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SEISMIC FORCE MODIFICATION FACTORS (R_d & R_o) IN NATIONAL BUILDING CODE OF CANADA: TOWARDS A UNIFIED PROCEDURE

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Abstract

The equivalent static force procedure in the National Building Code of Canada (NBC) is based on the conversion of the complex nonlinear dynamic response of the seismic force-resisting system (SFRS) in a building structure into an equivalent linear static response of a single-degree-of-freedom system. The NBC prescribes a series of seismic requirements specific to a variety of aspects of building characteristics (e.g., configuration, building height, construction material, ductility level, and building use and occupancy). These seismic requirements are combined with the implementation of two seismic force modification factors, i.e. ductility-related seismic force modification factor, R_d, and overstrength-related force modification factor, R_o, aiming to achieve the life safety objective that is the primary consideration in the seismic design of buildings as per the NBC.

The evolution of the NBC over the past seven decades (since its first edition in 1941) has resulted in a significant expansion of code-approved SFRSs from a few systems in the 1970 edition of the NBC to 45 systems in the 2015 edition. In the 1970 edition of the NBC, a single factor K was incorporated in the design base shear calculation, which reflects the building characteristics such as the construction material, type of construction, and ductility behavior. K values range from 0.67 for buildings with ductile moment-resisting frames to 1.33 for buildings with box systems. This factor remained in the NBC until the introduction of the seismic force modification factor, R, in the 1990 edition of the NBC. Different R values were assigned to different SFRSs of various ductility levels. In general, the R value increases with the elevation of ductility level corresponding to more stringent ductility detailing requirements in the design of the SFRSs. The 2005 edition of the NBC split the R factor into two separate seismic force modification factors R_o and R_d with clear physical meanings. The determination of R_d and R_o factors for different SFRSs was largely based on judgment and qualitative comparisons with similar SFRSs, without using a unified procedure. For example, the approach used in the determination of R_d and R_o factors for a timber SFRS may be different from the approach used for a concrete SFRS. The current R_d and R_o values are expected to meet the life safety objective as per the NBC, but the lack of a unified procedure poses several problems, including (1) inconsistent levels of performance among structures built with different materials, (2) overly optimistic R_d and R_o factors for some SFRSs and unduly low for others, resulting in a low resilient and uneconomical design, (3) uncertainties with regards to the seismic performance of post-disaster buildings, which are critical for disaster preparedness and public safety, thus posing a potential risk to the communities that are prone to strong earthquake ground motions, and (4) difficulty for introducing new and innovative solutions for SFRSs.

In this paper, potential issues in the state of practice in Canada for determination of R_d and R_o factors are identified, in addition to an overview of the seismic provisions in different editions of the NBC with a focus on the evolution of seismic force modification factors for different SFRSs. A roadmap towards a unified procedure for determining R_d and R_o is presented following the identification of the issues due to the lack of such procedure. Finally, the key tasks to be accomplished for developing the unified procedure are outlined.

Keywords: ductility-related seismic modification factor; overstrength-related seismic force modification factor; seismic design; seismic performance; National Building Code of Canada

1. Introduction

The equivalent linear static procedure in the National Building Code of Canada (NBC) is based on converting the nonlinear dynamic response of the seismic force-resisting system (SFRS) in a building structure into the linear static response of an equivalent single-degree-of-freedom (SDOF) system. Equal displacement rule, which states that the peak inelastic displacement remains almost the same as the peak elastic displacement regardless of the yield strength or yield displacement, is used to determine the seismic force modification factor that is defined as the ratio of peak inelastic displacement to the peak yield displacement. The 2005 and newer editions of the NBC divides the seismic force modification factor into two separate seismic force modification factors with clear physical meanings: (1) ductility-related seismic force modification factor, R_d, which acknowledges the structural nonlinear capacity for inelastic energy dissipation; and (2) overstrength-related force modification factor, R_o, which represents the dependable portion of reserved structural strength in the design. The minimum design lateral force (i.e. base shear) is determined by dividing the elastic seismic demand of an equivalent SDOF system by the multiplication of R_d and R_o factors. The following section presents an overview of the seismic provisions in the NBC with a focus on the evolution of seismic force modification factors.

