NON-LINEAR DYNAMIC MODELLING OF A 14-STOREY BUILDING CONTAINING SPECIAL DUCTILE SHEAR WALLS WITH CONFINED BOUNDARY ELEMENTS

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ABSTRACT

In part one, a set of prescriptive design requirements for a new category of masonry shear wall is proposed based on synthesis of experimental data and verified with accepted theoretical analysis. In part two, a part of the ongoing effort of the CAN/CSA S304 committee to introduce and qualify new reinforced masonry (RM) Seismic Force Resisting Systems (SFRS) within the upcoming 2015 edition of the National Building Code of Canada (NBCC-2015). Within this research effort, this report gives details of inelastic dynamic analyses of an archetype building designed using the currently proposed Ductile Special RM wall as the SFRS. The building design is representative of a typical residential insulated concrete forms or reinforced masonry shear wall building with eight walls acting as the main SFRS in the N-S direction and a floor area of 900 m^2. The 14 storey archetype building is first designed to meet the requirements of a Class C site located in Vancouver, B.C., Canada using the proposed $R_d = 4.0$ and $R_o = 1.5$ values. The building was subjected to a series of twelve synthetic ground motion records scaled to the Vancouver area design spectrum and different design alternative are proposed to limit the inter-storey drifts to 2.5% (NBCC limit for general buildings) or 1% (NBCC for post-disaster buildings). The inelastic dynamic analyses conducted using the non-linear dynamic analysis code CANNY shows that Ductile Special RM shear wall building designed using the proposed R_d=4.0 and R_o=1.5 values can be designed to meet different drift limits specified by the NBCC. This and similar analyses along with the growing experimental result database of this category of walls, are expected to facilitate adoption of such SFRS as an attractive solution in mid-rise construction in Canada, similar to the USA and New Zealand, in the very near future.

KEYWORDS: boundary elements, confinement, design codes, seismic design, shear walls

INTRODUCTION

There is a need to introduce new masonry construction techniques that meet the ever-increasing requirements for reduced damage and minimum repair cost following a medium to large earthquake event. Such techniques need not impose additional financial constraints or involve proprietary products, and should, as much as possible, capitalize on the current state of analysis, design, and construction. One possibility of reaching this goal is to adapt well-established construction techniques of RC shear wall systems to RM construction. The current proposal to change the SFRS categorization for RM construction in the upcoming NBCC-2015 includes a new category of *Special Ductile Reinforced Masonry Walls*. The proposal is to assign a R_d value of 4.0 and R_o of 1.5 to *Special Ductile Reinforced Masonry Walls*. One of the requirements to justify the proposed SFRS category is to conduct a thorough experimental study to document the performance of such RM wall system as was described in Part of this two part paper. The other requirement is conduct an inelastic dynamic analysis to justify the performance of buildings designed under an elastic force that are reduced by the proposed R_d and R_o values and subjected to realistic ground motion conditions. The current study focuses on this requirement. In the following section, a review of recent advancement in ground motion selection and scaling is presented, followed by a detailed description of the ground motion records selected for the current study and the technique adopted for their scaling. Finally an analytical study that dealt with alternative wall designs in a prototype (archetype) building in order to meet different drift limits set out by the NBCC is presented.

