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HIGHLIGHTS OF THE SEISMIC DESIGN GUIDE FOR MASONRY BUILDINGS

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ABSTRACT

Changes in the seismic design provisions contained in Part 4 of the National Building Code of Canada 2005 (NBCC 2005) and the CSA S304.1-04 masonry design standard impact masonry design and construction in Canada. The Canadian Concrete Masonry Producers Association has responded by sponsoring the development of the *Seismic Design Guide for Masonry Buildings*. CSA S304.1-04 does not contain a commentary explaining the underlying theoretical background and rationale for the requirements in the standard. The Guide fills this need by explaining the seismic provisions of the standard and of the NBCC, and is intended to assist practicing structural engineers in the seismic design of concrete masonry elements for low- to medium-rise structures.

This paper presents highlights of the Guide, which includes a review of the general seismic design provisions contained in Part 4 of NBCC 2005, an overview of CSA S304.1-04 seismic design requirements for reinforced masonry walls, and a summary of the differences in the seismic design provisions contained in the 1995 and 2005 editions of NBCC and the 1994 and 2004 editions of CSA S304.1 including a case study of a typical warehouse building designed to both NBCC 1995 and NBCC 2005 for three Canadian locations characterized by different seismic hazard (Vancouver, Calgary, and Toronto).

The guide also provides twelve design examples that illustrate seismic load calculations and distribution of forces to building elements in accordance with NBCC 2005, and the design of masonry shear walls in accordance with CSA S304.1-04. Research needs and code issues emerging from the development of this guide are also presented.

KEYWORDS: concrete masonry, seismic design, reinforced masonry, shear walls, CSA S304.1-04

INTRODUCTION

Changes in the seismic design provisions contained in Part 4 of the 2005 NBCC [1] and the CSA S304.1-04 masonry design standard [2] impact masonry design and construction in Canada. The Canadian Concrete Masonry Producers Association has responded by sponsoring the development of the *Seismic Design Guide for Masonry Buildings,* referred to as the Guide in this paper [3]. CSA S304.1-04 does not contain a commentary outlining the underlying theoretical background and rationale of the code requirements. The Guide addresses this need by explaining the seismic provisions of the standard. It is a comprehensive state-of-the-art guide to the seismic design and construction of masonry structural elements in low- to medium-rise structures, such as warehouses, industrial buildings, schools, commercial buildings, and residential/hotel structures. The Guide is restricted to masonry structures designed using concrete block units, although most concepts are applicable to designs using clay brick units.

This paper provides a general overview of the Guide contents, along with summaries of three specific topics: seismic design requirements; key changes in codes and standards; and research needs.

AN OVERVIEW OF THE GUIDE

The material is presented in a simple and user-friendly manner. It facilitates the application of seismic design provisions, and provides cross-referencing of code clauses. The Guide has been developed in a modular form, with the content divided into four chapters, each of which can be used in a stand-alone manner. The appendices contain useful resources such as design procedures, and provide research background for some of the design provisions. For easy reference, relevant code clauses have been identified by framed boxes wherever appropriate. A "road map" summarizing the content of the Guide is presented in Table 1.

Chapter 1 provides a review of the general seismic design provisions contained in Part 4 of NBCC 2005, including seismic hazard levels and the equivalent static force procedure. It discusses key design parameters such as irregularities, torsion, height limitations, and ductility and overstrength factors for masonry structures. Additionally, there is an introduction to the dynamic analysis of structures to assist in understanding pertinent code provisions. Since there are major changes to the seismic provisions in NBCC 2005, some comparisons with the previous 1995 edition of the building code are included in Appendix A.

Chapter 2 provides an overview of seismic design requirements for reinforced masonry walls. Relevant CSA S304.1-04 requirements are presented, along with related commentary that provides detailed explanations of the code provisions. Topics include reinforced masonry shear walls subjected to in-plane and out-of-plane seismic loads, with a detailed discussion of the CSA S304.1 seismic design requirements. A few special topics such as masonry infill walls, stack pattern walls, masonry veneers, and construction-related issues are also included. Changes in CSA S304.1-04 seismic design requirements from the previous (1994) edition are identified and discussed, along with their design implications. Appendix B contains resources related to the Chapter 2 content, including findings of research studies and foreign code provisions related to seismic design of masonry structures.

