design procedures is then presented, both based on a prescriptive approach. The BSLJ features a two-phase seismic design. The primary seismic design is done following the allowable stress design method and considers medium-scale earthquakes. A secondary design then requires several additional checks for large-scale earthquake motions. The NBC, on the other hand, is based on load and resistance factored design and has a 2475-year return period design earthquake.

The parameters that influence the seismic demand are described and compared: importance factor, natural period of the building, seismic acceleration, local soil conditions, ductility, overstrength, storey stiffness, eccentricity and irregularities. The distribution of the force over the structures height is described and the load combination factors are discussed. Finally, some other design requirements are compared, including storey drifts and foundation design.

In conclusion, the BSJL explicitly considers two levels of demand, one for serviceability, and the other for life-safety, but does not quantify the return periods. The NBC only considers the life-safety earthquake and has an explicit return period. The BSLJ has simpler guidelines for ductile detailing, but application of ductility factors in analysis is more nuanced. Despite being an older code than the NBC, the pushover analysis required by the BSLJ explicitly considers the ductility of the structure. The NBC requirements for dynamic analysis focus on determining a more accurate linear distribution of forces, rather than an investigation of the true non-linear behavior.

Keywords: Code comparative study, National Building Code of Canada, Building Standard Law of Japan, seismic design methods.

INTRODUCTION

This paper presents a comparative study between the 2015 National Building Code of Canada (NBC) [1] and the 1981 Building Standard Law of Japan (BSLJ) [2]. While both codes have simplified procedures for small buildings and/or low seismicity, as well as more complex ones for high-rises and/or special structures, the intend of this paper is to compare the specifications for moderate size buildings most commonly used in both countries.

In Japan, the Urban Building Law, later replaced by the BSLJ was first enforced in 1919. Japan is a country with strong and frequent earthquakes and the evolution its seismic regulations has been largely influenced by these events. These first appeared explicitly in 1924, following the 1923 Great Kanto Earthquake. One allowable stress was specified for each structural material. Several important revisions were introduced in the 1930s, including specifications for concrete and steel joint strength and allowable stress, the distributing coefficients of horizontal forces, and the concept of ordinary and extraordinary state stresses. The Architectural Institute of Japan also published the first draft for the Standard for Structural Calculation of Reinforced Concrete Structures in that decade, followed by the Standard for Structural Calculation of Steel Members in 1941. It was only in the 1960s, with the advancement of dynamic analysis based on computers, that the 31-meter height limitation of the BSLJ disappeared and the first high-rise was built in Japan. In this era, more stringent detailing requirements were introduced for reinforced concrete columns as well. Methods for the seismic diagnosis and retrofit of concrete, steel and wood structures were developed in the 1970s, and the Seismic Retrofitting Promotion Law was introduced, although it was not fully enforced until 1995.

A major revision of the seismic design method was started after the 1968 Tokachi-Oki Earthquake. This revision was included in the BSLJ in 1981 and has been in use ever since. The major changes were mainly the introduction of two separate levels of earthquake motions, a single formula to evaluate seismic forces for buildings of long and short natural periods, the use of a seismic shear coefficient instead of a seismic coefficient, the consideration of structural irregularities in plan and elevation, consideration of the storey drift and the introduction of a structural characteristics factor to account for ductility. In 1998, the design method was slightly modified, and a performance-based response and limit capacity method was introduced as one option of seismic analysis [3].

In Canada the NBC, a model national building code developed by the National Research Council of Canada, is updated approximately every five years and comes into effect when adopted by provincial and local authorities. Seismic provisions appeared in the appendix of the NBC for the first time in 1941, with the lateral force dependent on the soil's bearing capacity and the building's weight. The first seismic zoning map was introduced in 1953 and remained unchanged until 1970, when the first probabilistic map was presented. The seismic maps only changed again in 1985, when seven distinct seismic zones were introduced. The latest Canadian seismicity provisions use the uniform hazard spectrum approach. They appeared in 2005 and were modified in 2010 and 2015. Spectral accelerations with a probability of exceedance of 2% in 50 years (2475-year return period) are presented for specific locations in Canada.