GROUND MOTION SELECTION IN THE CURRENT STUDY

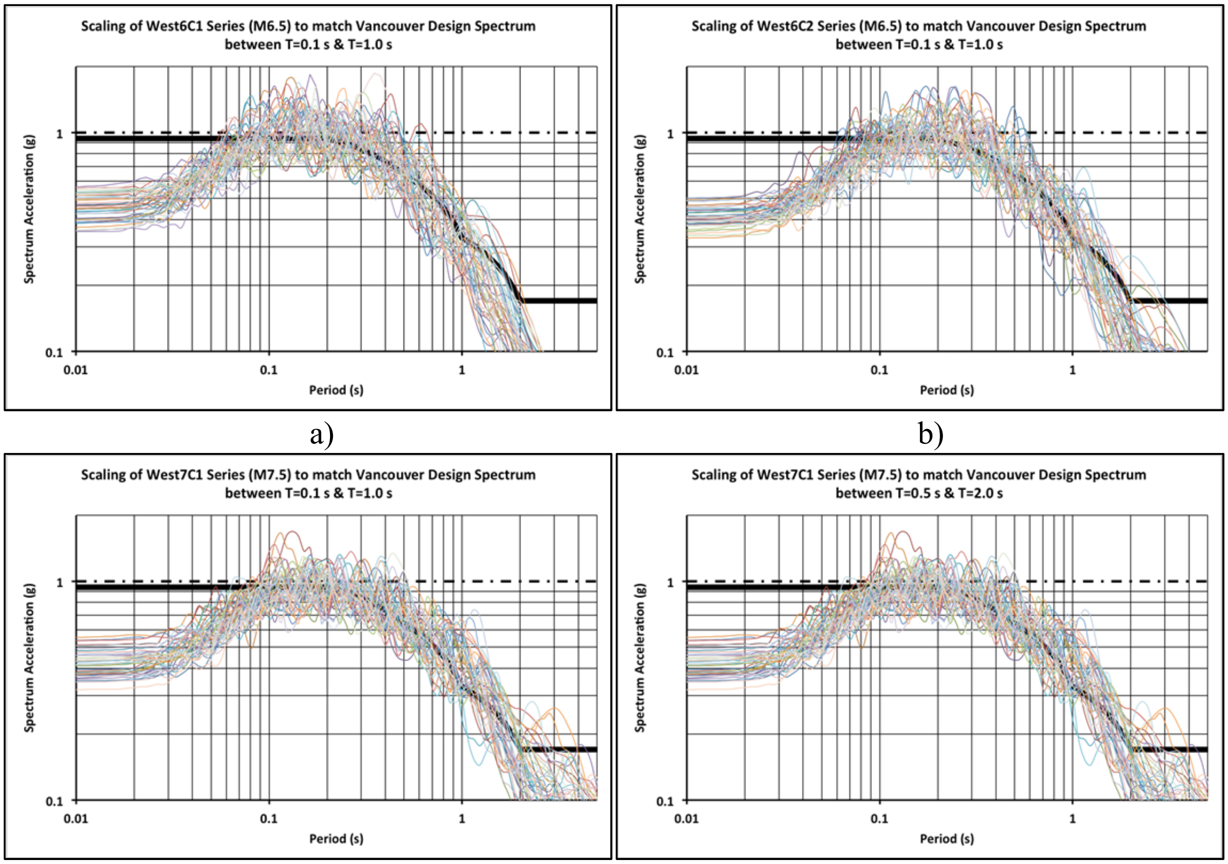
A thorough review of the current state-of-the-art demonstrates that, although there have been major advances in the area of ground motion selection and modification/scaling for nonlinear dynamic analyses of structures, there is still a large amount of uncertainty and no consensus regarding either ground motion selection or its scaling techniques amongst researchers working in these two areas.

It is the NBCC approach to subject structures located in the same geographical area and site condition to a uniform hazard spectrum (UHS) having a 2% chance of being exceeded in 50 years. The ground motion records provided represent the types of earthquake motions expected and match the target UHS from the NBCC over some prescribed period range. In her study, Atkinson [1] applied the stochastic finite-fault method is used to generate ground motion records that may be used to match the 2005 NBCC UHS for a range of Canadian sites. One may then select records from these suites that may be scaled (using simple linear scaling factors) to match the NBCC target UHS for 2% in 50 years for a specified generic site condition [1]. The time histories, along with their response spectra provide a convenient basis for comparison of the available simulated records with a target UHS, and for derivation of the appropriate scaling factor to match the time history to the target over the selected period range [1]. This will be described in the following sections.

Although Atkinson [1] provided records for Eastern and Western Canada, the more severe records of Western Canada were selected for the current study to present the worst case scenario. For western Canada, the hazard comes from a range of earthquake types [1]. The important contributions to hazard at intermediate-to-high frequencies are moderate-to-large earthquakes in the shallow crust or within the underlying subducting slab [2,3]. At long periods, the potential for great (M > 8 to 9) megathrust earthquakes on the Cascadia subduction zone is the main concern. Cascadia subduction events are at a significant distance (>100 km) from densely populated regions, but would produce long-periods motions that would have long duration (>1 min); the long duration of the motions could be very damaging if structures are pushed beyond their elastic limits. The magnitudes used for the simulation of crustal and in-slab events in western Canada are higher than those used for eastern Canada reflecting the greater contribution to hazard from larger events in British Columbia.

Thus for western Canada, for each site condition, Atkinson [1] provided four sets of 45 records (each of which can be considered as either 45 random horizontal components or 15 three-component sets): M6.5 at 10 to 15 km, M6.5 at 20 to 30 km, M7.5 at 15 to 25 km, and M7.5 at 50 to 100 km. The M9.0 Cascadia record has relatively low PGA, but very long duration, in comparison to local crustal or in-slab events.

The target UHS that we wish to match with the simulated time histories are the UHS for 2% exceedence probability in 50 years as given in [4]. The spectra are given in tables for the reference site condition of C, with prescribed amplification factors to convert to other site conditions. The factors are dependent on the expected response spectra on C, as described in [5]. The procedure followed for records response spectrum matching in this study followed the recommendation made by [1]. A site in Vancouver was selected and the results are demonstrated in Fig. 1. which shows different records scaling to match Vancouver design spectrum for site Class C for: a) West 6C1 Series matching between T=0.1-1.0 s; b) West 6C2 Series matching between T=0.1-1.0 s; c) West 7C1 Series matching between T=0.1-1.0 s; and d) West 7C1 Series matching between T=0.5-2.0 s.