Chapter 3 summarizes differences in seismic design provisions contained in the 1995 and 2005 editions of NBCC, and the 1994 and 2004 editions of CSA S304.1. Designers who are already familiar with the detailed seismic and masonry design issues discussed in Chapters 1 and 2 may wish to move directly to this summary chapter. The differences in code provisions have been presented in a tabular format. This chapter also summarizes the results of a case study of a typical warehouse building designed to both NBCC 1995 and NBCC 2005 for three Canadian locations characterized by different seismic hazard (Vancouver, Calgary, and Toronto).

Table 1: Seismic Guide – Road Map [3]

Chapter 1	**NBCC 2005 Seismic Provisions**	
Objective: to provide background on seismic response of structures and seismic analysis methods and explain key NBCC 2005 seismic provisions of relevance for masonry design		**DETAILED NBCC SEISMIC PROVISIONS**
Chapter 2	**Seismic Design of Masonry Walls to CSA S304.1**	
Objective: to provide background and commentary for CSA S304.1-04 seismic design provisions related to reinforced concrete masonry walls, and discuss the revisions in CSA S304.1-04 seismic design requirements with regard to the 1994 edition		**DETAILED MASONRY DESIGN PROVISIONS**
Chapter 3	**Summary of Changes in NBCC 2005 and CSA S304.1-04 Seismic Design Requirements for Masonry Buildings**	
Objective: to provide a summary of NBCC 2005 and CSA S304.1-04 changes with regard to previous editions (NBCC 1995 and CSA S304.1-94), and to present the results of a design case study of a hypothetical low-rise masonry building to illustrate differences in seismic forces and masonry design requirements due to different site locations and different editions of NBCC and CSA S304.1		**SUMMARY OF NBCC AND S304.1 CHANGES**
Chapter 4	**Design Examples**	
Objective: to provide illustrative design examples of seismic load calculation and distribution of forces to members according to NBCC 2005, and the seismic design of loadbearing and nonloadbearing masonry elements according to CSA S304.1-04		**DESIGN EXAMPLES**
Appendix A	**Relevant NBCC 1995 Seismic Design Provisions with Comparisons to NBCC 2005**	
Appendix B	**Research Studies and Code Background Relevant to Masonry Design**	
Appendix C	**Relevant Design Background**	
Appendix D	**Design Aids**	
Appendix E	**Notation**	

Chapter 4 provides illustrative design examples of seismic load calculations and distribution of forces to members according to NBCC 2005, and the design of loadbearing and nonloadbearing masonry elements. The layout of masonry buildings and the mechanical properties of their components in the examples have been chosen to reflect situations often encountered in design practice, particularly as they relate to torsionally unsymmetric buildings. These examples have been laid out in a step-by-step manner, with ample explanations and appropriate illustrations provided to clarify the design process. Appendix C provides relevant background information for the design examples, including an extensive discussion of in-plane wall stiffness. Appendix D contains design aids used in the Chapter 4 examples.

SEISMIC DESIGN REQUIREMENTS FOR MASONRY SHEAR WALLS

Table 4.1.8.9 of NBCC 2005 identifies the following five classes of masonry walls, based on expected seismic performance quantified by the ductility-related force modification factor, R_d, and height restrictions:

1. Unreinforced masonry and other masonry structural systems not listed below ($R_d = 1.0$)
2. Shear walls with conventional construction ($R_d = 1.5$)
3. Limited-ductility shear walls ($R_d = 1.5$)
4. Moderately ductile shear walls ($R_d = 2.0$)
5. Moderately ductile squat shear walls ($R_d = 2.0$) (note that this wall class was not identified in NBCC 2005 Table 4.1.8.9, however specific design and detailing provisions are stipulated by S304.1-04 Cl.10.16.6).

The last three classes are referred to as "ductile shear walls", although shear walls with conventional construction and shear walls of limited ductility have the same R_d value. The difference between these wall classes rests in their detailing requirements and height limitations. The same value of overstrength factor, R_o, of 1.5 is prescribed for all the above listed wall classes except for unreinforced masonry where R_o is equal to 1.0.

CSA S304.1-04 Clause 4.6 outlines the classes of reinforced masonry walls, while the seismic design requirements are provided in Clause 10. CSA S304.1-04 seismic design and detailing requirements for various masonry Seismic Force Resisting Systems (SFRSs) are summarized in Table 2. The key requirements are related to the need for a capacity design approach, and for ductile detailing and grouting in the plastic hinge region of shear walls. CSA S304.1-04 minimum seismic reinforcement requirements for ductile shear walls are summarized in Figure 1.