2. Evolution of Seismic Force Modification Factors in the NBC

The National Research Council Canada (NRC) published the first edition of the NBC in 1941 [1]. Since then, NBC was published periodically. Over the evolution of the NBC in the past seven decades, more and more comprehensive seismic provisions were adopted and enforced in the NBC and the Canadian Standards Association (CSA) standards for the design of steel, concrete, masonry, timber, and cold-formed steel structures [2-5]. The equivalent static force procedure has been the default seismic design procedure in the NBC for several decades until the 2005 edition of the NBC, which prescribed the dynamic analysis procedure as the default seismic design procedure. Nonetheless, the equivalent static force procedure is still permitted in the design of a variety of SFRSs that satisfy the limitations and restrictions prescribed in the NBC seismic provisions.

The concept of structural system was introduced in the seismic provisions of the 1970 edition of the NBC, in which structural systems were classified as follows: (1) ductile moment-resisting space frame, (2) dual system consisting of a complete ductile moment-resisting space frame and shear walls, (3) all framing systems except as hereinafter classified, and (4) box system. The factor, K, which reflects the material and type of construction, damping, ductility, and/or energy dissipation capacity, was used as a multiplier in the calculation of minimum design base shear. K values ranged between 0.67 for buildings with ductile moment-resisting space frames to 1.33 for buildings with box systems. The K factor remained the same in 1975, 1977, 1980, and 1985 editions of the NBC with the exception of rounding 0.67 for ductile moment-resisting space frames to 0.7. The K factor was replaced by the seismic force modification factor, R, in the 1990 edition of the NBC. The R factor reflects the capability of a structure to dissipate energy through inelastic behavior. The expected ductile behavior of buildings was achieved through the engorcement of seismic design and detailing requirements for different SFRSs. The 2005 edition of the NBC split the R factor into two separate seismic force modification factors: (1) ductility-related force modification factor (R_d) reflecting nonlinear structural capacity for inelastic energy dissipation, and (2) overstrength-related force modification factor (R_o) accounting for the dependable portion of reserved structural strength.

The 2015 edition of the NBC provides R_d and R_o values for 45 SFRSs with limitations and restrictions on the seismicity level, Site Class, building height, and building use and occupancy (e.g. post-disaster facilities). The minimum design lateral force and the expected performance of a building are dependent on R_d and R_o values specified for the SFRS in the building. Table 1 presents a summary of the seismic force modification factors for steel SFRSs in different NBC editions as an example.

Table 1 – Summary of seismic force modification factors for different steel SFRSs in different NBC editions as an example

Type of SFRS	2015		2010		2005		1995	1990
	R_d	R_o	R_d	R_o	R_d	R_o	R	R
Ductile moment-resisting frames	5	1.5	5	1.5	5	1.5	4	
Moderately ductile moment-resisting frames	3.5	1.5	3.5	1.5	3.5	1.5		
Limited ductility moment-resisting frames	2	1.3	2	1.3	2	1.3		
Ductile moment-resisting space frame								4
Moment-resisting frame with nominal ductility							3	
Moment-resisting space frame with nominal ductility								3
Ductile braced frame							3	3
Braced frame with nominal ductility							2	2
Moderately ductile concentrically braced frames								
Tension-compression braces	3	1.3	3	1.3				
Non-chevron braces					3	1.3		
Chevron braces					3	1.3		
Tension only braces	3	1.3	3	1.3	3	1.3		
Limited ductility concentrically braced frames								
Tension-compression braces	2	1.3	2	1.3				
Non-chevron braces					2	1.3		
Chevron braces					2	1.3		
Tension only braces	2	1.3	2	1.3	2	1.3		
Ductile eccentrically braced frames	4	1.5	4	1.5	4	1.5	3.5	3.5
Ductile buckling-restrained braced frames	4	1.2	4	1.2				
Ductile steel plate shear wall							4	
Nominally ductile steel plate shear wall							3	
Ordinary steel plate shear wall							2	
Ductile frame plate shear walls					5	1.6		
Moderately ductile plate shear walls					2	1.5		
Ductile plate walls	5	1.6	5	1.6				
Limited ductility plate walls	2	1.5	2	1.5				
Conventional construction of moment frames, braced frames, or shear walls					1.5	1.3		
Conventional construction of moment-resisting frames, braced frames, or plate walls								
Assembly occupancies	1.5	1.3	1.5	1.3				
Other occupancies	1.5	1.3	1.5	1.3				
Other steel SFRS(s) not defined above	1	1	1	1	1	1	1.5	1.5