a) b)

c) d)

Figure 1: Different Records scaling to match Vancouver Design Spectrum for Site Class C: a) West 6C1 Series matching between T=0.1-1.0 s; b) West 6C2 Series matching between T=0.1-1.0 s; c) West 7C1 Series matching between T=0.1-1.0 s; and d) West 7C1 Series matching between T=0.5-2.0 s

MODELLING SOFTWARE AND HYSTERETIC MODEL SELECTION

The computer program CANNY (Li, 2010) was selected for the inelastic dynamic analyses based on the experimental results of walls with boundary elements reported by [6,7,8]. The hysteretic models of interest within the program were CA4 and CA7, which can simulate pinching, stiffness degradation as well as strength degradation for the flexuraly dominated walls. However, model CA4 simulates strength degradation mainly through a negative stiffness in the post peak region, where different model parameters were selected for the load-displacement relationship in the push/positive direction compared to the pull/negative direction. On the other hand Model CA7 simulates strength degradation through a reduced stiffness of the next loading cycle and ultimately was found to simulate the hysteresis loops of the tested walls more accurately than model CA4. In addition, model CA4 was shown to be very sensitive to its input parameters, as a result of the negative stiffness approach in simulating strength degradation, especially in dynamic analysis runs. An example of a matched hysteresis loops is depicted in Fig. 2 for Wall 6 reported in Part 1 of this paper.

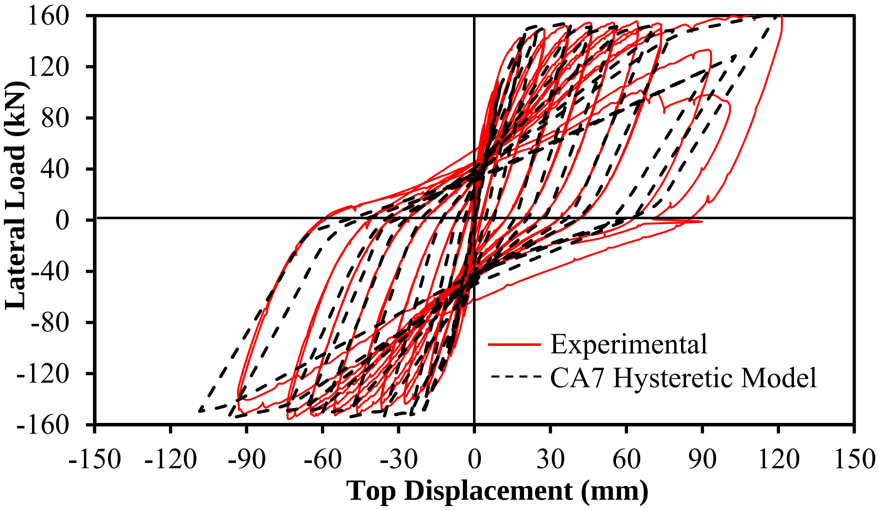


Figure 2: Matching of Hysteretic Model with Experimental Data

PROTOTYPE BUILDING

The prototype building plan selected for this study is shown in Fig. 3. The plan is actually for a 17 storey concrete building located in a non-seismic zone in Eastern Canada. Through a preliminary design, it was decided to design the same building plan for a target 14 story height to be located in Vancouver on site class C for the masonry shear wall structures with confined boundary elements. The building floors are made of precast hollow core slab system and the building characteristics is summarized in Table 1. As can be seen in Fig. 3, there are eight main identical walls in the N-S direction with only one of the critical walls (the most heavily loaded including torsional effects) was selected for the subsequent analyses. In these analyses it was decided to alter the wall cross sections along the building height to optimize the design and reduce unnecessary confinement detailing above critical sections. Unless stated otherwise in the next sections, the wall maintained the same cross section over the lower four stories of the building, then the cross section changed and was kept the same over the next four stories (i.e. from floor five to eight). Finally, the wall had its third cross section over the remaining floors (i.e. from nine to fourteen). The design walls were initially selected as 5.0 m long and were constructed with 25 cm units and 25 MPa block.

