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New Provisions in the National Building Code of Canada 2020 related to ‘No Structural Damage’ Earthquake Performance Requirements for Certain Buildings at Certain Hazard Levels

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ABSTRACT

The latest version of the National Building Code of Canada, the 2020 edition, was released in early 2022. New provisions were added in the ‘Earthquake Loads and Effects’ portion of the code, regarding additional performance requirements for Post-Disaster buildings, High Importance category buildings, and a subset of Normal Importance category buildings.

Prior to NBC 2020 (in the NBC 2015) all buildings were to be designed for only one earthquake level, based on a 2% probability of exceedance in 50 years. The performance objective for Normal Importance buildings is to ‘minimize loss of life’ (i.e., life safety) with the understanding that there could be extensive damage. The use of importance factors and reduced drift limits for High Importance and Post-Disaster buildings is to address performance objectives of ‘immediate occupancy’ and being ‘functional’, respectively. These requirements remain in NBC 2020 for the noted earthquake level.

The new provisions in NBC 2020 provide design requirement for other earthquake levels. The provisions require Post-Disaster buildings and High Importance buildings in defined hazard areas to ‘behave elastically’ with a performance objective of ‘no structural damage’ for earthquake demands based on a 5% probability of exceedance in 50 years and 10% probability of exceedance in 50 years, respectively. Reduced drift limits and additional requirements for connections of non-structural components are also specified. The new provisions require Normal Importance buildings more than 30-m high in defined hazard areas to have structural framing elements not considered to be part of the Seismic Force Resisting System to ‘behave elastically’ with a performance objective of ‘no structural damage’ for earthquake demands based on a 10% probability of exceedance in 50 years.

This presentation provides further details about the new provisions and provides some information on the building cost impact of these new provisions.

Keywords: Building Code, Higher Seismic Performance, New Buildings, Hazard Levels, Post-Disaster

INTRODUCTION

Article 4.1.8.23 was introduced in the latest version of the National Building Code of Canada with new provisions to achieve higher seismic performance for new buildings with importance categories of Post-Disaster, High-Importance, and a subset of Normal Importance buildings in defined areas of the country based on the level of seismicity (different areas for each category of buildings) [1]. Buildings categorized as Post-Disaster and High Importance must have all structural elements behave elastically and must meet reduced drift limits when subjected to lower intensity ground motions that occur more frequently than the design ground motion (DGM) defined in the NBC 2020. There are also requirements for most connections of elements and components to behave elastically when subjected to the lower intensity ground motions. The DGM has a 2% probability of exceedance in 50 years, while the additional performance requirements are for ground motions having a 5% and 10% probability of exceedance in 50 years, for Post-Disaster and High Importance category buildings, respectively.

Article 4.1.8.23 also introduces additional performance requirements for Normal Importance category buildings with a height above grade of more than 30 m and located in certain areas. For these buildings, only the structural framing elements not considered part of the Seismic Force Resisting System (SFRS) are required to be investigated and shown to behave elastically when subjected to ground motions having a 10% probability of exceedance in 50 years. For these buildings there are no reduced drift limits or specific requirements for connections of elements and components to behave elastically.

New buildings designed using seismic isolation or supplemental energy dissipation for the DGM, with a target to have all structural elements behave elastically, need no further assessment regarding this new Article.

DISCUSSION OF NEW PROVISIONS

Table 1 summarizes the additional performance requirements of Article 4.1.8.23. The table illustrates how the requirements differ for Post-Disaster buildings, High Importance category buildings, and the subset of Normal Importance category buildings.

The performance objective for Post-Disaster and High Importance category buildings subjected to the lower intensity, more frequently occurring ground shaking, with either 5% or 10% probability of exceedance in 50 years, is ‘no structural damage’ for the entire structure. This objective is intended to be achieved by requiring the entire building, including the SFRS and the structural framing elements not considered part of the SFRS, to behave elastically. A further objective is to reduce damage to elements of structures and non-structural components and equipment (also referred to as Operational and Functional Components, OFCs) for the lower intensity ground shaking, intended to be achieved by reducing the maximum interstorey drift limits from those allowed for the DGM; this is especially effective for drift-controlled OFCs.

