Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No

NETWORK FOR REDUCING CANADIAN URBAN SEISMIC RISK

Denis Mitchell[1]

ABSTRACT

A new Strategic Research Network, "The Canadian Seismic Research Network", has been funded by the Natural Sciences and Engineering Research Council of Canada for a period of five years. The goal of the Network is to reduce urban seismic risk in Canada. The Network involves 26 researchers from eight universities across the country. Performance-based design guidelines will form the basis for developing evaluation and retrofit guidelines for critical infrastructure. The research program is divided into three themes. Theme 1, "Hazard Assessment", involves the development of probable ground motions, microzonation of key cities, assessing liquefaction potential, use of real-time ShakeMaps and assessing risk for some cities. Theme 2, "Vulnerability Assessment", involves the development of an inventory of structural deficiencies, rapid screening procedures, and includes projects examining the performance of masonry, concrete, steel and bridge structures as well as the performance of operational and functional components of buildings. Theme 3, "Mitigation" will examine seismic upgrading using supplemental damping devices, adding structural stiffness, implementing innovative materials, adding base isolators and upgrading of operational and functional components.

Introduction

The Canadian Seismic Research Network (CSRN) was formed with funding received from the Natural Sciences and Engineering Research Council of Canada. The Award is for a five-year period From October 2008 to September 2013. This paper describes the CSRN and the efforts being made to achieve the goal of reducing urban seismic risk in major cities in Canada.

The Need for the Network

A major study on natural hazards and disasters concluded that "a significant earthquake…is probably Canada's greatest potential natural disaster" (Etkin *et al* 2004). A high percentage of urban infrastructure was constructed prior to the introduction of modern seismic provisions in the mid-1970s, and thus there is a large inventory of deficient infrastructure that needs to be identified and upgraded. It is essential that Canada's critical urban infrastructure, hospitals, schools and bridges, remain operational after a seismic event.

The Network will focus on the major Canadian urban centers that dominate our national

[1]Professor, Dept. of Civil Engineering, McGill University, Montreal, QC and Program Leader of the Canadian Seismic Research Network (CSRN)

seismic risk: Vancouver, Victoria, Montréal, Ottawa, Toronto and Québec City; these cities comprise approximately 2/3 of Canada's population and more than ¾ of its seismic risk (Fig. 1).

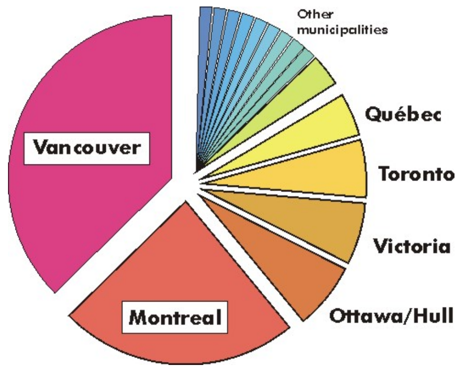


Figure 1. Relative contributions to seismic risk in Canada (Geological Survey of Canada).

Overview of the Network

Figure 2 shows the three interacting themes that have been developed to guide the activities of the Network. Fig. 3 illustrates the performance-based approach that will be used in the evaluation and possible retrofit of a structure. This figure also shows how the three themes are integrated into this performance based approach.

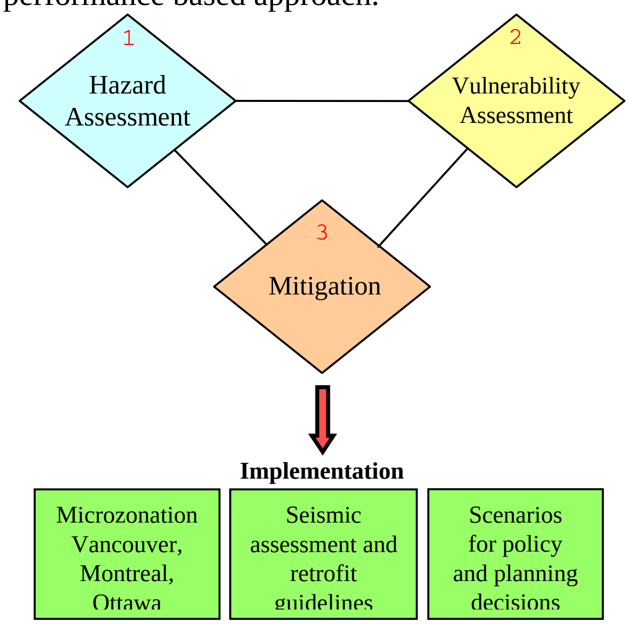


Figure 2. The three Research Themes and Deliverables.