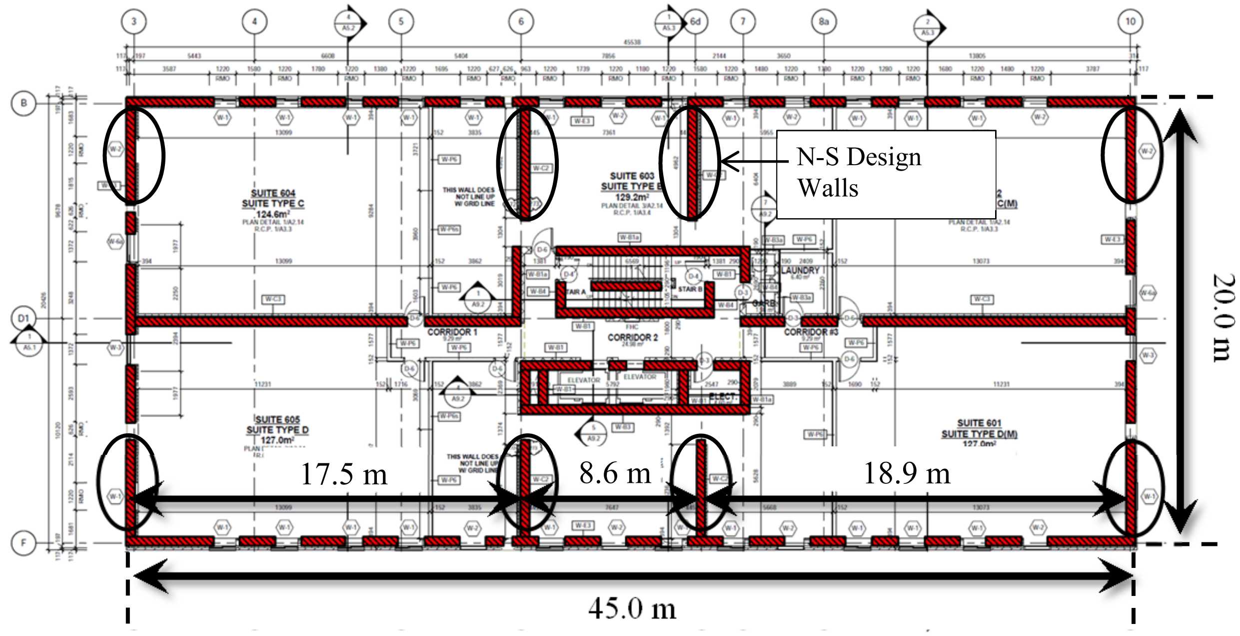


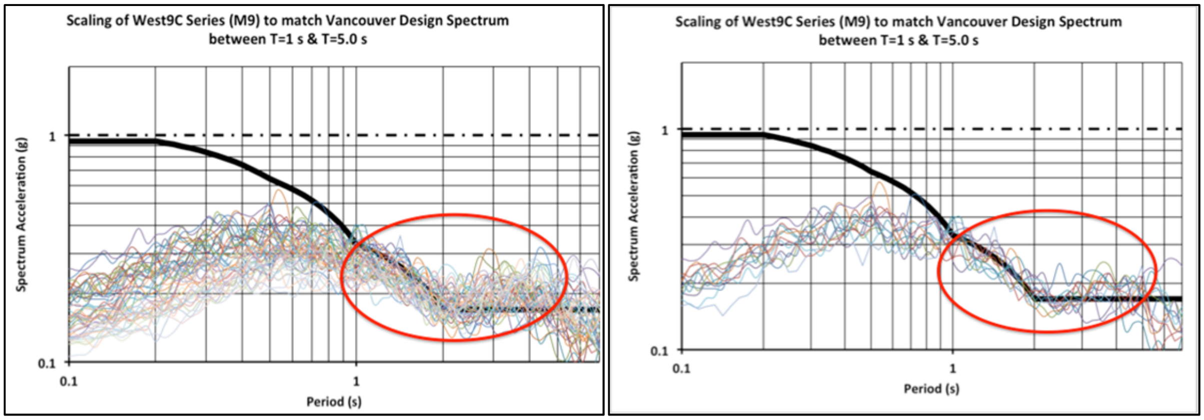
Figure 3: Selected Prototype Building 14-Stories, Vancouver, Site Class C

Table 1: Prototype Building Properties

Building Characteristics		
E-W Dimension	45,000	mm
N-S Dimension	20,000	mm
Height of a Storey (h_{storey})	2,845	mm
Number of Stories ($n_{stories}$)	14	
Total Height of Building (h_{total})	39,830	mm

ANALYSIS RESULTS

Alternative A: The building (wall) analyses followed different iterations/alternatives. Although expected to fail meeting the drift limits of the NBCC, the first iteration attempted to design the critical wall as 5.0 m long wall that varied in cross section along the building height as explained in the previous section. Following this design, the wall was found to have a period of approximately 3.2 seconds, which meant that the M9.0 records given by [1] were to be used. Fig. 4a shows the scaled records of Series West9C to match the high-period (1-5 s) range of the Vancouver deign spectrum for site class C. Following the procedure recommended by [1], a subset series of twelve records out of the records shown in Fig. 4a that met the selection criteria were chosen and are shown in Fig. 4b with their scaling factors given in Table 2.



a) b)

Figure 4: West 9C Records scaled to match Vancouver Design Spectrum for Site Class C between T=1-5 s: a) Full Series and b) Selected Subset

Table 2: Selected Subset of Series West 9C Record Numbers and Scaling Factors to match Vancouver Design Spectrum for Site Class C between T=1-5 s

Record Number	3	4 6		7	8	9	10	11	13	15	28	30
Scale factor	1.01	1.07	1.11	1.16	1.17	1.24	1.14	1.25	1.16	1.35	1.69	1.52

As the original prototype building was constructed out of concrete 5.0 m walls in a non-seismic zone in Eastern Canada rather than in Vancouver, B.C. it was expected that keeping the same wall length and, using RM with its reduced strength compared to concrete will almost certainly fail meeting the inter-storey drift limits of the NBCC. Nevertheless, it was of interest to investigate the prototype building response by a simple SFRS replacement (i.e. keeping the same wall length) of the concrete wall by equivalent RM walls but placing the building in a high seismic zone and reducing three floors.