The importance of the lateral load resisting system was first indirectly acknowledged in the 1965 NBC, where a type of construction factor was introduced in the calculation of the minimum seismic shear force. From 1970 to 1985 more construction types were added. Only in 1990 a factor that directly accounts for the ductility of the lateral load resisting system appeared. It was also the first time that clear design and detailing requirements for ductile structures were stipulated in the Canadian Standard Association Standards related to steel and reinforced concrete structural design, complementing the NBC [4].

GENERAL DESIGN PROCEDURE

The Canadian and the Japanese regulations have a somewhat different intend. The BSLJ explicitly requires that buildings withstand moderate earthquakes with almost no damage, while collapse prevention and life-safety is required for severe earthquakes. It is expected that a typical building will be subjected to several moderate earthquakes during their service life, while the likelihood of occurrence of a severe earthquake during the same period is rare.

On the other hand, the primary objective of the NBC seismic regulations is to minimize loss of life during strong earthquake motions. It is implied that the structure will likely be heavily damaged during this event. Secondary objectives are to limit the building's damage to low to moderate earthquakes (considered to be achieved implicitly) and to ensure that post-disaster buildings can continue to operate after a strong ground shaking [5].

In accordance to the BSLJ's intend, it features a two-phase seismic design. The primary seismic design is done following the allowable stress design method and considers medium-scale earthquakes of an approximately 50-year return period. A secondary design, also relying on the allowable stress method but with other material resistances considered, then requires several additional checks for large-scale earthquake motions of an approximately 500-year return period. For earthquake loads, the relevant seismic load combination for allowable stress design method is shown in Eq. (1), where G represents the dead, P the live, K the seismic and S the snow load. The bracketed snow load only applies in heavy snow areas. The live load P shall be excluded where it is beneficial for the structure.

$$G + P + K(+0.35S) \tag{1}$$

In comparison, the NBC is based on load and resistance factored design and has one specific 2475-year return period design earthquake. For seismic design, the load combination shown in Eq. (2) is used for buildings without crane loads, where D is the dead, E is the seismic, L is the live and S is the snow load. E includes horizontal earthquake pressures from backfill or natural ground on the basement walls. The load factor for the L is increased from 0.5 to 1.0 for storage areas, equipment areas and service rooms.

$$1.0D + 1.0E + 0.5L + 0.25S \tag{2}$$

SEISMIC DEMAND

In the BSLJ, the seismic loads which a building must withstand are defined by story shear forces. For the medium-scale earthquake, the story shear force at level i, Q_i, is calculated by Eq. (3), where C_i is the lateral seismic shear coefficient of level i as defined in Eq. (4), and W_i is the weight of the building above level i. In Eq. (4), I_E is the importance factor, Z is the seismic hazard zoning factor, R_t is the design spectral factor, A_i is the lateral shear distribution factor, and C_0 is the standard shear coefficient.

$$Q_i = C_i W_i = C_i \sum_{j=i}^{n} w_j \tag{3}$$

$$C_i = I_E Z R_t A_i C_0 \quad (4)$$

For the large-scale earthquake, the story shear forces are calculated by Eq. (5), where Q_{un} is the required ultimate storey shear strength, D_s is the ductility factor, F_s is the storey stiffness factor, F_e is the eccentricity factor.

$$Q_{un} = D_s F_s F_e (I_E Z R_t A_i C_0) W_i \quad (5)$$

The NBC uses two main methods for the seismic analysis: the equivalent static and the dynamic methods. For the equivalent static method, the seismic demand is defined by the base shear a building is subjected to, calculated as shown in Eq. (6), where V is the lateral earthquake design force at the base of the structure, $S(T_a)$ is the spectral acceleration at the building's natural period in the direction under consideration, T_a, M_v is the factor to consider higher mode effects, I_E is the importance factor, R_d is the ductility factor, R_o is the overstrength factor and W is the total weight of the building. The dynamic method still requires that the base shear be calibrated with this same value, although a factor of 0.8 can be used if the building is regular.