The performance objective for the subset of Normal Importance Category buildings subjected to the lower intensity, more frequently occurring ground shaking, with 10% probability of exceedance in 50 years, is ‘no structural damage’ for the structural framing elements not considered part of the SFRS. This objective is intended to be achieved by requiring the structural framing elements not considered part of the SFRS, to behave elastically.

Table 1. Summary of Additional Performance Requirements in Article 4.1.8.23

Importance Category	**Seismic Category (1)**	**Earthquake Ground Motion Level (Probability of Exceedance)**	**Maximum Interstorey Drift**	**Items required to behave elastically**
Post-disaster	SC2, SC3, SC4	5% in 50 yrs.	$0.005h_s$	Building, including SFRS and structural framing elements not considered part of SFRS Connections of elements and components described in NBC 2020 Table 4.1.8.18 with $R_p > 1.5$ (3)
High	SC3, SC4	10% in 50 yrs.	$0.005h_s$	Building, including SFRS and structural framing elements not considered part of SFRS Connections of elements and components described in NBC 2020 Table 4.1.8.18 with $R_p > 1.3$ (3)
Normal, where height > 30 m	SC4	10% in 50 yrs.	(2)	Structural framing elements not considered part of SFRS

Notes:

(1) Seismic Category is determined using earthquake importance factor, I_E multiplying the design spectral accelerations, S(0.2) or S(1.0), based on a probability of exceedance of 2% in 50 years. SC4 being the category with the highest product of I_E times S(0.2) or S(1.0), with SC3 and SC2 with progressively lower products.

(2) There is no interstorey drift requirement for Normal Importance Category *buildings* when subjected to ground motions with a probability of exceedance of 10% in 50 yrs.

(3) R_p is the element or component response modification factor, that varies from 1.0 to 5.0 for design per DGM

For most structures, the end of the elastic range occurs when the structure reaches its yield point or elastic strength limit. Thus, the requirement that a structure behaves elastically can be achieved by ensuring the structure has adequate elastic strength. More information on the definition of 'behave elastically' can be found in the Structural Commentaries to the NBC 2020 (to be issued in 2023).

NBC 2020 specifies a minimum R_d value (ductility-related force modification factor) of 2.0 for Post-Disaster and 1.5 or 2.0 for High Importance buildings to ensure a minimum amount of dependable ductility in these buildings. If an SFRS with a larger R_d is used for the DGM design of a Post-Disaster or High Importance category building, the building will have a larger ductility capacity (ability to dissipate more energy via damage); but unless the designer provides a higher strength than the minimum required for the R_d value, the building will also have a lower yield point or elastic strength limit.

Such a building designed with a large R_d is more likely to experience inelastic action at the DGM, which could result in damage to the SFRS and other parts of the structure. Such a building is also more likely to experience damage when subjected to lower intensity ground shaking. The additional performance requirements of Article 4.1.8.23 will result in a consistent high level of performance at the specified lower intensity, more frequently occurring ground shaking, regardless of which SFRS (and corresponding R_d) is selected for the building. A secondary effect of meeting the requirements of Article 4.1.8.23 is that, depending on the relative intensity of the DGM and the more frequently occurring lower intensity ground shaking with either 5% or 10% probability of exceedance in 50 years, the additional required strength will result in less inelastic behavior when the structure is subjected to the DGM, thereby reducing the damage (increasing the performance) of the structure at the DGM.

Different approaches can be used to meet the 'behave elastically' and drift control requirements of Article 4.1.8.23. An initial discussion is provided below.

The designer can select and design an SFRS for the DGM, and then check that the building has adequate strength to behave elastically and has adequate stiffness to meet the drift requirements of this Article. If required, the strength and stiffness of the selected SFRS are increased. This is similar to how the lateral force resisting system in a building is designed to have adequate stiffness and strength to resist wind forces (and behave elastically under wind demand), which may result in a SFRS that is stiffer and stronger than required to resist DGM seismic demands. The strength and/or the stiffness of the SFRS may be governed by wind demands or the additional performance requirements of Article 4.1.8.23, but all the seismic design requirements for the DGM must still be met. The level of additional strength that will be needed beyond that required for the DGM depends on the R_d value of the system. Providing an SFRS with a higher R_d and then providing the strength needed to meet the additional performance requirements will result in a structure that has extra ductility capacity for the DGM.