In accordance with NBCC 2005 Cl.4.1.8.1.1, seismic design must be performed for a seismic hazard $S(0.2) > 0.12$, where $S(0.2)$ denotes the design spectral acceleration for a structure with the period of 0.2 sec. Reinforced masonry is required at sites for a seismic hazard index $I_E F_a S_a(0.2) \geq 0.35$ (S304.1-04, Cl.4.5.1). Note that the seismic hazard index is defined as a product of the earthquake importance factor of the structure, I_E, acceleration-based site coefficient, F_a, and the 5% damped spectral acceleration for the period of 0.2 sec, $S_a(0.2)$. As a result, reinforced masonry is required for some locations, particularly in Eastern Canada, which did not need reinforcement according to earlier editions of NBCC.

Table 2: Summary of Seismic Design and Detailing Requirements for Masonry SFRSs in CSA S304.1-04 [3]

Type of SFRS	Common applications	R_d	R_o	Expected seismic performance	Summary of CSA S304.1-04 design requirements	CSA S304.1 reinforcing and detailing requirements
Unreinforced masonry	Low-rise buildings located in low seismicity regions	1.0	1.0	Potential to form brittle failure modes	▪ Can be used only at sites where $I_E F_a S_a(0.2) < 0.35$ ▪ Walls must have factored shear and flexural resistances greater than or equal to corresponding factored loads	Reinforcement not required
Shear walls with conventional construction	Used for most building applications	1.5	1.5	Design to avoid soft stories or brittle failure modes	Walls must have factored shear and flexural resistances greater than or equal to corresponding factored loads	Minimum seismic reinf. requirements (Cl.10.15.2.2) apply if $I_E F_a S_a(0.2) \geq 0.35$, otherwise follow minimum non-seismic reinf. requirements (Cl.10.15.1.1)
Limited ductility shear walls	Used only when required to comply with the NBCC 2005 height restrictions (Table 4.1.8.9)	1.5	1.5	Limited dissipation of earthquake energy by flexural yielding in specified locations; shear failure to be avoided	▪ Can be used for shear wall design when height/length ratio $h_w / l_w \geq 1.0$ ▪ Walls to be designed using factored moment resistance such that plastic hinges develop without shear failure and local buckling ▪ Sliding shear failure at joints to be avoided ▪ Expected ductility level to be verified ▪ Wall height-to-thickness ratio restrictions prescribed	Minimum seismic reinforcement requirements (Cl.10.15.2.2) must be satisfied, as well as seismic detailing requirements for limited ductility walls (Cl.10.16.4)
Moderately ductile shear walls	Used for post-disaster or high risk buildings, or where $R_d = 2.0$ is desired	2.0	1.5	Dissipation of earthquake energy by ductile flexural yielding in specified locations; shear failure to be avoided	▪ Walls to be designed using factored moment resistance such that plastic hinges develop without shear failure and local buckling ▪ 50% reduction in masonry resistance for V_r calculations ▪ Sliding shear failure at joints to be avoided (additional requirements compared to limited ductility walls) ▪ Expected ductility level to be verified ▪ Wall height-to-thickness ratio restrictions more stringent than limited ductility walls	Minimum seismic reinforcement requirements (Cl.10.15.2.2) must be satisfied, as well as seismic detailing requirements for moderately ductile walls (Cl.10.16.5)