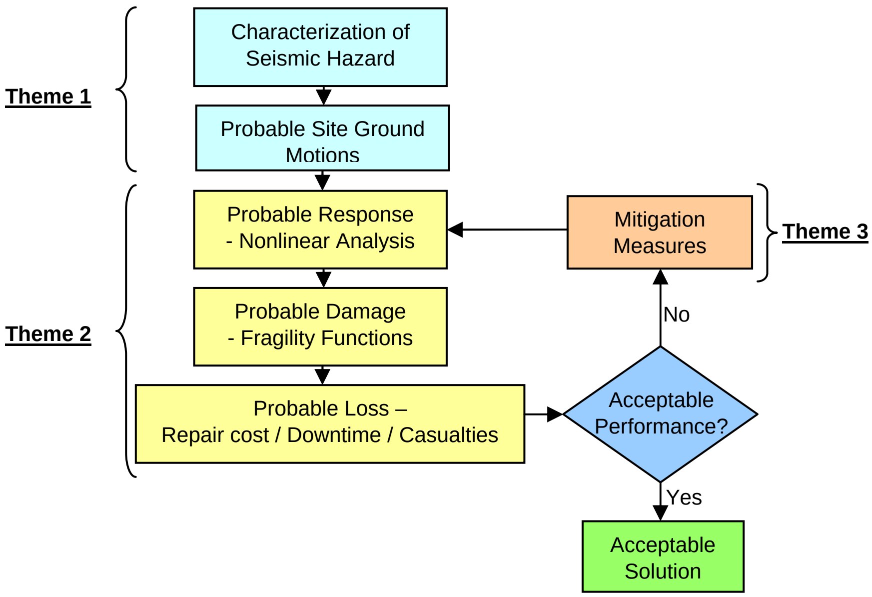


Figure 3. The integrated performance-based approach applied to evaluation and retrofitting.

Theme 1 – Hazard Assessment (Theme Leader: Gail Atkinson)

The five projects in theme 1 are described below.

Project 1.1 – Probable Ground Motions (Project Leader: G. Atkinson)

The objectives of this project are:

- Determine the expected ground motions at the 6 cities over a range of probabilities and provide updated Uniform Hazard Spectra (2% in 50 years)
- Develop time histories for nonlinear analyses including a range of return periods suitable for use in non-linear dynamic analyses, including Incremental Dynamic Analysis.

Project 1.2 – Microzonation Studies (Project Leaders: D. Motazedian and L. Chouinard)

Various techniques are being used to develop seismic microzonation maps for Vancouver, Ottawa and Montreal. These techniques include soil properties collected from borehole data, ambient noise measurements and determination of shear wave velocities. These studies enable the determination of fundamental frequencies, soil classification and the amplification factors. In September 2009, the Network completed the seismic microzonation of the city of Ottawa in collaboration with the Geological Survey of Canada.

Project 1.3 – Liquefaction Potential (Project Leader: L. Finn)

Project 1.3 involves assessing the liquefaction potential for susceptible areas in Vancouver, Ottawa and Montreal. Studies will include the evaluation of the potential for liquefaction for critical locations by determining the seismic shear stresses using seismic response analysis (non-linear analysis). Particular emphasis will be placed on the studies for

Richmond, British Columbia, an area with known susceptibility to liquefaction.