As shown in the table above, in the 1990 and 1995 editions of the NBC, R values ranged from 2 to 4 for different types of steel SFRSs of different ductility levels (i.e., nominal and ductile) associated with different levels of stringency of seismic design and detailing requirements provided for design of the SFRSs. In general, the R value increases with the elevation of ductility level. The 2005 edition of the NBC divided the R factor into R_d and R_o factors with clear physical meanings. The definitions for different types of SFRSs were further refined in terms of ductility level (i.e., limited ductile, moderately ductile, and ductile), type of braces (e.g., tension-compression brace and chevron brace), and type of construction (e.g., conventional construction). Comparing with the R values for ductile SFRSs (e.g. ductile moment-resisting frame) in the 1995 edition of NBC, greater values of $R_d \cdot R_o$ were provided for ductile SFRSs in the 2005 edition of the NBC, indicating that larger inelastic capacity for energy dissipation is expected. It is recognized that significant improvements have been made in the seismic provisions for design of steel SFRSs in the 2005 edition of NBC based on the lessons learnt from previous major earthquakes in the 1990s, especially the 1994 Northridge earthquake. The seismic performance of ductile SFRSs designed as per the 2001 edition of the CSA standard for steel structures that was referenced in the 2005 edition of the NBC, however, has never been quantified in Canada. The increase of the values of $R_d \cdot R_o$ for different types of SFRSs was largely based on judgment and qualitative comparisons with the R values for similar SFRSs in the 1995 edition of the NBC. In the 2010 edition of NBC, a number of new steel SFRSs (e.g., buckling-restrained braced frames) were introduced, reflecting the state of practice in Canada in the design and construction of steel structures. The same approach for determining R_d and R_o factors in the 2005 edition of NBC was used to determine the R_d and R_o values for these newly added SFRSs. In the following sub-sections, key parameters affecting the values of R_d and R_o factors, i.e. seismic hazards and life safety objective in the NBC, are introduced and discussed.

2.1 Five Generations of Seismic Hazards for Canada

Seismic hazard forms the basis for the seismic design provisions in the NBC since its original publication in 1941. The Natural Resources Canada (NRCan) (and its predecessors) has been responsible for the development of seismic hazard maps for design of buildings in Canada [6]. The first generation of seismic hazard map in Canada was introduced in the 1953 edition of NBC, in which four seismic zones, i.e., 0, 1, 2, and 3, were qualitatively defined to describe the relative intensities of earthquake shaking in different regions of Canada. Seismic coefficients (i.e. the ratio of the design base shear to the building weight) for design of buildings were provided as a function of the seismic zone. The second generation of seismic hazard map was introduced in the 1970 edition of the NBC, which was based on the extreme-value method that calculated the seismic hazards corresponding to a 100-year return period. The 1985 edition of the NBC introduced the third generation of seismic hazard maps, which were developed by adapting the probabilistic seismic hazard analysis approach in the ATC-3-06 document [7] to Canadian seismology and earthquake characteritics. The seismic zones were defined in terms of either peak ground velocity or peak ground acceleration with a 10% probability of exceedance in 50 years (475-year return period). The number of seismic zones was increased from four to seven, aiming to obtain more accurate design base shear for design of buildings. The fourth generation of seismic hazard maps was introduced in the 2005 edition of NBC, in which the concept of seismic zones in the 1990 and earlier editions of the NBC was dropped. The seismic hazards were represented by 5%-damped design response spectra that were calculated for code-level earthquake ground motions with 2% probability of exceedance in 50 years (2,475-year return period). The concept of seismic zones was dropped in this NBC edition and spectral accelerations from the design response spectra for specific locations were used to calculate the minimum design lateral forces. The current 2015 edition of NBC adopted the fifth generation of the seismic hazard maps, in which newer seismological models and ground motion prediction models were introduced to calculate the seismic hazards. In addition, period-dependent site coefficients, $F(T)$, for addressing local site effects, and an adjustment measure, PGA_{ref}, for addressing the difference in seismicity in eastern and western Canada, were incorporated in the calculation of minimum design lateral forces for design of buildings in this NBC edition.

2.2 Life Safety Objective in the NBC

The NBC is an objective-based national model code; the objectives in the NBC describe undesirable situations, and their consequences, which the code intends to avoid in buildings. Life safety, which is the primary consideration in the seismic design of buildings, is to provide an acceptable level of safety for building occupants and general public as the building is subjected to code-level earthquake events.

