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Evolution of the NBCC seismic provisions for operational and functional components in buildings

Rola Assi and Ghyslaine McClure

Rola Assi¹, École de Technologie Supérieure, Department of Construction Engineering, 1100, Notre-Dame West, Montreal, Québec, Canada, H3C 1K3.

Ghyslaine McClure, McGill University, Department of Civil Engineering and Applied Mechanics, 817 Sherbrooke Street West, Montreal, Québec, Canada, H3A 2K6.

¹Corresponding author (e-mail: rola.assi@etsmtl.ca, Tel: (514) 396-8492, Fax: (514) 396-8584)

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Abstract: This paper provides a summary of the evolution of the Canadian seismic design provisions for operational and functional components (OFCs) in buildings. The evolution of horizontal seismic force and displacement requirements in the National Building Code of Canada is presented and significant changes and parameters are discussed. Numerical examples illustrate the seismic design force levels as stipulated in recent editions of the NBCC for architectural, mechanical and electrical components attached at different elevations to buildings located in moderate and high seismic zones in Canada. Also, the seismic design force levels, computed according to different editions of the NBCC, are compared for a mechanical component and for an architectural component attached to buildings located in Vancouver.

Key words: Operational and functional components, non-structural elements, National Building Code of Canada, seismic force, seismic acceleration, seismic displacement, seismic risk

Résumé: Cet article résume l'évolution des normes canadiennes pour la conception parasismique des composants fonctionnels et opérationnels (CFO) des bâtiments. L'évolution des exigences du Code National du Bâtiment canadien quant aux forces sismiques horizontales et aux déplacements différentiels est présentée et les principaux paramètres et changements sont discutés. Des exemples numériques illustrent les niveaux de forces sismiques, tel que stipulé dans les éditions récentes du CNBC, pour des composants architecturaux, mécaniques et électriques. Une comparaison de ces forces sismiques, calculées selon les différentes éditions du CNBC, est présentée pour le cas précis d'un composant architectural et d'un composant mécanique attachés à des bâtiments situés à Vancouver.

Mots-clés: composants opérationnels et fonctionnels, éléments non-structuraux, Code National du Bâtiment canadien, force sismique, accélération sismique, déplacement sismique, risque sismique.

Introduction

A building comprises various components that can be divided into two groups: structural components and operational and functional components (OFCs). The OFCs are those systems and elements housed or attached to floors, roofs, and walls of a building or industrial facility. Although they are not part of the main or intended load-bearing structural system, OFCs may still contribute to the structural integrity of the building, depending on their location, type of construction, and method of fastening. Some of the alternative names by which these systems are known are: non-structural components or elements, secondary systems, and building attachments. According to Chen and Soong (1988), secondary systems (that is OFCs) can be classified into non-structural secondary systems and structural secondary systems. For the latter type, concern is not only to their seismic behaviour, but also to their dynamic interaction with the primary structural system. Operational and functional components can generally be divided into three categories of sub-components according to CSA S832 (CSA 2014) and Villaverde (1997): architectural (*internal* like interior partition walls, ceilings and lighting fixtures and *external* like cladding and parapets), building or operational services including plumbing systems (like piping and sprinklers), mechanical systems (like heating, ventilation and air conditioning systems, and elevators), electrical systems (like electric generators, transformers, and battery racks), information technology and telecommunications (like telephone system, communication system, and cable trays) and building contents (*common* like supplies, computer systems, record storage, and *specialized* like fine arts, medical equipment and hazardous laboratory or medical materials). Globally, OFCs account for 75-85% of the original construction cost in commercial buildings as illustrated in Figure 1 (Miranda and Taghavi 2003). Therefore, their failure in an earthquake can not only result in important direct financial losses, but can significantly disrupt the function of the