An alternate approach is to select an SFRS that has a lower value of R_d that still meets the minimum required for the DGM design ($R_d = 2.0$ for Post-Disaster buildings and $R_d = 1.5$ or 2.0 for High Importance buildings) such that less additional strength is required to satisfy the additional performance requirements to behave elastically. The stiffness of the selected SFRS must still be checked to ensure it meets the requirements of Article 4.1.8.23. The appropriate SFRS (R_d value) to use in this approach depends on the ratio of lateral earthquake forces due to the ground shaking with either 5% or 10% probability of exceedance in 50 years to the lateral earthquake forces due to the DGM. This varies at different locations in Canada and also varies based on site designation and the building period. Equations are provided in the Structural Commentaries to the NBC 2020 to assist with this alternate approach.

EXAMPLES RELATED TO ARTICLE 4.1.8.23

'The building shall be shown to behave elastically' means that all structural elements, including the SFRS, all structural framing elements not considered to be part of the SFRS, and all structural components such as diaphragms, collectors, chords, struts and connections that connect the structural elements, must behave elastically. Inelastic behavior generally involves damage to the structure. Thus, 'elastic behavior' is required in order to achieve the performance objective of 'no structural damage'.

Members of the SFRS and other structural elements and components shall be considered to behave elastically if the factored resistance using resistance factors (Ø) from the appropriate CSA material standards and the specified strength, including buckling resistance of the SFRS members, is equal to or exceeds the load in the member computed when the building is subject to the lower intensity ground motions with the load computed using R_dR_o =1.3 (see discussion regarding R_o later in this section). Further discussion follows.

For many elements and structures, a simple definition of behave elastically for a specified lateral earthquake force is that the calculated force on the element or structure is less than the strength. For the additional performance check at the lower intensity ground motions, it is appropriate to account for the dependable portion of strength rather than the factored resistance, which is significantly less. To simplify the design procedure and avoid having to calculate a second strength value (i.e., the dependable strength), a minimum overstrength ratio of 1.3 is included as the overstrength-related force modification factor R_o used to calculate the force demands at the lower intensity ground motions. That is, the requirement for the structure to behave elastically is met by comparing a reduced force demand calculated using $R_dR_o = 1.3$ ($R_d = 1.0$) with a reduced strength (i.e., the factored resistance) of the element or structure.

In addition to ensuring the calculated force on the element or structure is less than the factored resistance, consideration should be given to any special aspects of the particular type of structure, as discussed further below. A rigorous definition of behave elastically is that all linear and nonlinear deformations recover when the structure is unloaded; in reality, there may be some negligible residual deformations. By comparison, inelastic behavior results in appreciable residual deformations that do not recover when the structure is unloaded. Steel SFRSs with tension-compression braces may experience buckling of the braces in compression before the strength of the structure is reached, resulting in residual deformations of the structure. Thus, buckling of these braces should be avoided. For steel SFRSs with tension-only braces, buckling is acceptable provided that the braces remain elastic in tension. Cracking in concrete and masonry is acceptable so long as the crack widths are not too large and do not require repair (except for cosmetic purposes, or perhaps for corrosion protection). Large residual crack widths may occur if the element does not contain sufficient reinforcement, especially if the cracks are not perpendicular to the reinforcement such as is the case with diagonal shear cracks. Cracks are expected to remain small in structural elements and connections with good crack-control reinforcement as required in the CSA standards. Timber systems are more flexible than other systems and generally expected to behave elastically within the 0.5% drift limit. For light-frame wood shear walls, there may be some cracking of gypsum wallboard, stucco, or other finishes that would not be considered structural damage. For the other timber SFRSs, 0.5% drift is expected to cause minor crushing of wood around the fasteners and some fastener bending that should result in negligible residual displacement.

In Article 4.1.8.23, the specified lateral earthquake force is determined using $I_e = 1.0$. This is because with the requirement to 'behave elastically' at the 5% and 10% in 50-year level of ground shaking, it would not be appropriate to use an I_e value > 1.0, as is the case for the DGM design of Post-Disaster and High Importance buildings. For the DGM design of these buildings, the use of $I_e > 1.0$ provides a means to reduce the extent of inelastic behavior or damage of the ductile system selected. By contrast, there is no inelastic behavior expected when meeting the requirements of Article 4.1.8.23.

