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IMPROVED SEISMIC BRACED WALL REQUIREMENTS FOR CONVENTIONAL WOOD-FRAME BUILDINGS

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ABSTRACT

Wood-frame construction of single-family and low-rise multi-family dwellings in North America is largely designed and built to meet prescriptive requirements found in building codes, as opposed to being designed by detailed engineering methods. In the US and Canadian codes, the minimum lateral resistance for this type of building to resist high earthquake loading is typically expressed by the "total length of braced wall panels" as a percentage of the building length parallel to the direction of seismic loading. An improved method is presented for specifying this total braced length for conventional wood-frame buildings based on the floor area of the building. This method can readily be adapted for conventional wood-frame construction in the US and Canadian building codes.

Introduction

Wood-frame construction is by far the most common structural system in North America for single-family houses and low-rise multi-family dwellings, constituting over 80% of all residential housing (Fischer et al. 2001). In North-America, wood-frame construction can be built either by following prescriptive codes or by engineering design codes. Conventional wood-frame buildings in Canada are designed and built according to the prescriptive rules of Part 9 of the National Building Code of Canada (NBCC 2005), and in the USA, the International Residential Code (IRC 2009).

Wood-frame buildings designed and constructed with the prescriptive rules have performed well in past earthquakes and resulted in relatively few casualties (Rainer and Karacabeyli 1999, 2000). Recent shake table tests carried out in North America and elsewhere of both engineered and conventional wood-frame building specimens subjected to a variety of amplitudes and types of earthquake motions have further affirmed the good performance of this type of construction (Fischer et al. 2001, Mosalam et al. 2002, Ventura et al. 2002, Rainer et al. 2007). A number of full-scale shake table tests of wood-frame buildings were also carried out in Japan. These shake table tests as well as additional full scale static and cyclic load tests on full-scale specimen buildings have complemented the field observations and affirmed the generally good seismic performance of wood-frame

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construction as it is commonly employed throughout North America and elsewhere.

The prescriptive rules in the codes for conventional wood-frame construction for housing and small buildings have been largely based on historical practice, augmented by pre-engineered solutions. Despite the past good seismic performance of these buildings there is an ongoing need to examine current building code provisions in light of recent field experience, laboratory testing, theoretical considerations, and changes in building technology and practice.

This study presents a brief survey of current seismic requirements for conventional wood-frame construction in Canada and the USA, followed by the presentation of a method for specifying the length of braced wall panels in the two orthogonal directions of conventional buildings as a function of the building area, rather than the current method of specifying a percentage of the building length. The area method would be expected to give more consistent results for seismic resistance of conventional buildings, especially those of rectangular shapes.

Current Seismic Requirements for Conventional Wood-Frame Construction

Canadian Wood Council (CWC) Design Guide

The 2004 CWC Design Guide (CWC 2004) requires that where the spectral acceleration S_a (0.2) is greater than 0.74 g, the minimum length of braced wall panels in the first storey shall be: a) 25% of braced wall length for one and two storey buildings, and b) 40% of braced wall length for three storey buildings. The minimum length of a braced wall panel is 1.2 m for interior walls with GWB sheathed on both sides and for exterior walls with wood-based panels sheathed on one side and GWB on the other. The distance from the end of the first or last braced wall panel to the building corner shall not exceed 2.4 m, and the distance between braced wall panels shall not be greater than 6.4 m. Maximum building dimension in high seismic areas is 15.0 m and the spacing between braced wall lines shall not be greater than 7.6 m for $0.99\ g < S_a\ (0.2) \leq 1.2\ g$, 10.6 m for $0.74\ g < S_a\ (0.2) \leq 0.99\ g$ and 12.2 m for $S_a\ (0.2) \leq 0.74\ g$, where S_a (0.2) is the design spectral acceleration in the short period range. Hold-downs are generally not required for conventional construction.