building and pose a safety risk to building occupants and passersby: OFCs are far from being secondary in importance when it comes to seismic risk analysis. A review of the typical damage sustained by various OFCs in recent earthquakes (including reviews by McKevitt et al. 1995; Kao et al. 1999; Naeim 1999; Naeim 2000; Filiatrault et al. 2001; Achour et al. 2011; Miranda et al. 2012) highlights the fact that the dysfunction/failure of OFCs is the greatest contributor to damage, losses and business interruption in most facilities. The vulnerabilities of OFCs in modern buildings were not clearly exposed until the M_w 9.2 March 27, 1964 Alaska and M_w 6.6 February 9, 1971 San Fernando earthquakes (Lagorio 1990). Experience has shown that in moderate earthquakes (1994 M_w 6.7 Northridge earthquake, CA; 2003 M_w 6.5 San Simeon earthquake, CA; 2009 M_w 6.3 L'Aquila earthquake, Italy; 2011 M_w 6.7 Christchurch earthquake, NZ), damage to critical equipment and contents is typically more important than damage to structural framework in buildings that abide by seismic code requirements. In active seismic zones, strong aftershocks exacerbate OFC damage.

In recent years, engineers, researchers, and building code committees have paid increasing attention to the seismic performance of secondary systems attached to primary building structures. Earthquake-resistant design of building structures is now a relatively mature discipline, and the seismic behaviour of OFCs is now considered a major factor to be accounted for while assessing the overall building performance and functionality. As a result, the seismic requirements for non-structural elements in the 2005 and 2010 editions (and the upcoming 2015 edition) of the NBCC are more detailed than in previous editions and include explicit provisions for more specific items (more categories of elements) that apply to facilities that require post-earthquake functionality. The evolution of the NBCC seismic provisions for OFCs will be discussed in the following sections: it should be further noted that no significant changes have

been implemented in the forthcoming 2015 edition of NBCC in terms of calculation of seismic force demand so that the 2010 edition can be considered as current.

Evolution of the NBCC seismic design provisions for OFCs in new buildings

This review of the recommended provisions in the different editions of NBCC is intended to reveal the variations in seismic design requirements for OFCs. Seismic design practice in Canada and in other countries has evolved significantly over the past seventy years, after the Second World War.

The first edition of the NBCC appeared in 1941 (NRCC 1941); it contained seismic provisions only in an appendix, based on the concepts presented in the 1937 United States Uniform Building Code (UBC) (Heidebrecht 2003). However, specific provisions for seismic design of structural components and OFCs in buildings and essential facilities were first introduced only in the 1953 edition. In all editions of the NBCC, the provisions concerning the OFCs are given in Part 4 (currently Division B) and Commentary J in the supplement of Part 4 (currently called the User's Guide).

1953 to 1965

Seismic force requirements

In the 1953, 1960 and 1965 editions of NBCC (NRCC 1953, 1960, 1965), the seismic zoning map divided the country into four seismic regions based on earthquakes having a return period of 100 years (i.e. probability of 0.01 per annum). The minimum horizontal force for which portions of a building or structure should be designed to resist is given by:

$$[1] \quad V_{1953,1960} = CW$$

Where V is the lateral seismic force in pounds, W is the total dead load tributary to the point where the earthquake force is to be calculated, including machinery and other fixed concentrated loads, C is a constant specified in the code for the part of the building being considered. The values of C are minimum and correspond to zone 1; they should be multiplied by 2 for zone 2 and 4 for zone 3. The minimum values of C that correspond to zone 1 vary between 0.05 and 0.25.

This simple equation was then refined in the 1965 edition to include more parameters to describe the C coefficient of Equation (1):

$$[2] \quad V_{1965} = \max(2K; 0.2Rg) * W$$

Where $K = RCIFS$.

K takes into account the intensity of the earthquake in the area considered (R), with values of 0, 1, 2, and 4 for seismic zones 0, 1, 2, and 3 respectively; the type of construction (C), with values of 0.75 for buildings having moment resisting frames or reinforced concrete shear walls and 1.25 for all other types of buildings; the importance of the building (I), with values of 1.3 for buildings having large assembly occupancies or which are important for well-being such as hospitals and power stations and 1.0 for all other buildings; the foundation conditions (F) with values of 1.5 for buildings on highly compressible soil and 1.0 for all other sub-soil conditions; and the number of stories N of the building through the factor S where $S = 0.25/(9+N)$.