Figure 1 presents some graphs that illustrate the fundamental concepts related in Article 4.1.8.23 for both Post-Disaster buildings and High Importance category buildings. The graphs show the lateral force versus lateral displacement (drift) relationships for buildings relative to a linear response noted by the red dashed line, with the inelastic response noted by the grey dashed lines to the right of the red dashed line (elastic perfectly plastic behavior for illustration purposes). The vertical (force) axis of all graphs is shown in terms of the minimum "elastic" force for the DGM design determined with $R_dR_o = 1.0$ (and $I_e = 1.0$). This force, which is labelled $V_{e\text{-}DGM}$, depends on the location, site designation, and building period. The graphs are also shown with the minimum permitted stiffnesses resulting in the maximum permitted drifts. A comparison of the graphs provides information about the relative required strengths and relative required stiffnesses for DGM design and the additional performance requirements of Article 4.1.8.23.

For the purposes of the figure and the equations later in this paragraph, the subscript DGM is added to V determined for DGM design, and the subscripts 5% and 10% are added to V determined from Sentences in Article 4.1.8.23. Furthermore, the term "V_e" with the above noted subscripts is used to indicate "elastic demand" determined with $R_dR_o = 1.0$ (and $I_e = 1.0$).

Figure 1 (a) and (b) show, respectively, the force versus displacement relationships for High Importance category buildings and Post-Disaster buildings having the minimum stiffness resulting in the maximum permitted drift due to the DGM demand. The graphs also show the range of design points for the various SFRS acceptable for DGM design. There are 29 acceptable SFRS for post-disaster buildings with R_dR_o varying from 5 x 1.5 = 7.5 to 2 x 1.3 = 2.6 and 38 acceptable SFRS for High Importance buildings with R_dR_o varying from 5 x 1.5 = 7.5 to 1.5 x 1.3 = 1.95. The 'Design Range V_{DGM}' labelled in Figure 1 (a) and (b) indicates the range of required factored resistances for DGM design. The 'Performance Range' indicates the range of actual strengths of the SFRS calculated from the required factored resistances times R_o.

Figure 1 (c) and (d) illustrate, respectively, the design of a moderately ductile steel moment frame SFRS (R_dR_o = 3.5 x 1.5 = 5.25) in the Vancouver area, with a period of 1 sec, site designation X450 (a site with V_{s30} = 450 m/s), for a High Importance category building and Post-Disaster building. For such a High Importance category building, Figure 1 (c), the required factored resistance needed for the building to behave elastically for ground motions having a 10% probability of exceedance in 50 years ($V_{10\%}$) is 0.35 of the elastic demand due to the DGM ($V_{e\text{-}DGM}$), while the factored resistance required for DGM design (V_{DGM}(example)) is only 0.25 of the $V_{e\text{-}DGM}$. Thus, a 0.35/0.25 = 1.4 times larger factored resistance is required to meet the additional performance requirements of this Article than is required for DGM design. The slope of the load-deflection relationship is the minimum stiffness of the structure in order to meet the interstorey deflection requirements of this Article. Comparing the slopes in Figure 1 (a) and (c) indicates that a significantly larger stiffness of the SFRS is required to meet the additional performance requirements of this Article compared to what is required for DGM design. For the Post-Disaster building, Figure 1 (d) indicates $V_{5\%}$ is 0.52 $V_{e\text{-}DGM}$ compared to V_{DGM}, which is 0.29 $V_{e\text{-}DGM}$. In this case, a 0.52/0.29 = 1.8 times larger factored resistance is required to meet the additional performance requirements of Article 4.1.8.23. The slope of the line in Figure 1 (d) is only slightly larger than the slope of the line in Figure 1 (b), indicating that only a slightly larger stiffness is required to meet the interstorey deflection requirements of Article 4.1.8.23 compared to DGM design.

