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Assessment of Overstrength-related Factors for Conventional Construction Concrete Shear Wall Archetypes in Canada using the Performance-Based Unified Procedure

Mahsa Hosseini[1*], Parsa Taghvaei[2], Carlos E. Ventura[3], Tony Yang[3], Farrokh Fazileh[4], Reza Fathi-Fazl[4]

[1]PhD Candidate, Department of Civil Engineering, The University of British Columbia, Vancouver, BC, Canada

[2]Structural Engineer, Glotman Simpson Consulting Engineers, Vancouver, BC, Canada

[3]Professor of Structural Engineering, Department of Civil Engineering, The University of British Columbia, Vancouver, BC, Canada

[4]Senior Research Officer, National Research Council Canada, Ottawa, ON, Canada

[*]mahhsn@mail.ubc.ca (Corresponding Author)

ABSTRACT

Seismic force modification factors, including the ductility-related (R_d) and the overstrength-related factors (R_o) for different Seismic Force-Resisting Systems (SFRSs), are listed in the National Building Code of Canada (NBC). Overstrength-related factor represents the minimum dependable strength of the structure beyond its design level. National Research Council Canada (NRC) recently developed a performance-based unified (PBU) procedure to systematically calculate the seismic force modification factors for all existing and new SFRSs to be introduced into the code. Prior to the development of the PBU procedure, these factors in the code were originally developed based on engineering judgment.

It is essential to evaluate the effectiveness of the PBU procedure for various types of SFRSs, such as conventional construction shear walls. This assessment is primarily performed to validate the efficiency of the screening process of the PBU, as well as enhancing the PBU procedure in ensuring the safety and integrity of different SFRSs.

This conference paper presents the results of an assessment using the PBU procedure to determine the R_o factor for conventional construction concrete shear wall structures in Canada. The study includes the examination of several archetypes of concrete shear wall structures, which are designed based on NBC 2020 [1] and CSA A23.3-19 [2] for the normal importance category. These archetypes are categorized into several performance groups. However, only the results for selected performance groups are presented here. The R_o factors are determined using the PBU procedure through the utilization of the pushover analysis. The results indicate that the employed factors in NBC provide a safe estimate of this seismic force modification factor for the studied performance groups of concrete shear wall structures.

Keywords: Overstrength-related factor, performance-based unified procedure, pushover analysis, conventional construction, concrete shear wall.

INTRODUCTION

Ensuring the seismic performance of structures is of great significance, given its direct implications for the safety of occupants and the stability of buildings. Seismic force modification factors, such as ductility-related (R_d) and overstrength-related factors (R_o), play a significant role in enhancing the seismic performance of structures. R_o is a factor that accounts for the additional strength of a structural system beyond its designed strength under typical loads. This additional strength is intended to provide a margin of safety against extreme loading events, such as earthquakes. The value of R_o should be greater than one. The value of R_d represents the ductility or deformation capacity level of the seismic force-resisting system. A higher value of R_d indicates a more ductile system that can undergo significant deformation while maintaining strength and stability. These factors are listed in the National Building Code of Canada [1] for different seismic force resisting systems (SFRS). The seismic force modification factors in the code were mainly established through engineering judgment.

The realization of the necessity for a consistent and rational approach to determine these seismic force modification factors was already apparent in the United States. This led to the development of FEMA P695 [3], which aimed to determine the response coefficients (R, Cd, Ω0) of various structural systems in the ASCE/SEI 7 [4].

The application of FEMA P695 methodology to evaluate seismic response in Canada is not straightforward due to variations in performance objectives, seismic hazard determination, building design requirements, and construction practices between the US and Canada. Nonetheless, research has been conducted in recent years to assess the seismic response of various structures in Canada using the FEMA P695 methodology, including reinforced masonry shear walls [5], Concrete-timber hybrid systems [6], CLT structures [7], and steel buckling-restrained braced frames [8]. However, these studies needed consistency regarding the definition of collapse, selection of ground motion records, the inclusion of spectral shape effects, overstrength factor calculations, and total uncertainty calculations. As a result, their modifications to the FEMA P695 methodology were inconsistent.

Fazileh et al. discuss the need for a consistent and efficient methodology for the structural performance assessment of different SFRSs in Canada. Currently, NBC employs seismic force modification factors for different SFRSs, but there is no unified procedure in Canada for systematically quantifying these values. The PBU procedure, developed by NRC in collaboration with several Canadian universities, including the University of British Columbia, aims to systematically assess the ductility and overstrength factors of different SFRSs in NBC. This performance-based approach involves two screening stages that utilize nonlinear pushover and time history analyses before carrying out the incremental dynamic analysis (IDA). The researchers created 21 concrete moment frame archetypes with varying key parameters to test the effectiveness of the PBU procedure. The findings confirm that the screening process of the PBU procedure is efficient as it considerably decreases the number of archetypes that require IDA [9].