Project 1.4 – Real-Time ShakeMaps (Project Leader: G. Atkinson)

A ShakeMap program for Ontario, which provides rapid assessment of earthquake ground shaking and its likely effects across the province, within minutes of the occurrence of an earthquake was developed (Kaka and Atkinson 2005, 2006). A major goal of the Network is to extend the application of ShakeMaps to other regions of Canada. The researchers will work with the Geological Survey of Canada to achieve this goal. The deliverables for this project are: The development of real-time ShakeMaps for urban areas of Canada (incorporating microzonation) to provide rapid earthquake information, and the use of Scenario ShakeMaps to assist in emergency planning.

Project 1.5 – From Hazard to Risk (Project Leaders: C. Ventura and L. Chouinard)

In this project, seismic risk maps will be prepared for Vancouver, Ottawa and Montreal. The main tasks involved in assessing the seismic risk for a city are: determine the seismic hazard for various probabilities of exceedance and scenario earthquakes (from Project 1.1); determine ground motion amplification due to local soil conditions (from Project 1.2); compile a block-by-block building inventory classified into prevalent building types; assess the vulnerability of the building inventory using rapid screening guidelines (from Project 2.1); and assess building damage for selected levels of probability.

Theme 2 – Vulnerability Assessment (Theme Leader: Patrick Paultre)

The five projects in theme 1 are described below.

Project 2.1 – Inventory of deficiencies and Development of Rapid Screening Guidelines (Project Leaders: P. Paultre and K. Elwood)

Inventory of Deficiencies

The first step in this project is to identify and document common deficiencies in existing structures in Canada, designed and constructed prior to the introduction of modern seismic design codes. The inventory of older deficient urban infrastructure includes: unreinforced masonry buildings, concrete buildings and bridges, and steel structures. This is a crucial step in the research program and will drive the research needed to fill gaps in knowledge concerning the effects of these deficiencies such that evaluation and assessment guidelines can be developed.

Rapid Screening Guidelines

While a Canadian guideline for rapid seismic screening of buildings was developed in 1992 (NRC, 1992), the Network will update this document to reflect advancements in knowledge and code development that has taken place.

Project 2.2 – Masonry Buildings (Project Leader: K. Elwood)

Unreinforced Masonry Buildings:

Although the vulnerability of unreinforced masonry buildings is well known, these types of structures are prevalent in a variety of buildings such as schools, hospitals, government buildings, and port facilities. Figure 4 shows damage to a City Hall in Montréal East and a school in Chicoutimi, due to the moderate M5.9 1988 Saguenay earthquake in Québec. Considerable savings in the retrofit of such buildings can be achieved through an improved understanding of the probable seismic performance of URM buildings and quantification of the uncertainty in the seismic performance.

(a) Damage to Montréal East City Hall located 350 km from the epicenter

(b) Out-of-plane collapse of unreinforced masonry wall in school

Figure 4. Damage to unreinforced masonry structures in Québec due to the 1988 magnitude 5.9 Saguenay earthquake (Mitchell et al, 1990).

This research project will focus on experimental studies on out-of-plane response of masonry walls considering the influence of simultaneous in-plane shear demands and the consideration of mortar degradation in the seismic assessment.

Infilled Masonry Frames:

A very common type of construction involves concrete frames infilled with unreinforced masonry blocks. This type of construction was used in many structures such as hospitals, schools, government buildings, industrial facilities, etc. This structural system is known to have very poor performance in past earthquakes. The brittle unreinforced masonry, combined with non-ductile frames, results in severe damage to the masonry infill and the columns. Reversed cyclic loading tests will be performed on one-story infilled frames to characterize the behavior and to provide a benchmark for the seismic retrofit measures that will be developed in Theme 3.

Project 2.3 – Reinforced Concrete Buildings (Project Leader: D. Mitchell)

Concrete Frames:

Deficiencies in beam-column frame structures include: inadequate column confinement; inadequate shear resistance in columns and beams; lack of confinement and shear reinforcement in joints; insufficient and inappropriate location of lap splices of column longitudinal bars; and inadequate anchorage of beam reinforcement in joints. Full-scale beam-column and slab-column subassemblages will be tested under reversed cyclic loading to characterize the non-linear behaviour to develop performance-based evaluation procedures. Test data will be used to develop fragility functions for application in the performance-based assessment framework.