National Building Code of Canada (NBCC)

The current 2005 National Building Code of Canada (NBCC 2005) does not have specific seismic requirements for conventional wood-frame buildings. However, Appendix A-9.4.1.1.(3) of 2005 NBCC references the CWC Design Guide as an acceptable solution.

Bracing requirements to resist lateral loads due to high wind and earthquakes have now been proposed for Part 9 of 2010 NBCC. These are essentially the same as those in the 2004 CWC Guide except that instead of 1.2 m the minimum length of braced wall panel shall be 600 mm if the wall panel is located at the end of a braced wall band and connected to an intersecting braced wall, or 750 mm otherwise.

International Residential Code (IRC)

In the USA the 2009 International Residential Code (IRC 2009) contains seismic provisions that are applicable to one and two-family dwellings in Seismic Design Categories from A to E. For illustrative purposes of this presentation, only the requirements for Seismic Design Category D_1 will be discussed here, for which the Short Period Design Spectral Acceleration S_{DS} is between 0.67 and 0.83 g. Wood framed buildings are permitted up to 3 stories above grade having a maximum dimension of 50 feet (15.25 m). For buildings with wood structural panels of continuous sheathing located on a soil site "Class D", the amount of bracing is presented as "Minimum total length (feet) of braced wall panels required along each braced wall line" in Table R602.10.1.2(2) of IRC (2009). These total lengths amount to 17%, 38%, and 51% of the length of the braced wall line for the first story of, respectively, one, two and three story buildings with continuous sheathing. Braced wall lines at exterior walls shall have a minimum of 24-inch-wide (610 mm) panel applied to each side of the building corner or a hold-down device installed at the ends of the braced wall (R602.10.4.1). Minimum total braced wall length shall be at least 48 inches (1219 mm) (R602.10.1.2) and for a wall height of 10 feet (3048 mm) each braced wall panel shall be at least 30 inches (762 mm) in length for adjacent clear opening height up to 80 inches (2032 mm) (Table R602.10.4.2). Spacing of braced wall lines shall not exceed 25 feet (7620 mm) on center in both the longitudinal and transverse directions in each story, with some exceptions.

Area-Based Approach for Specifying Braced Wall Panel Lengths of Conventional Wood Frame Buildings

Because the seismic force on a building is a function of the mass of the building, the specifications of the length of braced wall panels as a constant percentage of building lengths are not compatible with the physics of the phenomenon. It would make more sense if the lengths of braced wall panels were a function of the mass of the building, or as a close approximation, the floor area of the building, since the floor and the roof are the major contributors to the total mass. Area-based methods are also employed in building codes for seismic resistance of conventional wood-frame buildings in New Zealand (NZS 1999) and in Japan (JGHLC 1998).

The area-based method

The area-based method will be illustrated for the proposed Part 9 provisions of the 2010 NBCC, but the principle is equally applicable to other codes.

The seismic base shear V is determined by the quasi-static force procedures in Part 4 of NBCC (2005)

$$V = 2/3\, I_E\, F\, S_a(0.20)\, W / (R_o\, R_d) \qquad (1)$$

where

I_E = earthquake importance factor of the structure (assumed to be 1.0)
F = site factor (assumed to be 1.0)
$S_a(0.20)$ = spectral response acceleration at period 0.20 seconds (fractions of gravity g)
R_d = ductility-related force modification factor (Rd = 2.0)
R_o = overstrength-related force modification factor (Ro = 1.7)
W = seismic weight, for a uniform building given by Eq. 2

$$W = A_r\, \omega_r + \tfrac{1}{2} A_w\, \omega_w + (n-1)(A_f\, \omega_f + A_w\, \omega_w) \qquad (2)$$

where A = area, ω = weight per unit area, and subscripts r, f and w refer to roof, floor and walls, respectively.