The commentary of the 1970 edition of the NBC provided some insight on the performance objective of the NBC when designing for earthquake loads, which reads: "The earthquake-resistant design of the National Building Code of Canada 1970 provides minimum standards which assure an acceptable level of public safety by designing to prevent major failure and loss of life. Structures designed in conformance with its provisions should be able to resist moderate earthquakes without significant damage and resist major earthquakes without collapse. [Collapse is defined as the state when egress of occupants from the building has been rendered impossible because of the failure of the primary structure]". The commentary for 1975 NBC slightly revised the definition of the collapse as the state which exists when the exit of the occupants from the building has become impossible because of failure of the primary structure. This definition remained unchanged in 1977, 1980, 1985, 1990, and 1995 editions of the NBC.

The commentary of the 2005 edition of NBC provided the intent of the seismic provisions in the code, which reads: "(1) to protect the life and safety of building occupants and the general public as the building responds to strong ground shaking, (2) to limit building damage during low to moderate level of ground shaking, and (3) to ensure that post-disaster buildings can continue to be occupied and functional following strong ground shaking, though minimal damage can be expected in such buildings". This intent remained the same in the 2010 and 2015 editions of NBC. In addition, the commentaries of these three NBC editions emphasized that the life safety objective is the primary consideration for seismic design of buildings, which intends to provide an acceptable level of safety for building occupants and the general public as the building is subjected to code-level earthquake events. "This implies that although there may be extensive structural and non-structural damage during the design ground motion with 2% probability of exceedance in 50 years, there is a reasonable degree of confidence that the building will not collapse nor will its attachment break off and fall on people near the building. This performance level is termed "extensive damage" because although the structure may have lost a substantial amount of its initial strength and stiffness, it retains a margin of resistance against collapse."

Since life safety protection is achieved through the inelastic energy dissipation, which is explicitly considered in the seismic design provisions, some structural damage can be expected when subjected to code-level earthquake ground motions. The structural damage can be reduced by choosing a structural system with sufficient stiffness to ensure that the maximum interstorey drift limit does not exceed a specified drift limit, which is intended to limit the probability of partial or complete structural collapse. Damage to non-structural components can be minimized by limiting their deflections, limiting the interstorey drift in the structure, paying attention to the component restraints and connections, providing adequate clearances from the structure, and protecting elements tied rigidly to the structure from deformations. Table 2 presents the interstorey drift limits for buildings of different importance categories. As shown in in the table, for a code-level earthquake event (2% probability of exceedance in 50 years), a building of normal importance is expected to be in a state of near collapse when the interstorey drift ratio approaches 2.5%. As importance category elevates, more stringent interstorey limits are applied. In particular, the interstorey drift limit for post-disaster buildings is chosen as 1% of the storey height because these buildings are expected to remain operational immediately following an earthquake [8, 9]. The drift limits in Table 2 were based on the interstorey drift ratios provided for different performance objectives in the SEAOC Vision 2000 document [10], which is one of the major pieces of documentation regarding the performance-based seismic design of buildings.

Table 2 – Interstorey drift limits for buildings of different importance categories in the 2015 edition of NBC

Importance Category	Interstorey drift limit
Post-disaster	$0.01h_s$
High	$0.02h_s$
Low and normal	$0.025h_s$
Note: h_s represents the storey height.	

It should be noted that the interstory drift limits in the 2015 edition of NBC are independent of the type of SFRS. Given various deformation capacity and nonlinear capacity for inelastic energy dissipation among different SFRSs, different levels of damage and performance can be expected for different SFRS when subjected to strong earthquake ground motions. For example, when subjected to code-level earthquake events, wood buildings generally perform better than unreinforced masonry buildings because wood buildings have larger deformation capacity and can dissipate more energy through nonlinear hysteretic response.

In summary, life safety objective is the primary objective for seismic design of buildings as per NBC. Life safety does not mean that there will be no risk to life loss or serious injuries, but the level of the risk is acceptable as required by the code. There is a wide range in defining the life safety objective as per NBC. While the objective of buildings of normal importance is set at near collapse, the objective of post-disaster buildings can best be described as immediate occupancy. Although the seismic provisions in the NBC are intended to provide life safety protection, experience and observations during past earthquakes elsewhere in the world have shown that a wide variation in the extent of damage can be expected during any future earthquake event.

3. Current Issues in Determination of R_d and R_o Factors

There is no standard procedure in Canada for quantifying the values of R_d and R_o for different SFRSs. The R_d and R_o values provided in the current NBC edition (NBC 2015) were largely based on judgment and qualitative comparisons of seismic response characteristics of SFRSs. The lack of a unified procedure can pose a number of issues that are summarized as follows:

- The lack of unified procedure leads to inconsistent levels of performance between structures built with different materials;
- Current R_d and R_o values may be overly optimistic for some SFRSs and unduly low for others, resulting in a design that has low resiliency in the first case and is uneconomical in the latter;
- The operational performance of post-disaster buildings, which are critical for disaster preparedness and public safety, may not be warranted as per the seismic provisions in the NBC, thus posing a potential risk to communities that are prone to major earthquake events; and
- Lack of unified procedure makes it extremely difficult to introduce new and innovative solutions for SFRSs. For example, the introduction of cross-laminated timber SFRS took almost two code cycles and required significant effort and time from everyone involved with the resolution of this issue.