These early editions of NBCC covered only the architectural components, towers, chimneys and tanks. In both the 1953 and 1960 editions, the same seismic force requirements apply to all building components (structural and non-structural), while the requirements of the 1965 edition are introduced in a separate clause and are more stringent for architectural components and

curtain walls than for structural components by introducing the factor of 2, which means that the seismic lateral force for OFCs is twice the force for structural components.

Starting from the 1965 edition, dynamic analysis was mentioned as an alternative to simple static analysis for earthquake-resistant design. However, no details were provided about the definition of dynamic analysis methods.

Also, in these early editions of NBCC, the OFC seismic risk was not associated with a probability level.

Seismic displacement requirements

In these early editions of the NBCC, there were no provisions related to displacements.

1970

Seismic force requirements

The 1970 edition of NBCC (NRCC 1970 a, b) introduced a more refined seismic contour map of the country based on expected ground accelerations having a return period of 100 years. The new map was based on the analysis of past earthquakes (1899-1963) throughout the country. Building parts and portions (this is when the subscript p was introduced) and their anchorage to the supporting structure were then required to be designed for a minimum lateral force given by:

$$[3] \quad V_{1970} = \frac{1}{4} RC_p W_p$$

Where W_p is the weight of the part or portion of a structure, such as cladding, wall partitions and appendages; R is the seismic regionalization factor, which is a measure of the seismic activity and hazard in the area considered (it is equal to 4 in zone 3, 2 in zone 2, 1 in zone 1 and 0 in zone 0); and C_p is the horizontal force factor for the part or portion of the structure (varying from 0.1

to 2). Interestingly, the importance of the building, introduced with the I factor in 1965 was not considered for OFCs in this later edition.

In the commentary to the 1970 edition, it was noted that machinery and electrical/mechanical components mounted within buildings should be designed to withstand the forces and displacements that arise from the seismic response of the structure, but no further specific provisions were given.

Seismic displacement requirements

In this edition, although there were no specific provisions for seismic displacement, it was recommended in the commentary that the interstory drift be limited to $0.005 h_s$, where h_s is the story height. It was also noted there that the deflections obtained from an elastic (static) analysis using the lateral force determined in Equation (3) should be multiplied by 3.

1975 and 1980

Seismic force requirements

In these editions of NBCC (NRCC 1975a, b, 1980a, b), the same zoning maps as of the 1970 edition were used. A new equation was proposed for the minimum seismic lateral force for buildings parts and their anchorage:

$$[4] \quad V_{1975,1980} = AS_p W_p$$

Where A is the acceleration ratio or assigned horizontal design acceleration as a fraction of g, assumed constant over each seismic zone; and S_p is the horizontal force factor for the part or portion of the building.

It is in these NBCC editions that specific S_p factors for machinery and electrical/mechanical components mounted within buildings were introduced for the first time. The range of variation

of the factor was from 1.0 to 25. The building importance factor was not taken into account in this edition. The type of OFC connection to the structure, flexible or rigid, was not considered either.

Seismic displacement requirements

The requirements were unchanged from the 1970 edition.

1985

Seismic force requirements

In the 1985 edition of NBCC (NRCC 1985a, b), new seismic zoning maps were introduced, dividing the country into seven acceleration and velocity related zones. The new maps were based on a much lower probability of exceedence, 10% in 50 years (i.e. 0.0021 per annum compared to 0.010 in previous editions). In this edition, the minimum lateral force for which buildings parts and their anchorage shall be designed is given by:

$$[5] \quad V_{1985} = v S_p W_p$$

Where v is the zonal velocity ratio expressed as a ratio of the specified zonal horizontal ground velocity to 1 m/s; and S_p is the horizontal force factor for the part or portion of a structure. Higher S_p factors were introduced for machinery, equipment and pipes that are not rigid or rigidly connected, varying from 0.9 to 11, while the type of connection was not addressed in the previous editions of NBCC.

Seismic displacement requirements

The same requirements of the 1970 edition of NBCC were used.