For uniform wall properties and identical floor weights, the total length of braced wall panels L_R required to resist the base shear along the main axes of a building is then:

$$L_R = \frac{V}{v_R} = \frac{\frac{2}{3} I_E}{R_d R_o} \frac{w_r (1+\lambda_r)\frac{A_r}{A_f} + (n-1) w_f (1+\lambda_f)}{v_R} S_a(0.2) A_f = K_R S_a(0.2) A_f \qquad (3)$$

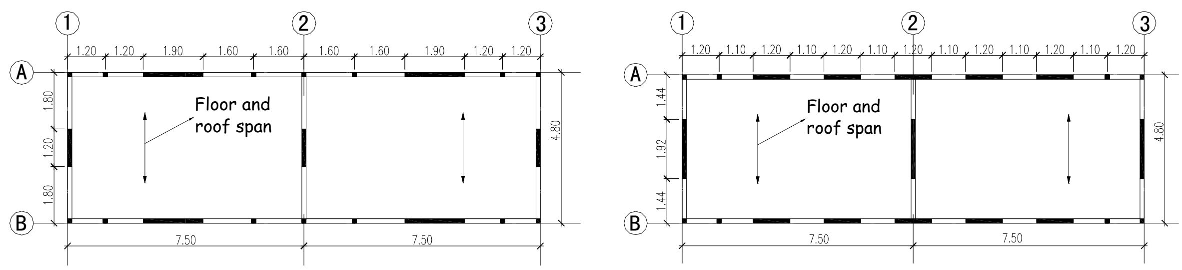
where

v_R = unit capacity of braced wall panels
n = number of storeys
λ_r = ½ $(A_w\ \omega_w) / (A_r\ \omega_r)$ = coefficient to account for the weight of interior and exterior walls of ½ storey height below the roof
λ_f = $(A_w\ \omega_w) / (A_f\ \omega_f)$ = coefficient to account for the weight of interior and exterior walls of ½ storey height above the floor and the same below the floor
K_R = factor representing total braced exterior wall length as a function of building area

Equation (3) was used to study the required braced wall lengths for seismic lateral resistance of the two building types described in the subsequent section. Initially the braced wall lengths will be determined for wall panels that are assumed fully restrained against uplift; the effect of partial restraint will be considered later.

Description of Buildings Studied

The first storey of buildings with two floor dimensions, 4.8 m × 15 m and 15 m × 15 m, that meet the minimum seismic bracing requirements of the CWC Design Guide and the proposed Part 9 of 2010 NBCC were considered. For each dimension, buildings of one, two and three storeys were studied. The length of 15 m represents the maximum building dimension allowed in Canadian codes for high seismic regions. The building length of 4.8 m represents the smallest building dimension which meets the requirements of minimum 25% of braced wall length and 1.2 m braced wall panel. Plan views of the building layout are shown in Figures 1 and 2.



a) First storey floor layout of one- and two-storey building

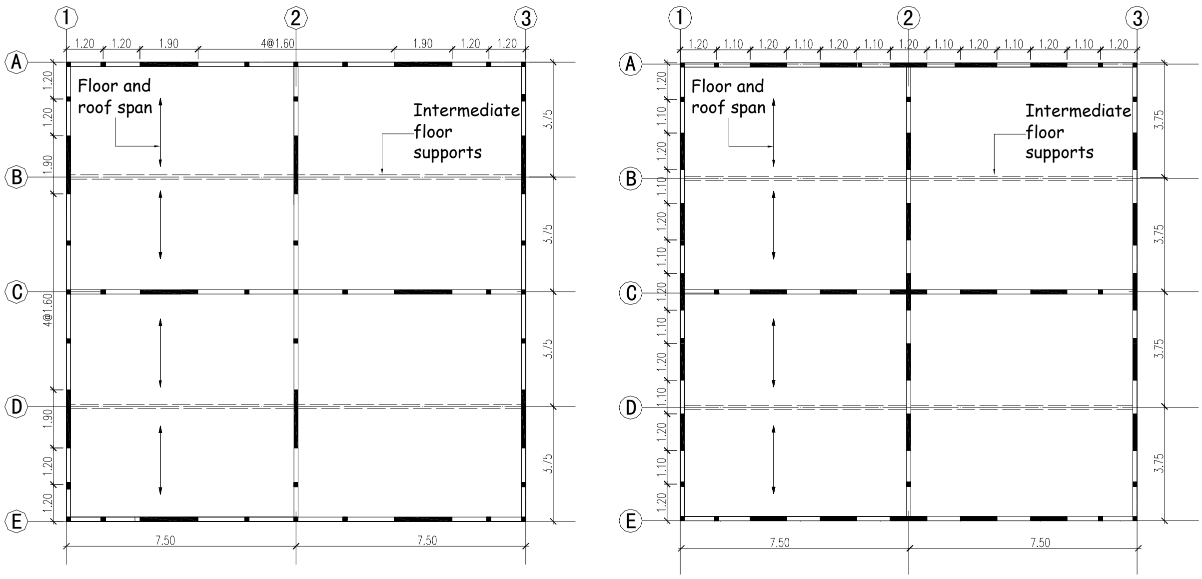
b) First storey floor layout of three-storey building