$$V = \frac{S(T_a) M_v I_E}{R_d R_o} W \quad (6)$$

Minimum and maximum values of V are also given by the NBC. For walls, coupled walls and wall-frame systems, V shall not be less than Eq. (7). For moment-resisting frames, braced frames and other systems, the minimum value of Eq. (8) applies. On the other hand, for buildings located on a site other than class F and having an R_d value of 1.5 or larger, V need not be greater than the larger of Eq. (9) and (10).

$$V_{min} = \frac{S(4.0) M_v I_E}{R_d R_o} W \quad (7)$$

$$V_{min} = \frac{S(2.0) M_v I_E}{R_d R_o} W \quad (8)$$

$$V_{max,1} = \frac{2}{3} \frac{S(0.2) I_E}{R_d R_o} W \quad (9)$$

$$V_{max,2} = \frac{S(0.5) I_E}{R_d R_o} W \quad (10)$$

Importance Factor, I_E

There is no statutory importance factor for non-public buildings in the BSLJ, while some private clients request to set an importance factor on their own. For public buildings, the importance factor is stipulated by national or ordinance laws. Standard importance factors for public buildings depend on the usage as shown in Table 1.

Table 1. Importance Factors for Public Buildings, BSLJ.

Usage	Condition	I_E
National and local government offices	Located in main districts such as Tokyo and Osaka	1.5
	Located in other districts	1.25
Hospitals and fire stations	Designated to operate as base in disaster	1.5
	Not designated to operate as base in disaster	1.25
Schools	Designated as refuge	1.25
Storage of dangerous materials	Storing radioactive matter or germs	1.5
	Storing oil, gas, poison or explosives	1.25
Public buildings	Cultural, educational or welfare facilities for public	1.25
Others		1.0

To establish I_E, the NBC defines four importance categories: low, normal, high and post-disaster. The values of I_E are 0.8, 1.0, 1.3 and 1.5 respectively. Buildings of low importance are those that represent a low direct or indirect hazard to human life, as for example low human-occupancy buildings or minor storage buildings. Normal buildings are most of the buildings and are defined as those that do not fall into any of the other categories. High importance buildings are those that are likely to be used as post-disaster shelters (including schools and community centers) and facilities containing hazardous substances in large quantities. Post-disaster buildings are those that provide essential services in disasters, as for example hospitals, public water treatment plants or telephone exchanges.

Natural Period of the Building

In the BSLJ, the fundamental period of the building is defined as $T = h(0.02 + 0.01\lambda)$, where h is the total height of the building in meters and λ is the ratio of the total height of stories of wood or steel construction to the height of the building. This implies that $T=0.02h$ for concrete structures, and $T=0.03h$ for steel structures. This period is used in the determination of the design spectral factor R_t.

The NBC gives prescriptive formulae for determining the fundamental frequency of the building. This is referred to as the code period, T_{CODE}. Values of T_{CODE} for different types of lateral load resisting systems are presented in Table 2, where h_n is the height of the structure above ground in meters and L is the shortest length, in meters, of the diaphragm between adjacent vertical elements of the lateral load resisting systems in the direction perpendicular to the direction under consideration. T_a may be taken as T_{CODE} or may be determined by other established methods of mechanics using a structural model, provided that maximum values of T_a are respected. These values are 1.5 T_{CODE} for moment resisting frames, 2.0 T_{CODE} for braced frames and shear wall structures and 1.0 T_{CODE} for other structures. This upper limit does not need to be considered for the calculation of deflections, except that for walls, coupled walls and wall-frame systems T_a should not exceed 4.0s and for all other systems, including moment resisting frames and braced frames T_a should not exceed 2.0s.

Table 2. Prescriptive formulae for the fundamental frequency, NBC.