4. Roadmap towards a Unified Approach for Determination of R_d and R_o Factors

To address the issues identified in the preceding section, there is a clear need for the development of a unified procedure for quantifying the R_d and R_o factors that are used in the equivalent static force procedure in the 2015 edition of NBC. The methodology for the unified procedure will be quantitative and aims to achieve more uniform and consistent seismic performance in different types of SFRSs. The primary application of the procedure will be the evaluation of newly approved types of SFRSs and of construction in the NBC. To maintain the consistency with the 2015 edition of NBC, life safety objective is the primary consideration in the quantification of R_d and R_o values for SFRSs when subjected to code-level earthquake ground motions with 2% probability of exceedance in 50 years (2,475-year return period). Although R_d and R_o factors are of most concern, nonlinear capacity and seismic detailing requirements that have been enforced to achieve expected ductility levels as required in the NBC and relevant CSA standards are also investigated.

The roadmap towards the development of a unified procedure for determining R_d and R_o factors consists of the following tasks:

- Comparative review of the state of the practice in Canada and the seismic design and detailing requirements for different SFRSs in the NBC;
- Investigation of the evolution of seismic design and detailing requirements since the introduction of seismic modification factors in the NBC;
- Summary and discussion of the rationale for the changes made in different NBC editions, and for the introduction of new seismic provisions into the NBC and relevant CSA standards;
- Review and summary of the similarities and differences in seismic design detailing requirements between CSA material design standards and applicable U.S. material design standards;
- Review and comparisons of the seismic force modification factors used in Canada and the U.S. for different SFRSs in concrete structures;
- Review of the state-of-practice and state-of-art approaches for determining the seismic force modification factors such as the quantitative methods provided in FEMA P695 and the NIST document entiled "Tentative Framework for Development of Advanced Seismic Design Criteria for New Buildings" [12];
- Propose the unified approach for determining R_d and R_o factors for different SFRSs in the NBC;
- Validate the proposed procedure by comparing the R_d and R_o values with experimental results; and
- Carry out an assessment of R_d and R_o factors for the SFRSs that are currently included in the NBC.

5. Conclusions

The National Building Code of Canada (NBC) is an objective-based national model building code. The life safety objective is the primary consideration for the seismic design of buildings. The life safety protection is achieved by enforcing the seismic provisions in the code and relevant Canadian design standards, in which the nonlinear capacity of a building is acknowledged through the implementation of two seismic force modification factors: (1) ductility-related force modification factor, R_d, which recognizes the nonlinear capacity for inelastic energy dissipation, and (2) overstrength-related force modification factor, R_o, which represents the dependable portion of reserved structural strength from the design. Different R_d and R_o values are provided as a function of the type of seismic force-resisting system (SFRS), construction material, seismicity, Site Class, ductility level, and building use and occupancy (e.g., post-disaster facilities). The determination of R_d and R_o values in the NBC was largely based on judgment and qualitative comparisons of the SFRSs without using a unified procedure.

This paper presents an overview of the evolution of the seismic provisions in different editions of the NBC with a focus on the introduction of seismic force modification factors. A number of issues due to the lack of a unified procedure for determining the R_d and R_o factors are identified and summarized as follows: (1) inconsistent levels of seismic performance in different types of SFRSs, (2) overly optimistic R_d and R_o values for some SFRSs while excessive conservative R_d and R_o values for other SFRSs, (3) large uncertainty in the seismic performance of post-disaster facilities, and (4) difficulty for introducing new and innovative solutions for SFRSs. To address these issues, a roadmap has been proposed by the National Research

Council Canada, in which the key tasks to be accomplished for developing the unified procedure have been outlined. The proposed procedure will be based on a quantitative methodology and aims to achieve more uniform and consistent levels of seismic performance for a variety of SFRSs in the NBC. The primary application of the proposed procedure will be determining the R_d and R_o values for the newly approved SFRSs in the NBC. It can also be used to assess the R_d and R_o factors for the SFRSs that have been included in the NBC.

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