Figure 1 Plan views of the first storey of 4.8 m × 15 m buildings in accordance with the bracing requirements in Canadian codes

The lengths and locations of the braced wall panels were chosen to represent as much as possible the most unfavourable case for lateral load resistance. Thus, panels are located at or close to the maximum permitted distance of 2.4 m from the building corners and the maximum distance between braced wall panels is 6.4 m. Although the sample buildings may have less than optimum architectural and functional features, they nevertheless satisfy the minimum building code requirements and therefore could be built. In reality, wood-frame houses generally contain more walls than the minimum wall lengths required by building codes, and thus would possess larger lateral resistance than the minimum required.

The buildings studied have storey height of 3.0 m and the roof area is 20% greater than the floor area. The unit weights are: exterior and interior walls 0.25 kPa, floors 0.5 kPa, and the roof 1.0 kPa including 0.50 kPa snow load.

Exterior walls consist of spruce-pine–fir (SPF) studs spaced at 400 mm on center and 9.5 mm wood-based panels sheathed on one side and 12.5 mm gypsum wallboard on the other side. The wood-based panels are fastened to wall framing with 8d common nails (3.3 mm in diameter) spaced at 150 mm on center at panel edges and 300 mm at intermediate studs. Interior walls consist of SPF studs spaced at 400 mm on center and 12.5 mm gypsum wallboard on both sides. The gypsum wallboards are fastened to wall framing with drywall screws spaced at 200 mm on center at panel edges and intermediate studs.



a) First storey floor layout of one- and two-storey building

b) First storey floor layout of three-storey building

Figure 2 Plan views of the first storey of 15 m × 15 m buildings in accordance with the bracing requirements in Canadian codes

The lateral load capacities, v_R, of fully restrained exterior and interior walls are 5.48 kN/m and 1.96 kN/m, respectively (CSA 2001). For the regular buildings the unit weights are the same as for the example buildings above; for the heavy buildings the unit weights are 1.6 kPa for tile roof (including 0.50 kPa snow), 1.3 kPa for concrete-topped floor, and 0.25 kPa for interior and exterior walls.

A third set of buildings of floor dimensions 5.0 m x 5.0 m was also considered, these having the same material properties and loadings as the previous two sets of buildings.

Numerical results

For the case where only the fully restrained exterior walls are assumed to resist the seismic shear, the factor K_R is presented in Table 1.

Table 1 Factor K_R (units of 1/m) for fully restrained exterior walls of the buildings considered.

	Size (m)	Supporting roof only	Supporting roof plus one floor	Supporting roof plus two floors	Supporting roof plus three floors
Regular buildings	15 x 15	0.048	0.077	0.106	0.134
	4.8 x 15	0.051	0.086	0.120	0.155
	5 x 5	0.054	0.093	0.132	0.172
Heavy buildings	15 x 15	0.074	0.131	0.188	-
	4.8 x 15	0.077	0.140	0.203	-
	5 x 5	0.079	0.147	0.216	-

It may be observed that with increasing number of storeys, K_R increases as the floor area decreases. This is due to the fact that the ratio of wall area A_w to the floor area A_f is not constant for different sizes of square and rectangular building shapes.