1990

Seismic force requirements

The same zoning maps as in the NBCC 1985 edition were used (NRCC 1990a, b) and the equation to calculate the lateral seismic force demand was unchanged as well:

$$[6] \quad V_{1990} = \nu S_p W_p$$

However, there were refinements in the evaluation of the horizontal force factor, S_p , for various types of components. For architectural components, the values of S_p vary between 0.7 and 6.5, while for mechanical/electrical components an equation is introduced as:

$$S_p = C_p A_r A_x,$$

where A_x is the amplification factor at floor level x to account for variation of response of the mechanical/electrical component according to its location along the building elevation; A_x is equal to $(1 + h_x/h_n)$ where h_x , h_n are the heights above ground at levels x or n respectively (level n is the roof level); the maximum value of A_x at roof level is 2.0; A_r is the response amplification factor to account for the type of attachment of mechanical/electrical component, it is equal to 1.0 for components that are both rigid and rigidly connected, 2.0 for flexible components or flexibly mounted components located on ground, and 4.5 for all other cases; C_p is the seismic coefficient for mechanical/electrical components, which varies from 0.7 to 1.5.

In this edition, the provisions for mechanical/electrical components are more elaborate and rational than in previous editions, namely with the introduction of the A_r and A_x factors. The provisions for architectural components remained practically unchanged except for the increase in the S_p values.

Seismic displacement requirements

A major change was introduced for so-called post-disaster buildings such as hospitals, police and fire stations, and other buildings related to public safety that must remain functional during and immediately after an earthquake with a $0.01 h_s$ limit on the interstory drift at any level, based on the lateral deflections obtained from linear elastic analysis. The value of $0.02 h_s$ remained unchanged for all other buildings. Instead of specifying a fixed value of 3.0 to multiply the lateral deflections obtained from elastic analysis, as stipulated in the previous edition, a factor R was introduced to give more realistic values of anticipated deflections. R reflects the capacity of the structure to dissipate energy through inelastic behavior, and suggested values varied from 1.0 to 4.0.

1995

The NBCC 1995 (NRCC 1995a, b) had the same earthquake design hazard levels and the same zoning maps as its previous edition.

Seismic force requirements

The provisions for building parts and portions are similar to those of the 1985 edition of NBCC, which introduced a distinction in force requirements for architectural components and for mechanical and electrical equipment. The lateral force, V_p , is taken as :

$$[7] \quad V_p = \nu I S_p W_p \quad \text{For architectural components}$$

$$[8] \quad V_p = \nu I C_p A_r A_x W_p \quad \text{For mechanical/electrical components}$$

The importance factor I is introduced again, to establish compatibility of design risks with the structural system of post-disaster buildings ($I=1.5$) and schools ($I=1.3$). A_r is equal to 1.0 for

components that are both rigid and rigidly connected and for non-brittle pipes and ducts, 1.5 for components located at ground level that are flexible or flexibly connected except for non-brittle pipes and ducts and 3.0 for all other cases.

The seismic design forces in the 1995 edition differ from the earlier editions of the NBCC due to several reasons (Tauby et al. 1999): 1) earthquake, geological, and tectonic information was analyzed using a new seismic risk approach; 2) newly developed strong ground motion attenuation relations were included; and 3) both horizontal acceleration and horizontal velocity have been considered.

Seismic displacement requirements

The requirements in the 1995 edition are the same as those given in the 1990 edition.

2005 and 2010

The formulation of the 2005 and 2010 provisions (NRCC 2005a,b; NRCC 2010a,b) for OFCs is based on the uniform hazard spectrum approach used for the design of structures (Adams and Halchuck 2003; Adams J. and Atkinson G. 2003). The new uniform hazard spectrum model and resulting maps account for soil type and near-fault effects since they incorporate a significant amount of new earthquake data, recent research on source zones and earthquake occurrence, together with complementary research on strong ground motion relations. In contrast to the 1985 maps, which gave values for peak horizontal ground velocity and peak horizontal ground acceleration, peak horizontal spectral acceleration values ($S_a(T)$; 5% damped) are now directly specified, where T is the period of the building structure. The seismic hazard at the site of the structure is included in the design force formula through the spectral acceleration value $S_a(0.2)$, which is taken from the uniform hazard spectrum at 0.2s period. It is assumed that most non-structural components in buildings are stiff or rigid (which is far from true in many instances),

and research from past earthquakes has shown that the forces on such components correlate most closely with this $S_a(0.2)$ acceleration ordinate (NEHRP 2009).