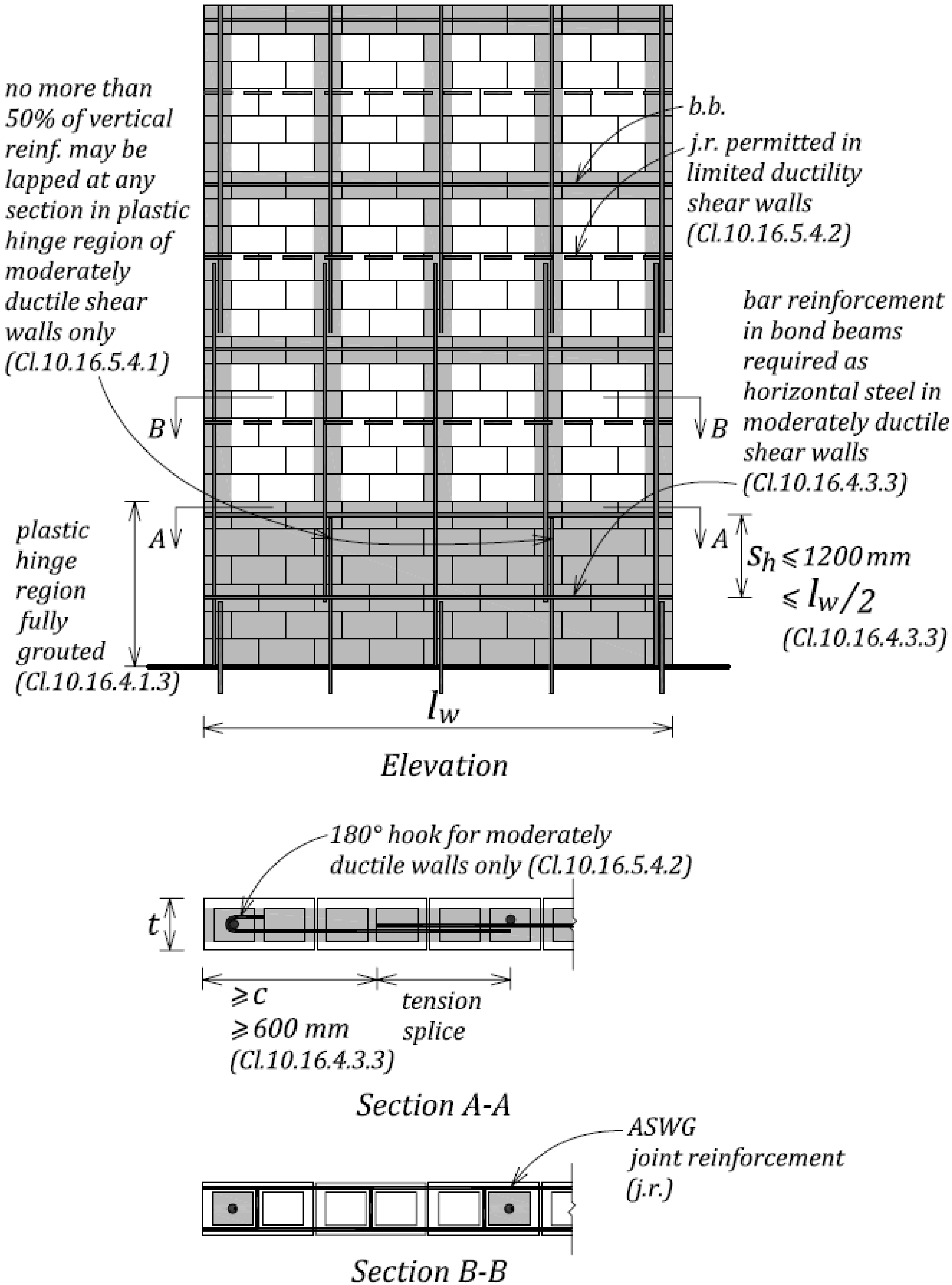

Figure 1: Summary of CSA S304.1 minimum seismic reinforcement requirements for ductile shear walls [3]

KEY CHANGES IN NBCC 2005 AND S304.1-04 SEISMIC PROVISIONS FOR REINFORCED MASONRY SHEAR WALLS AND THEIR DESIGN IMPLICATIONS

The classification of masonry walls has been expanded, and new definitions introduced in NBCC 2005 and CSA S304.1-04 as follows (note that new terms were introduced to provide consistency with the concrete design standard, CSA A23.3-04):

- New term "shear walls with conventional construction" (previously "reinforced masonry"),
- New term "limited ductility shear walls" (S304.1-04, Cl.10.16.4),
- New term "moderately ductile shear walls" (note that S304.1-94 used term "masonry with nominal ductility"), and
- New term "moderately ductile squat shear walls" (S304.1-04, Cl. 10.16.6).

Walls with "limited ductility" are a new classification with the same R_d and R_o values as "conventional construction", but are allowed higher height limits because of more stringent detailing requirements.

A new restriction has been introduced in NBCC 2005 (Sent. 4.1.8.10.2), by which post-disaster facilities are now required to have an SFRS with R_d of 2.0 or higher. The implication of this provision for masonry is that shear walls in post-disaster buildings must be designed to the CSA S304.1-04 provisions for either "moderately ductile shear walls", or "moderately ductile squat shear walls", both of which provide the required R_d of 2.0 (S304.1-04, Cl. 10.16.5 and Cl. 10.16.6).

Height-to-thickness ratio restrictions have been introduced for the ductile shear wall classes, that is, limited ductility shear walls (Cl.10.16.4.1.2), moderately ductile shear walls (Cl.10.16.5.2.2), and moderately ductile squat shear walls (Cl.10.16.6.3). The purpose of these provisions is to prevent instability due to out-of-plane buckling of shear walls when subjected to the combined effects of in-plane axial loads and bending moments. This provision was first introduced in the 1994 edition of CSA S304.1 (Cl.A5.2 related to "nominally" ductile walls) and is identical to the current CSA S304.1-04 provision for "moderately" ductile walls.