Recently, there has been a growing interest in applying the PBU procedure. As a result, several researchers have begun to investigate the performance of various seismic force resisting systems and assess the effectiveness of the PBU procedure. To illustrate, the National Research Council Canada (NRC) has initiated a multi-year research project with the University of British Columbia to evaluate the PBU procedure for conventional construction reinforced concrete shear walls.

This conference paper presents a portion of the project that utilizes pushover analysis in the PBU procedure to compute the overstrength factors for eleven archetypes. These archetypes are classified into four separate performance groups. This study indicates that the overstrength-related factors used in NBC offer a safe estimation of the seismic force modification factor for conventional construction concrete shear wall structures. Furthermore, the findings indicate that the overstrength-related (R_o) factor tends to increase with an increase in building height, and the seismicity of the site does not significantly impact the resulting $R_o$values. Additionally, lower axial loads on the wall result in higher $R_o$values.

Archetype Configurations Development

Our study focuses on four variables to define different building configurations:

1. Gravity Load Levels: The axial load on each wall varies from low to high and plays a key role in the building's response.
2. Seismicity: Our study considers two seismic categories, SC-3, and SC-4, which are defined per NBC and have different levels of seismic activity. Seismic categories SC-3 and SC-4 correspond to "moderate" and "high" seismicity, respectively.
3. Geometric Variations: Building height is limited, and the proposed archetypes are 5, 7, and 12 stories for the SC-3 category and 5, 7, and 9 levels for the other.
4. Irregularity: Two types of irregularities have been investigated in our study. Mass irregularity has been considered in some of our irregular archetypes by defining podium levels, while Gravity-Induced Lateral Demand (GILD) has been modelled for other irregular archetypes.

Several performance groups (PG) have been defined to enable feasible comparisons. Each performance group includes several archetypes with only one variable, such as axial load ratio, changing between them. In this conference paper, we are presenting only four of our performance groups. Table 1 provides detailed information about each archetype, including their corresponding performance group.

Table 1. Proposed archetypes and performance groups

PG	Regularity	Seismicity	Axial Load	No. of Archetypes	Archetypes Label	No. of Stories
1	Regular	High	High	3	A14 A18 A22	9 7 5
2	Regular	High	Low	3	A16 A20 A24	9 7 5
3	Regular	Moderate	High	2	A6 A10	9 5
4	Regular	Moderate	Low	3	A4 A8 A12	12 9 6

The development of the archetype layout involved collaboration with Glotman Simpson Consulting Company, an industry partner. This was undertaken to ensure that it reflects typical practices in Canada. As depicted in Figure 1, the structural wall configuration features a centrally located elevator core shear wall. This configuration was chosen due to its symmetrical nature, which helps minimize plan irregularities. Figure 1 showcases the range of height archetypes utilized in our study.