The 2005 and 2010 provisions use site values for design instead of zone values as used in previous editions of NBCC. They are based on a probability of exceedence of 2% in 50 years (instead of 10% in 50 years in previous editions), corresponding to a return period of approximately 2500 years. Site class C (very dense soil or soft rock) was adopted as a reference for reasons summarized in Adams and Halchuck (2003).

Seismic force requirements

These provisions (currently in effect) use the same generic equation to describe the lateral force requirements for architectural components and for mechanical and electrical components. Elements and components of buildings and their connections shall be designed for a lateral force V_p given by:

$$[9] \quad V_p = 0.3F_a S_a(0.2) I_E S_p W_p$$

Where F_a is the acceleration-based site coefficient that varies from 0.7 to 1.4. It is function of site class and $S_a(0.2)$; $S_a(0.2)$ varies from 0.12 (Inuvik) to 1.2 (Victoria). I_E is the importance factor for the building and it can take values of 1, 1.3 or 1.5. The same equation for horizontal force factor, S_p , is now introduced for all component types:

$$S_p = C_p A_r A_x / R_p .$$

The maximum value of S_p is 4.0 and its minimum value is 0.7. C_p is the element or component factor specified for different types of components. It considers the risk to life safety associated with failure of the component and release of contents if applicable; C_p varies from 0.7 for low risk and 1.5 for high risk. R_p is the element or component response modification factor that is

introduced for the first time to account for the energy-absorption capacity of the element and its attachment; R_p varies from 1.25 to 5. A_r is the element or component force amplification factor to account for possible dynamic tuning between the building and the component, and is function of the ratio of the natural frequencies of the component and the structure; A_r varies from 1.0 to 2.5. A_x is the height factor; a linear amplification of acceleration through the height of the building is assumed such that A_x is equal to $(1 + 2h_x/h_n)$. It should be noted that the maximum value of A_x at rooftop level is now 3.0 compared to the value of 2.0 in the 1995 edition of NBCC. In this edition, the height factor is considered for the first time for architectural components.

Seismic displacement requirements

Some refinements have been introduced compared to 1995. While the largest interstory drift at any level based on the lateral deflections obtained from linear elastic analysis is still limited to $0.010 h_s$ for post-disaster buildings ($I_E = 1.5$), the revised provisions indicate a new limit of $0.02 h_s$ for schools ($I_E = 1.3$) and a more relaxed limit of $0.025 h_s$ for all other buildings of normal importance ($I_E = 1$). The lateral deflections obtained from an elastic analysis are to be multiplied by $R_d R_o / I_E$ to give realistic values of anticipated deflections, where R_o is the force overstrength factor (varying between 1.0 and 1.7 depending on the lateral load resisting system) and R_d represents the energy dissipation capacity of the element or its connections (varying between 1.0 and 5.0 depending on the lateral load resisting system).

Comparison of the seismic force requirements for the 2005/2010 and the 1995 editions of the NBCC

In the following, we present design forces for mechanical/electrical components, and for architectural components in a normal importance category building ($I_E = 1$) located in Vancouver

(high seismic zone) and Montreal (moderate seismic zone) according to the 1995, 2005 and 2010 editions of the NBCC, so that one can assess the impact of code changes on the seismic design force levels at specific locations. The indicator is the ratio of the lateral seismic force, V_p , to the component weight, W_p . The values are taken at ground level, middle and rooftop of a regular four-storey building.

Mechanical/electrical components

The NBCC 2005/2010 and 1995 provisions give close values for V_p/W_p ratio at the ground floor level for mechanical/electrical components located in Vancouver and Montreal (Figures 2a and 3a). At the upper floor levels, the 1995 seismic design forces are higher than the 2005/2010 forces for most components, especially in Vancouver (Figures 2b and 2c), except for rigid/rigidly attached components. In Montreal (Figures 3b and 3c), the forces are similar at the mid-height and rooftop of the building, except for rigid/rigidly attached components.