Lateral load resisting system	T_{CODE}
Steel moment frames	$0.085{h_n}^{0.75}$
Concrete moment frames	$0.075{h_n}^{0.75}$
Other moment frames	0.1N
Braced frames	$0.025h_n$
Shear walls and other structures	$0.05{h_n}^{0.75}$
Single-storey building with steel deck or wood diaphragm and shear walls	$0.05{h_n}^{0.75} + 0.004L$
Single-storey building with steel deck or wood diaphragm and steel moment or braced frames	$0.035h_n + 0.004L$

Seismic Acceleration

The seismic acceleration of the BSLJ is given by the seismic hazard zoning factor Z and the standard shear coefficient C_0. Z varies depending on the geographic location. Four zones are defined for the entire territory, ranging from 0.7 to 1. C_0 is equal to 0.2 for the moderate earthquake and equal to 1.0 for the strong earthquake.

In the NBC, the spectral acceleration $S(T)$ is defined by a local response spectrum that considers the effect of the site's soil as explained in the next section. These acceleration response spectra represent the peak spectral acceleration of an elastic single-degree-of-freedom oscillator at the site for a given probability of exceedance in a selected time period. The NBC spectra are calibrated to represent a 2% probability of exceedance in 50 years, equivalent to a 2475-year return period. To determine the acceleration that a building will experience, its fundamental period, T_a as defined in the previous section is used.

Local Soil Conditions

The local soil conditions are considered by the BSLJ by the design spectral factor R_t. R_t is determined considering not only the type of soil but also its critical period T_c and the fundamental period of the building T as shown in Eq. (11). Three types of soil are defined: type I is hard soil (rock, gravel and sand) with $T_c = 0.4$ s, type II is medium soil (other than types I and III) with $T_c = 0.6$ s, and type III is soft soil (alluvial clay) with $T_c = 0.8$ s.

$$R_t = \begin{array}{ll} 1 & when\ T < T/T_c \\ 1 - 0.2(T/T_c - 1) & when\ T_c \le T \le 2T_c \\ 1.6\,T/T_c & when\ 2T_c \le T \end{array} \tag{11}$$

The NBC classifies soil into five categories, A thorough E, ranging from hard rock to soft soil. Poor soils not covered by this classification, as for example soils prone to liquefaction, are classified as F and require site-specific evaluation. The classification is used to determine the soil coefficient F, which is used to scale the response spectra to take the soil effects into account. F not only depends on the type of soil, but also on the site's peak ground acceleration and the period of interest of the structure. The values of F are tabulated for periods of 0.2, 0.5, 1.0, 2.0, 5.0 and 10s, each for different values of a reference peak ground acceleration and each soil. Interpolation is required for intermediate values. Values of F range between 0.62 and 2.93.

Ductility and Overstrength

As introduced before, the BSLJ only considers ductility in the calculations of the shear of each story for the large-scale earthquake, since buildings are expected to remain elastic under moderate earthquakes. D_s, the ductility factor, varies between 0.25 and 0.55, smaller values being associated to a more ductile structure. D_s must be calculated for each storey independently and in consequence can vary between different storeys of the same structure. Storey ductility is determined based on the ductility of structural members and the lateral contribution of shear walls or braces. The combination of different seismic force resisting systems (e.g. moment frames and shear walls) is considered implicitly in the determination of D_s. The failure mode is also considered when determining ductility. Storeys where columns yield are considered less ductile in the analysis. The same is true for shear walls with a shear failure instead of a moment failure mechanism.

The NBC has separate factors for ductility and overstrength, R_d and R_o. As opposed to the BSLJ, these factors are defined for the entire building in the direction under consideration. The factors depend solely on the type of lateral load resisting system used. Different levels of ductility are defined for each system, ranging from conventional construction (low ductility) to ductile structures. Companion codes specify the requirements to achieve the different levels of ductility, as for example the detailing requirements for shear walls or the section class for steel members. When two different systems are combined, the lower R_d and R_o values of the two systems has to be used.