The wall cross section is shown in Fig. 5 where the seismic load case resulted in assigning 14.1% of the total seismic load on the building to the critical wall. The wall cross-sections were varied over the height of the structure to reflect the fact that the more stringent boundary elements are necessitated within the plastic hinge region. As indicated in Fig. 5, maintaining the same wall lengths as the original structure, required high levels of vertical and horizontal reinforcement. As expected, the analysis results summarized in Table 3 showed that the building maximum inter-storey drifts were excessive, reaching more than 3%. Further analysis showed that one solution to limit the drift to the 2.5% limits of the NBCC was to reduce the building height to ten stories (compared to the original 17 storey concrete building or the target 14 RM buildings) and to increase wall length.

Table 3: Resulting Maximum Inter-story Drift (%) (5.0 m Walls, T=3.2 s)

Record number	**3**	**4**	**6**	**7**	**8**	**9**	**10**	**11**	**13**	**15**	**28**	**30**
Scale factor	1.01	1.07	1.11	1.16	1.17	1.24	1.14	1.25	1.16	1.35	1.69	1.52
Max. IS drift + (%)	3.23	1.92	2.94	2.86	3.33	2.78	3.70	3.23	3.70	2.86	3.45	3.70
Max. IS drift - (%)	-2.94	-2.63	-3.13	-2.63	-2.17	-3.13	-3.23	-2.22	-2.38	-5.00	-3.13	-2.17

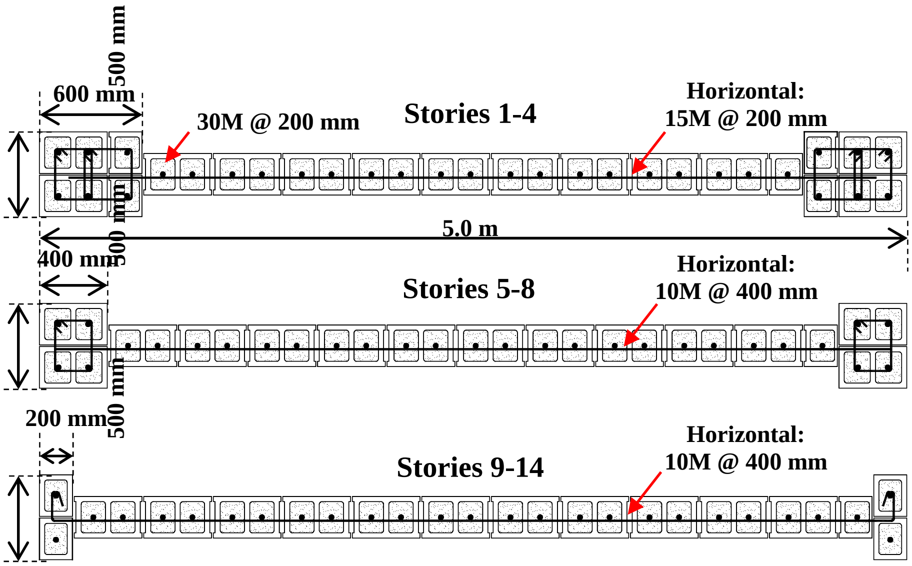


Figure 5: Initial Selected Wall Cross-Sections

Alternative B: The next iteration was to alter the wall design by using a 6.0 m (as opposed to 5.0 m) long wall. The wall cross-section and details are shown in Fig. 6. As can be seen in the figure, the wall boundary elements are made of 400 mm by 400 mm nominal dimensions pilaster units. The boundary element in floors one to four measures 400 mm by 800 mm and are depicted in detail in Fig. 7. The use of a pilaster unit allows greater freedom in placing vertical reinforcement, as opposed to standard units and thus each contained twelve M30 bars. The boundary elements reduces to 400 mm by 400 mm in floors five to eight, then to a flanged section of 400 mm by 200 mm in floors nine to fourteen. Following this design, the wall was found to have a period of approximately 2.5 seconds, which meant that the use of the same M9.0 records given by [1] as discussed earlier was still valid.