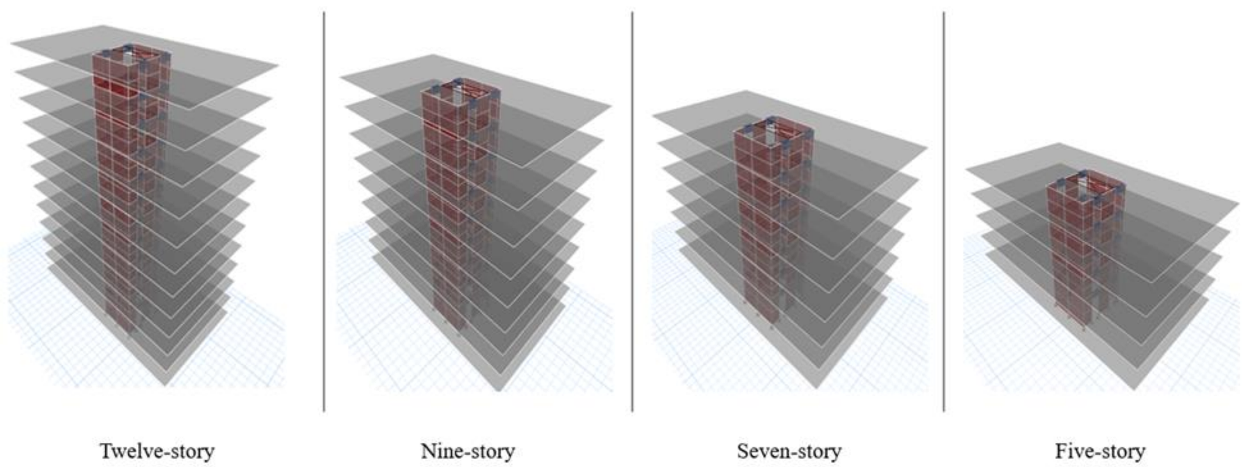


Figure 1. 3D view of regular archetypes

OpenSeesPy Modeling

In this study, three different types of structural elements have been utilized to model the different components of the system. Specifically, the fiber-type beam-column element has been employed to model the shear wall, the linear elastic beam-column element has been used to model the leaning column, and the truss element has been employed to model the links connecting the wall and the leaning column.

In the literature, there exist multiple modelling approaches for RC shear walls. However, a fiber-based modelling approach can effectively account for the independent behaviour of shear and axial-flexure. Therefore, it can provide a reasonable estimation of slender shear wall behaviour that is dominated by flexure [10]. Moreover, this particular modelling approach exhibits numerical robustness and lower computational demand than other approaches that account for the interaction of shear-flexure behaviour within the wall [11]. In this study, the axial-flexural response of the wall has been modelled using the fiber-type beam-column element. Furthermore, a linear stress-strain relationship has been assumed for the shear response of the shear wall. Finally, this shear response has been aggregated with the axial-flexural response of the wall using the "Section aggregator" command in OpenSeesPy [12].

Two distinct axial load scenarios have been considered to investigate the behaviour of the concrete shear wall under varying loading conditions. For the high axial load scenario, an axial load equal to 25% of the factored axial load resistance has been applied to the wall. Similarly, an axial load equivalent to 5% of the factored axial load resistance has been applied to the wall for the low axial load scenario.

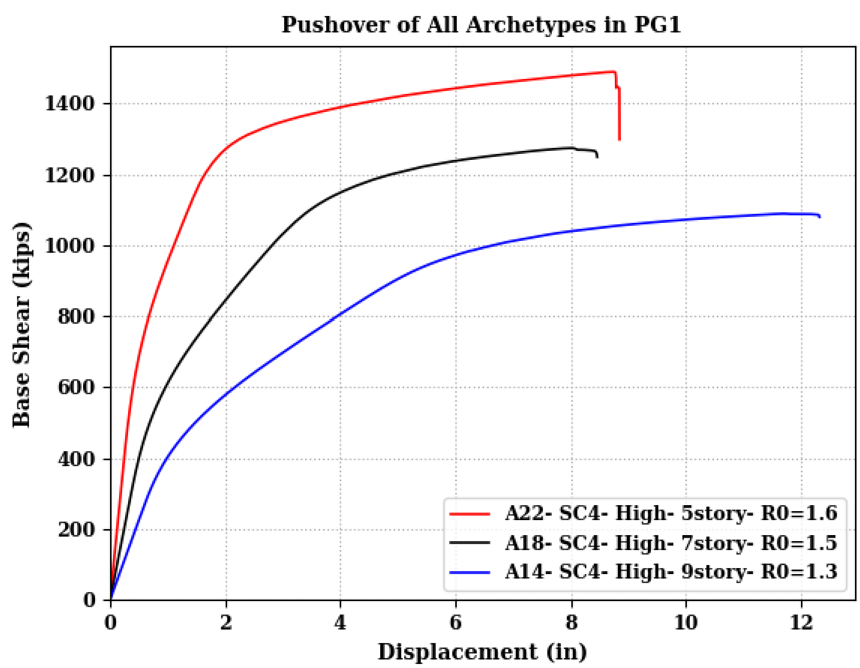
Pushover Results

Pushover analyses were conducted on all archetypes to evaluate the nonlinear behaviour of the models and determine overstrength-related factors (R_o). The pushover analysis involves the application of gravity load, followed by the lateral pushing of archetype models up to the level corresponding to the performance goal. During these analyses, the load distribution along the height was maintained proportional to the load distribution utilized during design or response spectrum analysis. The pushover analyses were performed before undertaking the more resource-intensive time history analyses. The pushover curves for each performance group are presented in Figure 2.