Storey Stiffness

F_s, the story stiffness factor used by the BSLJ, varies between 1.0 and 1.5. It is calculated based on the drift angles (r_s) of the storey of interest and other stories. The value of F_s is 1.0 unless the reciprocal of r_s is smaller than 0.6 times the average of r_s of all stories. With r_s smaller than 0.6, F_s becomes larger than 1.0. There is no equivalent in the NBC.

Eccentricity and irregularities

In the BSLJ, F_e, the eccentricity factor varies between 1.0 and 1.5. It is calculated based on the distance between the center of mass and the center of rigidity, and the torsional stiffness.

In comparison, the NBC requires that the torsional moments due to the eccentricity between the centres of mass and resistance be considered at the same time as torsional moments due to accidental eccentricities. This accidental torsion is calculated based on an eccentricity of 10% of the dimension of the building perpendicular to the direction being studied. The requirement can be relaxed in some cases to 5% of the dimension of the building when the structure in not deemed to be sensitive to torsion.

The NBC also classifies irregularities in nine distinct categories: vertical stiffness irregularity, weight (mass) irregularity, vertical geometric irregularity, in-plane discontinuity in vertical lateral-force-resisting element, out-of-plane offsets, discontinuity in capacity (weak storey), torsional sensitivity (to be considered when diaphragms are not flexible), non-orthogonal systems and gravity-induced lateral demand irregularity. If a building has one or several of these irregularities, different restriction and conditions apply, as for example the method of analysis (static or dynamic, see below), interdiction to use weak storey buildings unless the expected seismic demand is low and interdiction of most irregularities for post-disaster buildings.

Distribution of Seismic Force

For the medium scale earthquake of the BSLJ, the lateral shear distribution factor (A_i) is defined in Eq. (12), where $\alpha_i = W_i/W$ is the normalized weight of the i-th storey. This factor not only defines the vertical force distribution, but also accounts for higher-mode effects. As discussed before, the story shear forces are then calculated by multiplying the lateral load coefficient by each storey's mass.

$$A_i = 1 + \left(\frac{1}{\sqrt{\alpha_i}} - \alpha_i\right)\frac{2T}{1+3T} \tag{12}$$

For the extraordinary earthquake of the BSLJ, the forces from the medium-scale earthquake are increased incrementally in a pushover analysis. As members yield, hinges are inserted into the analysis. The pushover analysis is stopped when the storey drift reaches h/50 or a failure mechanism develops. The forces applied at this point are taken as the storey capacity and are compared to the storey demand from the extraordinary earthquake.

Using the static force method of the NBC, the shear applied to each level (F_x) is determined as shown in Eq. (13) and (14), where n is the total number of storeys of the building. F_t is a concentrated load at the top of the building and can be considered zero if T_a does not exceed 0.7 s.

$$F_x = (V - F_t)\frac{W_x h_x}{\sum_{i=1}^{n} W_i h_i} \tag{13}$$

$$F_t = \min(0.07 T_a V, 0.25V\ ) \tag{14}$$

The base shear and distribution of forces may also be determined by the dynamic method, a modal response spectrum method. This is mandatory under certain circumstances. As mentioned before, if the dynamic analysis is mandated by the code, the base shear, must be scaled up to match the static base shear or 80% of the base shear if the building is regular. Analyses that explicitly consider the non-linear behaviour of the structure, such as non-linear dynamic analysis or pushover analyses are generally not required by the NBCC 2010.

OTHER DESIGN PROVISIONS

Building Drifts

The story drift must not be larger than 1/200 (0.5%) against the medium-scale earthquake of the BSLJ unless some special considerations are made in the design of non-structural elements, but in no case should be larger than 1/120 (0.83%). For the extraordinary earthquakes, the storey drift must be less than 1/50 (2%), although recently a more stringent limit of 1/100 (1%) has been recommended. In practice, the pushover required for the extraordinary earthquake is conducted until this drift is reached, or until any storey reaches a collapse mechanism. In Canada, the storey drift must not exceed 1/100 (1%) for Post-Disaster buildings, 1/50 (2%) for High Importance buildings, and 1/40 (2.5%) for all other buildings. These drifts must include the effects of torsion, including accidental torsion, and when obtained from linear elastic methods as described above, they must be multiplied by $R_d R_o / I_E$ to obtain realistic values. It is interesting to notice that this is different as for the BSLJ, where the ductility factor will reduce the design force used to establish the drifts.