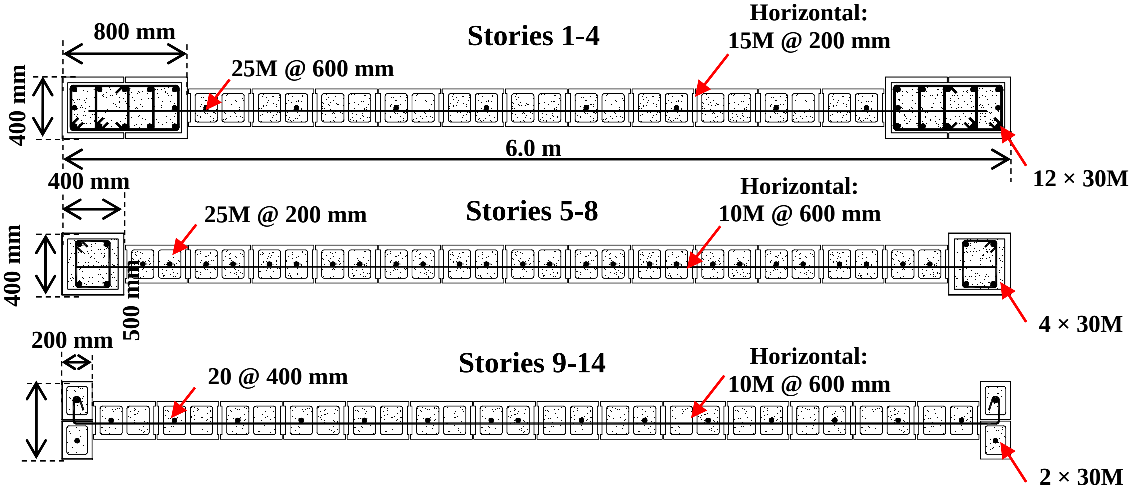


Figure 6: Second Iteration of Wall Design with 6.0 m Length

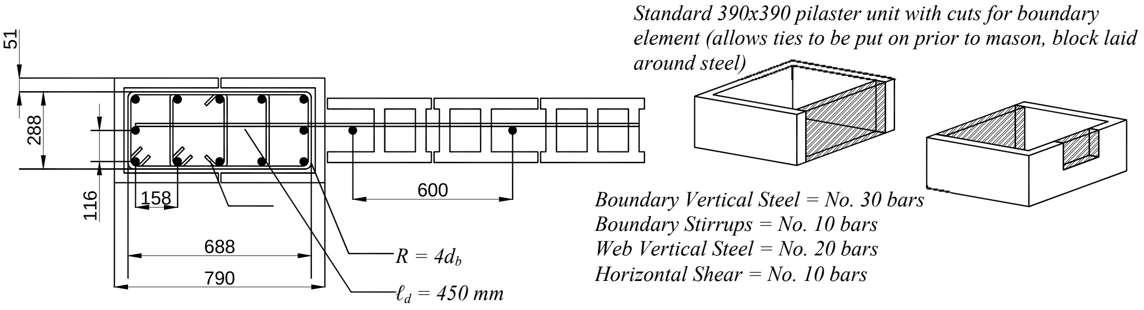


Figure 7: Detailed Dimensions of Confined Boundary Element

The results from the second design iteration showed a marked reduction in inter-storey drift as indicated in Table 4.

Table 4: Resulting Maximum Inter-story Drift (%) (6.0 m Walls, T=2.5 s)

Record number	**3**	**4**	**6**	**7**	**8**	**9**	**10**	**11**	**13**	**15**	**28**	**30**
Scale factor	1.01	1.07	1.11	1.16	1.17	1.24	1.14	1.25	1.16	1.35	1.69	1.52
Max. IS drift + (%)	1.52	2.22	1.61	1.92	2.17	1.64	1.96	1.47	1.69	1.85	1.67	1.43
Max. IS drift - (%)	-1.85	-1.64	-1.96	-1.67	-1.82	-1.08	-1.54	-1.79	-1.43	-2.22	-1.43	-1.49

<u>Alternative C:</u> Although the analysis results summarized in Table 4 showed that the building drifts were within the 2.5% drift limits of the NBCC, it was decided to re-run the analyses after rescaling the same record to match the Vancouver Site Class C design spectrum at the wall period (i.e. 2.5 s). This scaling is shown in Fig. 7. This approach was though to produce higher drifts than the spectrum matching over the 1.0 to 5.0 seconds range. The new scaling factors and resulting inter-storey drifts are given in Table 5.