Figure 1 (e) and (f) illustrate the design of a moderately ductile steel moment frame SFRS (R_dR_o = 3.5 x 1.5 = 5.25) in the Montreal area, with a period of 1 sec, site designation X450, for a High Importance category building and post-disaster building. For the High Importance category building, Figure 1 (e), $V_{10\%}$ is 0.25 $V_{e\text{-}DGM}$ and V_{DGM} is 0.25 $V_{e\text{-}DGM}$. That is, the same factored resistance is required for the DGM design and the additional performance requirements of Article 4.1.8.23. The slope of the line in Figure 1 (e) is slightly larger than the slope of the line in graph (a) indicating that only a slightly larger stiffness is required to meet the interstorey deflection requirements of Article 4.1.8.23 compared to DGM design. For the Post-Disaster building, Figure 1 (f), $V_{5\%}$ is 0.42 $V_{e\text{-}DGM}$ and V_{DGM} is 0.29 $V_{e\text{-}DGM}$. Thus, a 0.42/0.29 = 1.45 times larger factored resistance is required to meet the additional performance requirements of Article 4.1.8.23. The slope of the line in Figure 1 (f) is only slightly larger than the slope of the line in Figure 1 (b) indicating that only a slightly larger stiffness is required to meet the interstorey deflection requirements of Article 4.1.8.23 compared to DGM design.

In Figure 1 (c), (d), (e) and (f), the specified lateral earthquake forces $V_{5\%}$ and $V_{10\%}$ were determined by dividing the elastic demands $V_{e\text{-}5\%}$ and $V_{e\text{-}10\%}$ by the minimum overstrength-related force modification factor R_o = 1.3. The rationale behind this number is provided in the Structural Commentaries to the NBC 2020.

The Structural Commentaries to the NBC 2020 also provide examples of the effect of Article 23 on connection forces for OFCs. Whether or not the forces per Article 4.1.8.23 exceed those for the DGM design depends on the location, site designation, and OFC type.

Furthermore, the Structural Commentaries to the NBC 2020 provide guidance regarding modelling of buildings that ‘behave elastically’ as compared to modelling for DGM design, and guidance regarding what aspects of provisions for DGM design need to be considered or adjusted.