For the 15 x 15 m buildings the resulting lengths of fully restrained exterior braced walls are presented in Table 2 for different seismic design spectrum values $S_a(0.20)$.

Table 2. Total required length L_R of fully restrained exterior braced wall panels in each direction for the 15 x 15 m example buildings.

Building Type	$S_a(0.2)$	$L_R = K_R \times S_a(0.2) \times A_f$, (m)			
		Supporting roof only	Supporting roof plus one floor	Supporting roof plus two floors	Supporting roof plus three floors
Regular building	0.75	8.1	13.0	17.9	22.7
	1.0	10.8	17.3	23.9	30.2
	1.2	13.0	20.8	28.7	36.2
Heavy building	0.75	12.5	22.1	31.7	-
	1.0	16.7	29.5	42.3	-
	1.2	20.0	35.4	50.8	-

For a building with both exterior walls and interior braced partition walls, the length of exterior walls plus 40% length of interior walls in each of the two orthogonal building directions should be equal to or greater than the total required length of exterior braced walls in Table 2, since the capacity of the interior wall is approximately 40% that of the exterior walls.

Adjustment factors for partially restrained braced walls

As was noted before, the required lengths of braced wall panels in Table 2 were developed based on the assumption that the braced wall panels are fully restrained and therefore have reached their full capacity. This assumption is not always true for a "Part 9" building. Depending on the amount of restraints, the lateral load capacity of a braced wall could vary from minimum capacity with no restraint, to maximum capacity if uplift is fully prevented. As a result, the required lengths of braced walls in Table 2 need to be adjusted according to the boundary conditions of the wall.

Many factors affect the lateral load capacity of a braced wall. For example, gravity load on the braced wall could greatly increase the lateral load capacity of a braced wall (Ni and Karacabeyli 2000, 2002). Where the gravity load is large enough to prevent uplift, the braced wall is then fully restrained and the full capacity can be reached. The floor and/or the storey above the braced wall also have a direct impact on the lateral load capacity of the braced wall (Liu et al. 2006). A stiff floor and/or upper storey could provide significant restraint to counteract the uplift force and thus provide increased lateral resistance. In addition, transverse walls attached to the ends of the shear walls and sheathing above and below openings in the braced wall provide further resistance to the uplift at the ends of the full-height bracing panels (Cheng et al. 2006).

Because of the many combinations of braced wall configurations and difficulty to fully quantify the contribution of above factors, it was decided that a conservative adjustment factor be developed based on a braced wall panel in the most unfavorable conditions in a NBCC Part 9 building. For wall panels partially restrained against uplift, the lateral load capacities were determined based on a mechanics-based method that takes into account the dead load on the braced wall (Ni and Karacabeyli 2000, 2002). The adjustment factors were then developed from the ratios of the lateral load capacities of partially restrained walls and fully restrained walls of the sample buildings. These ratios were then further reduced based on panel tests that showed substantial increases in capacity due to restraints arising from top beams in wall, roof and floor construction (Cheng et al. 2006, Liu et al. 2006, Ni 2009). For heavy buildings, the increased dead load would further assist in preventing uplift, therefore increasing the lateral load capacity of braced walls. As a result the adjustment factors decrease. A summary of the resulting adjustment factors is provided in Table 3.

Table 3 Adjustment factors for the total required length of braced wall panels in Table 2

Building type		**Supporting roof only**	**Supporting roof plus one floor**	**Supporting roof plus two floors**	**Supporting roof plus three floors**
Regular building	Loadbearing	1.4	1.2	1.1	1.0
	Non-loadbearing	1.6	1.4	1.3	1.2
Heavy building	Loadbearing	1.2	1.0	1.0	-
	Non-loadbearing	1.4	1.2	1.1	

Summary and Conclusion

A method is presented for specifying the minimum total length of braced wall panels in the first storey of conventional wood-frame buildings as a function of floor area of the building. This area-based method is considered an improvement over current methods of specifying the required length as a percentage of building length since it would result in identical seismic capacities in both orthogonal direction of a building. The procedure can readily be adapted for conventional wood-frame construction in the US and Canadian building codes.