The height-to-thickness ratio restrictions for ductile shear walls have a significant affect on the required wall thickness in the plastic hinge zone located at the base of a wall. According to CSA S304.1-04, the unsupported wall height (h) limits for standard concrete block walls (190 mm nominal thickness) are as follows:

1. Limited ductility shear walls: maximum $h = 18(190 + 10) = 3600$ mm
2. Moderately ductile shear walls: maximum $h = 14(190 + 10) = 2800$ mm
3. Moderately ductile squat shear walls: maximum $h = 20(190 + 10) = 4000$ mm

Squat shear walls are very common in low-rise masonry construction, such as warehouses, schools and firehalls. Some of these buildings, firehalls for example, are defined as post-disaster facilities according to NBCC 2005, so the CSA S304.1-04 height-to-thickness restrictions for moderately ductile squat shear walls must be followed. However, S304.1 Cl.10.16.6.3 states that the h/t ratio limit for moderately ductile squat shear walls can be relaxed, if it can be shown for lightly loaded walls that a more slender wall is satisfactory for out-of-plane stability. A possible solution involves the provision of flanges at wall ends, as discussed in detail in the Guide. However, the out-of-plane stability of the compression zone, which includes the flange and sometimes a portion of the web, must be adequate.

RESEARCH NEEDS

Design codes and standards, such as NBCC 2005 and CSA S304.1-04 provide general guidance for the design of masonry shear walls subjected to seismic loads. However, due to insufficient experimental evidence, some code requirements for ductile shear walls appear to be overly conservative, and may lead to uneconomical designs that limit the use of masonry for post-disaster buildings. The height-to-thickness ratio limits in CSA S304.1-04 for ductile reinforced masonry shear walls, conservatively restricted to low values ranging from 14 to 20, are examples of such requirements.

Instability due to out-of-plane buckling of shear walls subjected to the combined effects of in-plane axial loads and bending moments is not only associated with compression in the masonry, but also with the compression stresses in the flexural reinforcement that has previously experienced large inelastic tensile strains. This instability occurs when there is a large neutral axis depth and the plastic hinge length is large (one storey high or more), which is typical for medium-rise buildings. These limits were prescribed to prevent out-of-plane instability of ductile masonry shear walls (as shown on Figure 2), however the code values do not appear to be supported by adequate evidence from Canadian experimental studies. There is limited international research evidence related to this subject [4].

A comprehensive research program is needed to: i) identify critical design parameters related to the stability of reinforced masonry shear walls under in-plane seismic loading, ii) develop a rational analysis procedure, and iii) propose revisions to the relevant CSA S304.1-04 seismic design provisions. The research could initially focus on squat reinforced masonry shear walls, since these walls are most commonly used for Canadian design applications, however a study on taller flexural shear walls is also of interest.

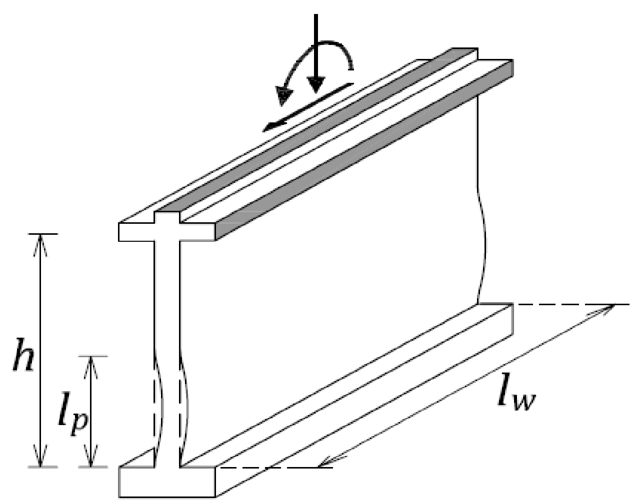

Figure 2: Out-of-plane instability in a shear wall subjected to in-plane loads [3]

CONCLUSIONS

This paper has provided an overview of a new publication titled *Guide to the Seismic Design of Low- and Medium-Rise Masonry Buildings in Canada*. The Guide is expected to serve as a useful resource for practicing engineers and students interested in gaining a thorough understanding of the seismic design provisions for masonry structures contained in NBCC 2005 and CSA S304.1-04. Several examples that illustrate real-life design applications are expected to be helpful in providing guidance to masonry designers in Canada, especially those with limited background and experience in seismic design and detailing.

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