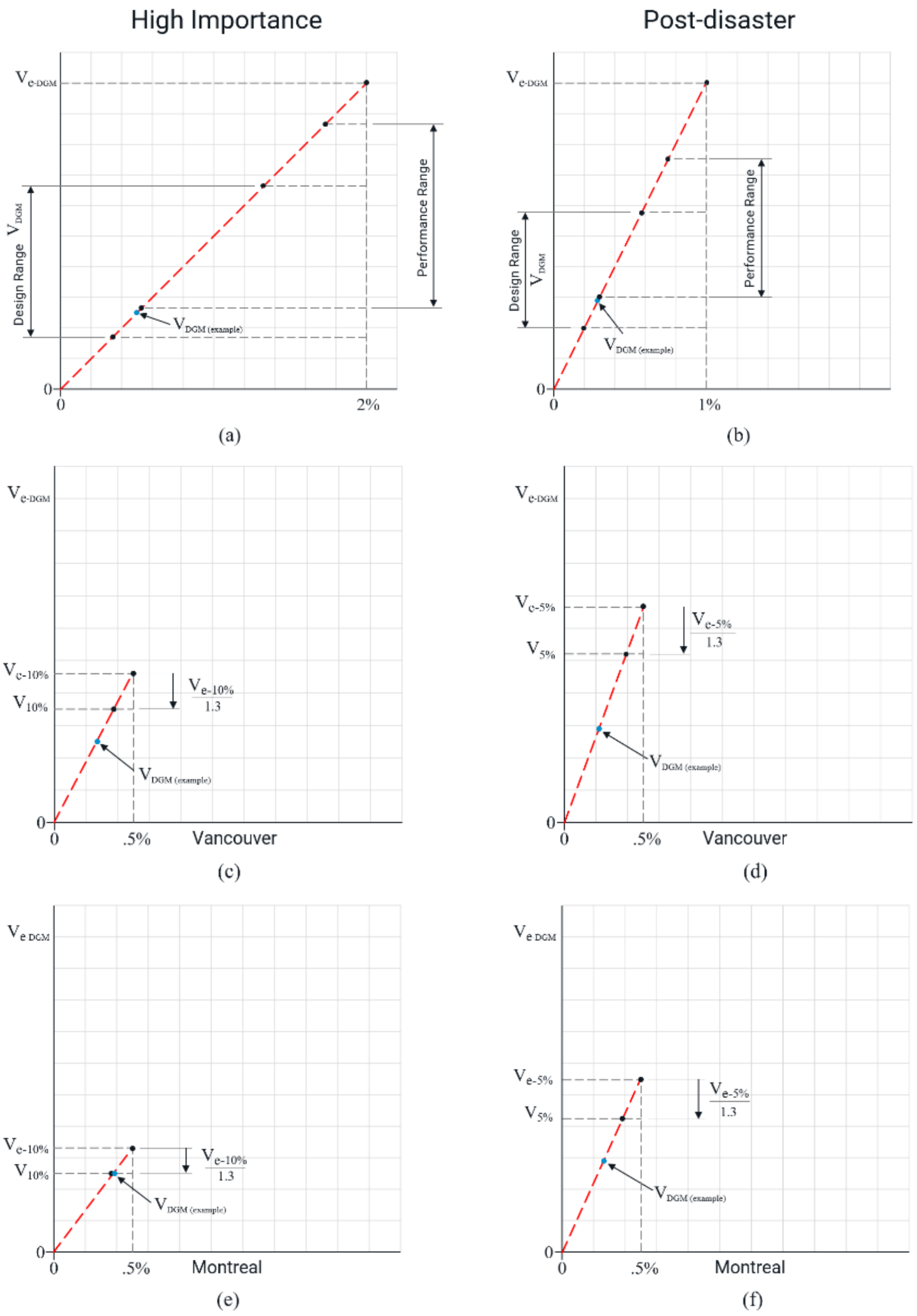

Figure 1. Lateral force versus lateral displacement (drift) relationships illustrating the additional performance requirements for High Importance category buildings (left) and Post-disaster buildings (right): (a) and (b) design for DGM; (c) and (d) design for additional performance requirements for buildings with SFRS having $R_dR_o = 3.5 \times 1.5 = 5.25$ located in Vancouver; (e) and (f) same buildings located in Montreal.

COST IMPLICATIONS OF ARTICLE 4.1.8.23

When the provisions for Article 4.1.8.23 were being developed, a cost impact analysis was carried out. This analysis included consideration of the following (a partial list provided here): locations in Canada that are SC2 or SC3 or SC4; what percentage of new buildings in those areas are Post-Disaster and High Importance category; assumed that all High Importance buildings are low rise buildings; estimated a blend of low-rise and mid-rise buildings for Post-Disaster buildings; used a structural cost as percentage of total building cost, specific and different for High Importance buildings and Post-Disaster buildings; used an SFRS cost as a percentage of structural cost, again specific and different for High Importance buildings and Post-Disaster buildings; and allowed for no cost increase related to the requirements for Normal Importance buildings. This analysis included input by a cost consultant, analyses regarding Normal Importance buildings, and detailed assessment of several buildings in both western and eastern Canada. The analysis also assessed the incremental cost to new buildings for enhanced connections for OFCs for High Importance category and Post-Disaster buildings.

As one would expect, the incremental cost for a specific building will depend on the location, site designation, building period and design approach for the DGM design. As part of the cost impact analysis, for a High Importance category building located in the south-west of Vancouver Island (highest seismic hazard in Canada) the increase in total building cost was approximately 2%. For a High Importance category building located in the Ottawa region (lower seismic hazard) the increase in total building cost was approximately 0.4%.

The analysis indicated that the cost impact, aggregated nationwide, was an increase of 0.11% of the total cost of new buildings.

CONCLUSIONS

The additional performance requirements of Article 4.1.8.23 will result in a consistent high level of performance at the specified lower intensity, more frequently occurring ground shaking, regardless of which SFRS is selected for the DGM design of the building. It will also result in less damage to deformation-controlled OFCs at the specified lower intensity, more frequently occurring ground shaking as well as targeting no damage to the OFC connections for certain building types.

DISCLAIMER

Information regarding Article 4.1.8.23 presented herein is based are extracts from the agenda and minutes of the meetings of the Standing Committee on Earthquake Design (SC-ED). The information has been modified for improving clarity by removing pending comments and notes. The final version of NBC 2020 Commentary J and text with regards to Article 4.1.8.23 may be different than that used in this paper; use information in this paper at your own discretion and at your own risk.

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REFERENCES

[1] Canadian Commission on Building and Fire Codes, National Research Council of Canada. (2022). “National Building Code of Canada 2020”. Volume 1. First Printing.