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References

AWC, 2001. *Wood Frame Construction Manual (WFCM) for One-, Two- and Three-Family Dwellings*, 2001 Edition, American Wood Council, Washington DC, 20036

Cheng, H., Ni, C., Lu, X., and Karacabeyli, E. 2006. Effect of transverse walls and vertical load on the performance of shear walls, *Proceedings of World Conference on Timber Engineering*, Portland OR.

CSA, 2001. *Engineering Design in Wood*, Standard CSA O86-01, Canadian Standards Association, 178 Rexdale Boulevard, Etobicoke, ON.

CWC, 2004. *Engineering Guide for Wood Frame Construction*, Canadian Wood Council, Ottawa, ON.

Fischer, D., Filiatrault, A., Folz, B., Uang, C-M., and Seible, F., 2001. *Shake table tests of a two-story wood-frame house*. Department of Structural Engineering, University of California, San Diego; *CUREE publication No. W-06*, Richmond, CA.

IRC, 2009. *International Residential Code for One- amd Two-Family Dwellings*, 2009 Edition. International Code Council, Inc., Falls Church VA.

JGHLC 1998. Japanese Government Housing Loan Corporation, *General Specifications for Wood Frame Housing – 2x4 Type*, translation from Japanese by Council of Forest Industries (COFI), Vancouver BC.

Liu Y., Ni C., Rainer H., and Lu W.S., 2006. Effect of upper storey / floor on the performance of wood shear walls, *Proceedings of World Conference on Timber Engineering*, Portland, OR.

Mosalam, K.M., Machado, C., Gliniorz, K.-U., Naito, C., Kunkel, E., and Mahin, S. 2002. Seismic Evaluation of an Asymmetric Three-Storey Wood-frame Building. *CUREE publication No. W-19.* Richmond, CA.

NBCC 2005. *National Building Code of Canada*, 2005 Edition, National Research Council of Canada, Ottawa, ON.

Ni, C. and Karacabeyli, E. 2000. Capacity of Shear Wall Segments Without Hold-Downs, *Proceedings, World Conference of Timber Engineering*, Whistler BC, paper 2-3-1.

Ni, C. and Karacabeyli, E. 2002. Capacity of shear wall segments without hold-downs, *Wood Design Focus*, Summer 2002, p. 10 – 17.

Ni, C., 2009. Wind and seismic design provisions for small wood buildings – Part A: Seismic, FPInnovations Forintek Division – Wastern Laboratory, Vancouver, BC, Prepared for Canadian Forest Service, Ottawa, ON, March 2009.

NZS, 1999. *Timber Framed Buildings*, New Zealand Standard NZS 3604:1999.

Rainer, J.H. and Karacabeyli, E., 1999. Performance of Wood-frame Building Construction in Earthquakes. *Special Publication No. SP-40*, FPInnovations Forintek Division, Vancouver BC.

Rainer, J. H, and Karacabeyli, E., 2000. Performance of wood-frame construction in past earthquakes, *Proceedings of 12th World Conference on Earthquake Engineering*, Auckland, New Zealand, 30 Jan. – 4 Feb, 2000.

Rainer H., Ni C., Cheng H., Li H., Lu W., Lu X. and Karacabeyli E., 2007. Research on seismic resistance of conventional wood-frame buildings, *Proceedings, Ninth Canadian Conference on Earthquake Engineering*, Ottawa, ON, 26-29 June 2007.

Ventura, C.E., Taylor, G.W., Prion, H.G.L., Kharrazi, M.H.K. and Pryor, S., 2002. Full-Scale Shaking Table Studies of Wood-frame Residential Construction. *Proceedings, 7th US National Conference on Earthquake Engineering*, July 21 – 25, Boston MA, p.528.