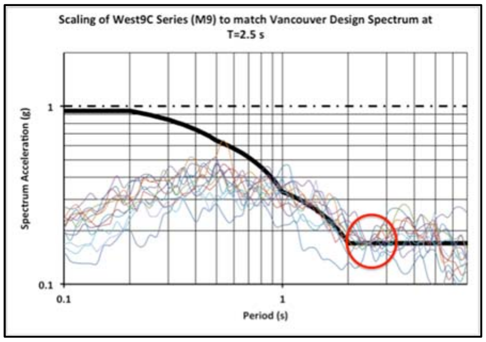


Figure 8: Selected Subset of Series West 9C Records scaled to match Vancouver Design Spectrum for Site Class C at T=2.5 s

Table 5: Resulting Maximum Inter-story Drift (%) (6.0 m Walls, T=2.5 s) with the selected M9.0 records scaled to match the Vancouver spectrum at 2.5 s

Record number	**3**	**4**	**6**	**7**	**8**	**9**	**10**	**11**	**13**	**15**	**28**	**30**
Scaling factor	1.08	1.24	0.77	1.23	1.31	1.42	1.10	1.40	1.19	1.41	1.62	1.62
Max. IS drift + (%)	1.5	2.6	1.1	2.2	2.6	2.1	1.9	1.7	1.4	1.9	1.6	1.5
Max. IS drift - (%)	-1.9	-2.1	-1.1	-1.9	-2.3	-1.4	-1.4	-2.1	-1.8	-2.4	-1.3	-1.6

Alternative D: As can be seen from Table 5, the resulting drifts are still relatively high although mostly within the 2.5 % drift limits of the NBCC. One alternative considered to reduce the drifts was to extend the boundary element in floors one to four to go up to floor eight, then switching to the 390 mm by 400 mm boundary elements from floors nine to fourteen. To facilitate comparison, the same records and scaling factors were used and the analyses results are given in Table 6.

Table 6: Resulting Maximum Inter-story Drift (%) (6.0 m Walls with cross section changing only at the 9th floor) with the selected M9.0 records

Record number	3	4	6	7	8	9	10	11	13	15	28	30
Scaling factor	1.08	1.24	0.77	1.23	1.31	1.42	1.10	1.40	1.19	1.41	1.62	1.62
Max. IS drift + (%)	1.5	1.5	1.1	1.5	2.3	2.0	1.6	1.5	1.4	1.9	1.4	1.4
Max. IS drift - (%)	-1.8	-1.6	-1.1	-1.6	-2.1	-1.2	-1.1	-2.1	-1.6	-2.2	-1.1	-1.4

Alternative E: In order to reduce the drifts even further, and to meet the possibility of a more stringent inter-storey drift limits (e.g. in the case of a post -disaster buildings), the wall design was finally altered to a 8.0 m long wall. The wall cross-section and details over different floors are shown in Fig. 9. As can be seen in the figure, the wall boundary elements are made of 390 mm by 390 mm pilaster units. The boundary element in floors one to four measures 390 mm by 800 mm and reinforced by twelve M30 bars. The boundary elements reduces to 390 mm by 400 mm in floors five to eight, then to the 390 mm by 200 mm flange in floors nine to fourteen. Similar to the 6.0 m wall design, the boundary element at the base of the wall had twelve 30M bars confined by 10M Stirrups. The wall web vertical reinforcement of 25M at 600 mm spacing and the horizontal reinforcement of 15M bars at 200 mm spacing.

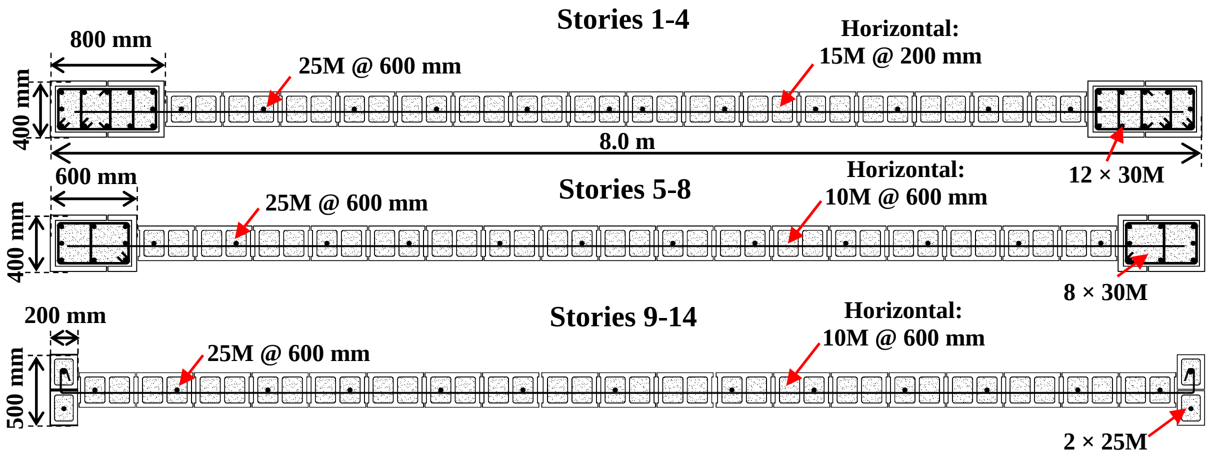


Figure 9: The 8.0 m Wall Details at for Changing Stories

Following this design, and the properties listed in Table 7, the wall was found to have a period of approximately 1.85 seconds, which meant that other records other than the one used throughout this study could have been used (e. g. M7.5 for British Columbia) as the wall period (i.e. 1.85 s) was within the range recommended by [1] (i.e. 0.5 to 2 s). However it was also indicated that the

Cascadia M9 records provide suitable motions for British Columbia for structures with periods of about 1 to 5 s [1]. As such, and to be consistent with the analysis outlined above, the same M9.0 records given by [1] were to be used as discussed earlier. The same selected record were re-scaled again to match the Vancouver Site Class C design spectrum at the wall period (i.e. 1.85 s). This scaling is shown in Fig. 10.