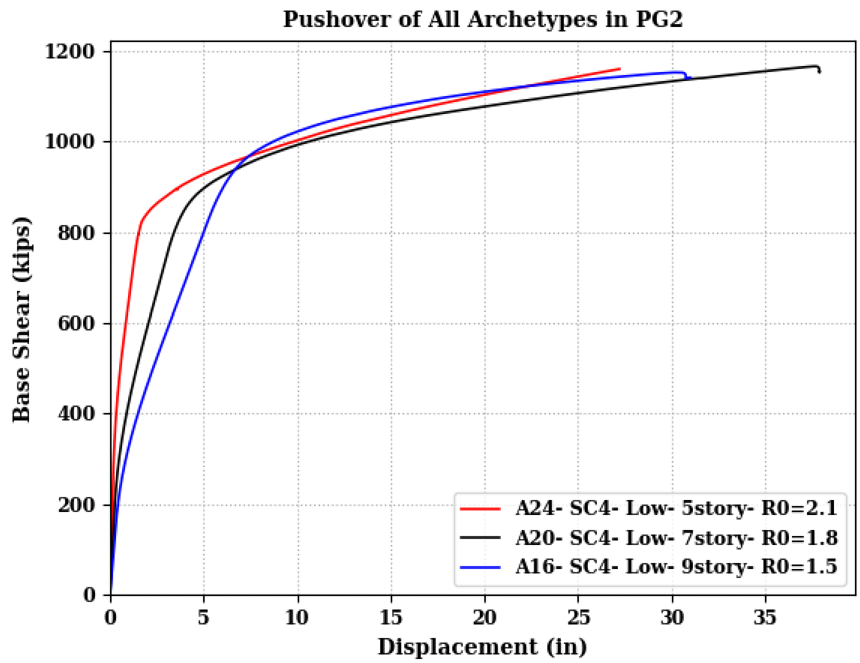
To carry out the PBU procedure, it is essential to determine the ultimate displacement, which corresponds to the desired performance level, using local and global criteria. The local criterion is often defined by a specific material and geometric properties and is generally assessed using nonlinear analysis techniques. The global criterion, on the other hand, refers to the overall behaviour of the structure and is typically evaluated using performance metrics such as lateral strength reduction and ultimate drift. In this study, the global criterion is defined as a significant reduction in the model's lateral strength and also 10% maximum drift, whereas the local criteria are identified by examining areas where the rebar strain exceeds the steel's rupture strain, which is assumed to be 0.13 [13].

According to the PBU procedure, the overstrength factor (R_o) for a given archetype model is defined as the ratio of its maximum base shear resistance to its design base shear. This overstrength factor is calculated for all archetypes in the system. The overstrength values are first averaged over each performance group, then the resultant value is determined by taking the smallest average value of all the performance groups. After calculating the system overstrength factor (R_o), it is compared to the trial value specified in the design requirements (1.3 for conventional construction concrete shear wall system). If the resulting value is lower than the trial value, then the design requirements and archetypes must be modified before proceeding to the next step defined in the methodology. According to the data presented in Table 2, the resultant overstrength factor (R_o) for the system is determined to be 1.4. This resultant value is greater than the prescribed value of 1.3 outlined by NBC.

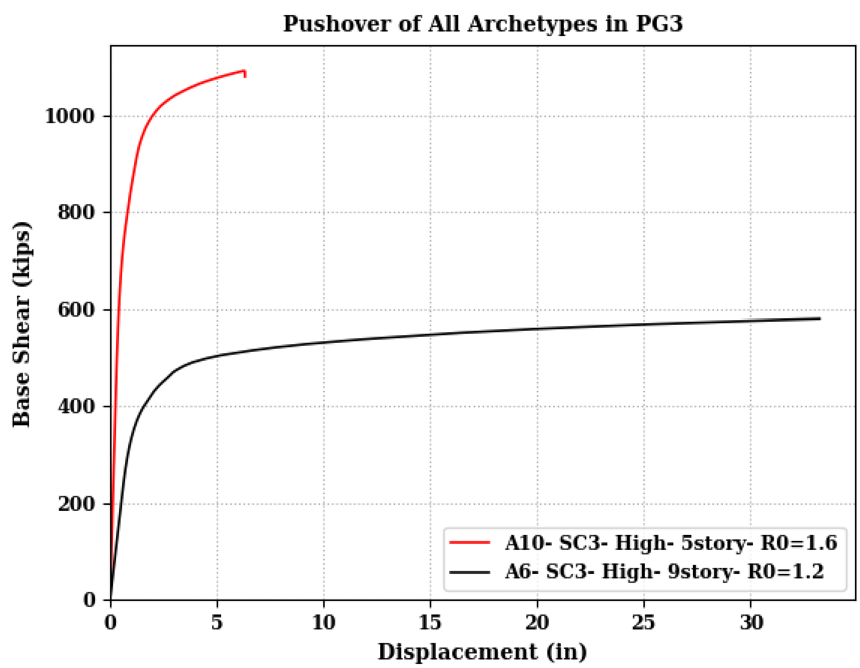
PBU suggests that if the resultant (R_o) value is lower than the trial value, then modifications need to be made to the design requirements and archetypes before moving to the next step. A smaller R_o value implies a premature failure due to either design requirements or problems with modelling. Further evaluation is needed to identify the source of premature failure for archetypes A4 and A6.