Basement and Foundations

The BSLJ includes special provision for the seismic force acting in basements. These need to be designed against the lateral seismic force of the medium-scale earthquake transferred from the superstructure plus approximately 0.1 times the basement's selfweight. Large-scale earthquakes are not considered in the design of the basements. This is mainly because no severe brittle failure of basements or foundations has been observed historically. As for the foundations, some special requirements pertaining their stability against sliding, overturning and local scouring when subjected to tsunamis are also included in the BSLJ.

The NBC allows two approaches for the foundation design. The first one is the traditional approach, where the foundation must have greater factored shear and overturning resistances than the lateral load capacity of the seismic force resisting system. As a second option, the foundation might be designed for rocking, and thus have less resistance that the lateral load resisting system, but several additional restrictions must be met. All footings must be tied together in two directions in zones of high seismic hazard, and the basement walls must be designed for seismic loads for all buildings except those located in zones of low seismic hazard.

Connections and Diaphragms

The BSLJ requires connections to be designed for higher forces than members. This is to prevent connection failure. In steel structures, the connections must be designed for 25% to 20% higher loads than the members that frame in.

For most buildings, diaphragms, including collectors, chords, struts and connections, must be designed to remain elastic during seismic events according to the NBC. The exception to this rule are low-rise buildings with steel deck roof or wood diaphragms that are designed and detailed to have a ductile behaviour.

CONCLUSIONS

Both the NBC and BSLJ are robust and reliable building codes. They specify significant levels of seismic activity, account for amplification of ground motion due to the local soil conditions and require ductile detailing for member design. Both codes require structural systems for high seismic regions that are robust and ductile. The BSLJ has evolved based largely on the large and frequent earthquakes that occur in Japan and has been tested in several of these events since it's introduction. The NBC, on the other hand, has relied on observed earthquake damage around the word and is updated roughly every five years to include state-of-the-art research. A major earthquake has still to test the NBC directly.

One key difference between the two analyzed codes is that the BSLJ explicitly considers two levels of earthquake demand, one for serviceability, and the other for life-safety. The BSLJ does not quantify the return periods of the two considered earthquakes. The NBC only considers the life-safety earthquake but has an explicit 2475-year return period. The BSLJ also requires a non-linear, displacement-based analysis of structures, whereas the NBC never requires a non-linear analysis.

Despite being an older code than the NBC, the pushover analysis required by the BSLJ explicitly considers the ductility of the structure. The NBC requirements for dynamic analysis focus on determining a more accurate linear distribution of forces, rather than an investigation of the true, non-linear behaviour. Non-linear analysis remains non-mandatory in most cases.

Another difference is that the BSLJ has a more nuanced application of ductility factors in analysis. The ductility factor varies from floor to floor and considers how the different components of the lateral load resisting system interact. The NBC simply requires that the ductility be determined based on the type of seismic force resisting system. If more than one system is used, the lower ductility of them must be taken.

As for irregularities and eccentricities, the BSLJ clearly acknowledges the fact that these can lead to a significantly worse performance by increasing the seismic force by up to 150% if irregularities are present. The NBC, on the other hand, while explicitly considering accidental torsion and imposing additional restrictions for irregular buildings, never requires such a marked increase.

Storey drift limits are not directly comparable between the codes since they are applied to earthquakes of different intensities. The BSLJ sets two distinct drift limits: one for service limit states under moderate earthquakes, and another one to avoid P-delta effects for large-scale earthquakes. The NBC, on the other hand, has different limits depending if the building is required to remain functional after an earthquake or not, but all for a single, large-scale earthquake.

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