Table 7: The 8.0 m Wall Characteristics

Storey	Effective Inertial Mass for Critical Wall (kg)	E (MPa)	I_{Gross} Section (m^4)	EI (MN·m^2)	G (MPa)	A (m^2)	GA (MN)	My (kN·m)	Mu (kN·m)	Vr (kN)
14	66,853	11,475	5.91	67,830	4,590	2.02	9,290	10,455	13,390	882
13	81,501	11,475	5.91	67,830	4,590	2.02	9,290	10,455	13,390	882
12	81,501	11,475	5.91	67,830	4,590	2.02	9,290	10,455	13,390	882
11	81,501	11,475	5.91	67,830	4,590	2.02	9,290	10,455	13,390	882
10	81,501	11,475	5.91	67,830	4,590	2.02	9,290	10,455	13,390	882
9	81,501	11,475	5.91	67,830	4,590	2.02	9,290	10,455	13,390	882
8	83,847	11,475	6.62	76,001	4,590	2.13	9,768	20,820	25,304	955
7	83,847	11,475	6.62	76,001	4,590	2.13	9,768	20,820	25,304	955
6	83,847	11,475	6.62	76,001	4,590	2.13	9,768	20,820	25,304	955
5	83,847	11,475	6.62	76,001	4,590	2.13	9,768	20,820	25,304	955
4	87,779	11,475	6.79	77,866	4,590	2.18	9,988	24,828	33,364	2,493
3	87,779	11,475	6.79	77,866	4,590	2.18	9,988	24,828	33,364	1,889
2	87,779	11,475	6.79	77,866	4,590	2.18	9,988	24,828	33,364	1,879
1	87,779	11,475	6.79	77,866	4,590	2.18	9,988	24,828	33,364	1,870

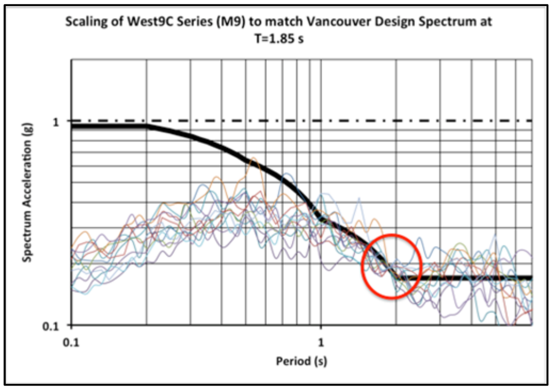


Figure 10: Selected Subset of Series West 9C Records scaled to match Vancouver Design Spectrum for Site Class C at T=1.85 s

The new scaling factors and resulting inter-storey drifts are given in Table 8 which meet the 1% inter-storey drift limits set by the NBCC for post-disaster buildings.

Table 8: Resulting Maximum Inter-story Drift (%) (8.0 m Walls, T=1.85 s) with the selected M9.0 records scaled to match the Vancouver spectrum at 1.85 s

Record number	**3**	**4**	**6**	**7**	**8**	**9**	**10**	**11**	**13**	**15**	**28**	**30**
Scaling factor	0.83	0.92	1.21	1.12	1.17	1.03	1.23	1.44	1.20	1.21	1.54	1.78
Max. IS drift + (%)	0.7	0.6	1.1	0.9	0.7	0.8	0.8	0.9	0.7	0.9	0.8	0.9
Max. IS drift - (%)	-0.8	-0.6	-0.9	-0.6	-0.7	-0.6	-0.8	-0.8	-0.8	-0.6	-0.7	-0.8

CONCLUSIONS

The current study forms a part of a larger research program aiming at testing, analyzing, qualifying and introducing new reinforced masonry seismic force resisting systems (SFRS) in Canada. The study focused on utilizing a 14 storey high prototype/archetype building with eight shear walls in the N-S directions acting as the SFRS. The inelastic dynamic analyses for the alternative critical wall designs showed that that the wall can be designed to possess adequate strength (flexural and shear) following the proposed CAN/CSA S304 provisions for Ductile Special Reinforced Masonry SFRS with R_d value of 4.0 and R_o of 1.5 while meeting the different maximum inter-storey drift limits of the NBCC. The results of this study support the idea that masonry structures as tall as 14 stories can be constructed in regions possessing a high degree of seismic risk by utilizing special ductile masonry shear walls possessing confined boundary elements.

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