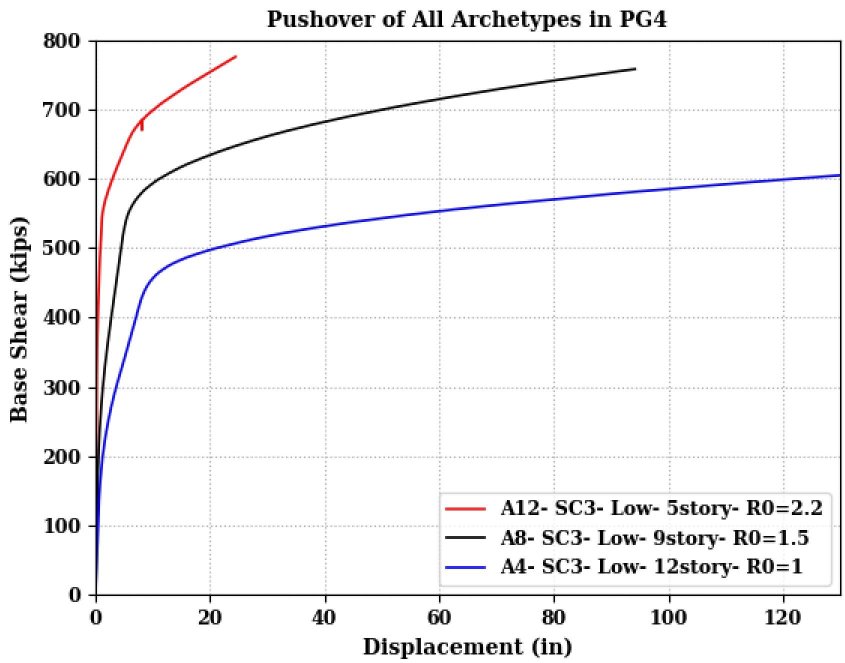
(a)


Pushover of All Archetypes in PG2
Base Shear (kips)
Displacement (in)
A24- SC4- Low- 5story- R0=2.1
A20- SC4- Low- 7story- R0=1.8
A16- SC4- Low- 9story- R0=1.5

(b)


Pushover of All Archetypes in PG3
Base Shear (kips)
Displacement (in)
A10- SC3- High- 5story- R0=1.6
A6- SC3- High- 9story- R0=1.2

(c)



(d)

Figure 2. Pushover curves for a) PG1, b) PG2, c) PG3, and d) PG4

Table 2. Overstrength-related factors (R_o)

PG	Archetypes Label	R_o	Avg. (R_o)
1	A14	1.3	1.5
	A18	1.5	
	A22	1.6	
2	A16	1.5	1.8
	A20	1.8	
	A24	2.1	
3	A6	1.2	1.4
	A10	1.6	
4	A4	1	1.6
	A8	1.5	
	A12	2.2	

CONCLUSIONS

In conclusion, the results of this study indicate that the employed overstrength-related factors in NBC provide a safe estimate of the R_o factor for the selected performance groups of conventional construction concrete shear wall structures, namely PG1, PG2, PG3, and PG4. According to this study, it was found that the overstrength-related (R_o) factor tends to increase as the height of buildings increases within each performance group. This observation is consistent with a previous study on the seismic performance of conventional construction concrete moment-resisting frame buildings [14]. The comparison of PG1 with PG3 and PG2 with PG4 indicates that the seismicity of the site does not significantly affect the resulting $R_o$values. Furthermore, this study shows that lower axial load levels on the wall results in greater $R_o$values when PG1 is compared with PG2 and PG3 are compared with PG4. Additionally, the effect of all studied variables in this study on ductility-related factors will be investigated and presented in future publications. These observations could provide important insights into the behaviour of concrete shear wall structures subjected to seismic loading. They can be used towards the enhancement of seismic design requirements for these structures.

ACKNOWLEDGMENTS

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