Architectural components

The NBCC 1995 seismic design forces of architectural components are higher than those of the 2005/2010 editions at ground level for all components in both Vancouver and Montreal seismic zones (Figures 4a and 5a). The difference is less noticeable at the rooftop level, especially in Montreal, except for cantilevered components (Figures 4b and 5b).

It is seen that the NBCC 1995 provisions yield conservative forces for architectural components at ground level, especially in high seismic zones, whereas this conservatism is less considerable and not systematic at the upper levels, particularly in moderate seismic zones. Therefore, the conservatism in the 1995 NBCC provisions for architectural components is somewhat proportional to the seismic hazard level.

Numerical examples for calculation of seismic forces according to (1970-2010) editions of the NBCC

In order to illustrate the evolution of the NBCC seismic force requirements for the OFCs over the years, forces were computed for an architectural component and a mechanical component assumed to be attached to buildings located in Vancouver that is considered a high seismic zone for Canada.

Architectural component

This example of architectural OFC is a suspended acoustic ceiling system rigidly connected to the structure of an office occupancy building ($I_E = 1$), it is the same component as used in Figures 4 and 5. Calculations were done at the ground floor and the rooftop levels. Figures 6a & 6b show that the variation in the force requirements was not uniform over the years, and, as mentioned before, the latest editions of NBCC 2005/2010 are less stringent for architectural components, especially at the ground floor. The variation in the force levels in the early editions is mainly attributed to the variation in the S_p values in different versions of NBCC, where conservative S_p values were initially proposed in order to cover a wide range of components. Starting from 1995, reduced S_p values were proposed specifically for suspended ceilings; this is a counterintuitive trend as several major recent earthquakes have triggered numerous failures of suspended ceiling systems.

Mechanical component

This example is a rooftop chiller on vibration isolators (flexible connection) attached to the rooftop of a hospital ($I_E = 1.5$), it is the same component as used in Figures 2 and 3 but with a different importance factor for the building. Figure 7 shows that the variation in the force requirements was not uniform over the years. Until 1980, no distinction was made between rigid

and flexible components; therefore, the forces were conservatively increased through the different editions. The decrease in the force level in 1985 is attributed to lower acceleration and S_p values. Higher design force levels in 1990 and 1995 are attributed to the introduction of the height and importance factors in the equation. Even though there was an increase in the height amplification factor in the 2005/2010 provisions, seismic force levels are lower than those of the 1995 provisions due to the introduction of R_p factors that account for the ductility and overstrength, the nonlinear OFC response is reflected by the upper limits for S_p , and lower A_r factors.

Conclusion

In this paper, the authors surveyed the evolution of the NBCC seismic force and displacement requirements for mechanical, electrical and architectural components. Substantial differences between the seismic design requirements in different NBCC editions (1953-2010) were emphasized and numerical examples of two acceleration-sensitive components (a suspended acoustic ceiling and a rooftop chiller) were used to illustrate the variations in the design force levels over the years. These variations are not uniform, but have a decreasing trend starting from the 1990 edition since there were significant improvements in the equations used to compute the seismic forces. Some of the differences in the force calculations are also attributed to the variations in the design ground motion specified over several decades based on seismicity models of various degrees of sophistication. It is noteworthy to mention that ground motion specifications have also changed slightly between the 2005 and 2010 editions of the Code, for Eastern Canada in particular. More of these adjustments are also to appear in the 2015 edition. All in all, it is not evident to compare seismic force requirements when such parameters vary from one edition to the next. To get a better grasp of the variations in seismic force demands, a

comparison of seismic force levels for various acceleration-sensitive components was done between the 1995 and 2005/2010 NBCC provisions for a building assumed to be located in Vancouver and Montreal, to consider high and moderate levels of seismic activity, respectively. It was observed that the difference between the seismic force demands is more pronounced for architectural components (the suspended ceiling example) especially at the ground level. On the other hand, the difference is not significant for mechanical/electrical components attached to buildings located in moderate seismic zones, while this difference becomes noticeable in high seismic zones, especially for components attached above the ground floor.

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