Concrete Shear Walls:

Typical deficiencies in walls of older structures include: inadequate lap splices located in regions of plastic hinging; lack of concentrated, well-confined bars at the ends of walls; and inadequate shear resistance. A combined experimental and numerical simulation effort is planned with researchers of the Network to investigate the deficiencies listed above. This joint effort will include the following experimental programs: reversed cyclic loading tests on full-scale specimens; shake table testing of reduced scale walls; pseudo-dynamic substructure testing of plastic hinge regions of walls; and reversed cyclic loading tests of squat walls.

Project 2.4 – Steel Structures (Project Leader: R. Tremblay)

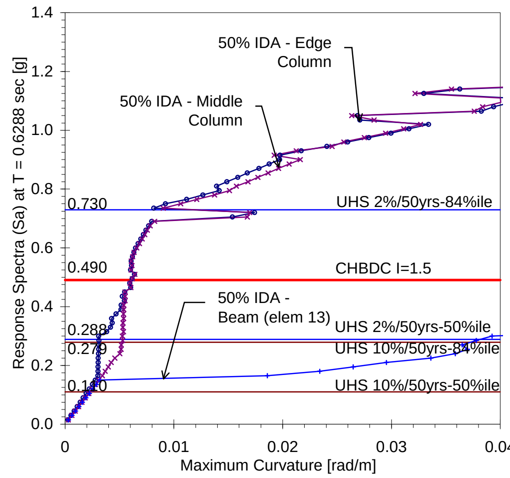
This project will concentrate on the study of typical construction details of potentially deficient concentrically braced frames in existing buildings (Tremblay 2001). Reversed cyclic loading testing of bracing members (angles, double angles, and HSS) and brace connections of typical old braced frame structures will be carried out to assess their inelastic deformation capacity. Hybrid testing will be also be carried out to evaluate the performance up to failure as well as residual lateral capacity when subjected to specific earthquakes such as expected ground motions from a Cascadia mega-thrust event, which will have very long duration.

Project 2.5 – Performance of Operational and Functional Components of Buildings (Project Leader: G. McClure)

Operational and functional components (OFCs) of buildings form a major portion of the cost of existing facilities and hence could represent a significant portion of the damage due to a seismic event (Aslani and Miranda 2003). These elements must remain operational in critical facilities (e.g., hospitals, schools) after a seismic event. Common deficiencies of OFCs include: improper attachment to the supporting structure; pipe breakages due to induced deformations; insufficient anchors for cladding; and inadequate anchoring of suspended ceilings. The research will contribute to the recently developed CSA Standard S832-06 on the Seismic Risk Reduction of Operational and Functional Components of Buildings (CSA 2006).

Project 2.6 – Bridge Substructures (Project Leaders: P. Paultre and Carlos Ventura)

After the identification and inventory of deficiencies that are common in older Canadian bridges (see Project 2.1), a collaborative experimental effort will be used to categorize the behaviour of typical deficiencies. The experimental program will evaluate the performance of concrete substructures such as single columns, multi-column bents and walls. This research will enable the determination of fragility curves to identify the most vulnerable types of bridges in different locations. This will also provide means for prioritizing bridges that need to have more detailed evaluations and retrofit. In addition to laboratory testing, detailed in-situ assessment of critical bridge structures will be conducted. Figure 5 shows an “emergency-route” bridge in the Montreal area for which detailed evaluation was carried out. Non-linear incremental dynamic analyses were performed, including the effects of local soil amplification (ground ambient noise measurements), the deteriorated concrete, the spalling of the concrete cover and the corrosion of the reinforcing bars. The cap beams are deficient in shear.



(a) "Emergency-route" bridge (b) Incremental dynamic analysis results

Figure 5. Detailed evaluation of "emergency-route" bridge in the Montréal urban Community (de la Puente et al. 2006)

The deliverables from this project include: development of fragility curves for deficiencies in bridge substructures based on experimental results and the revision of Section 4.12 "Seismic Evaluation of Existing Bridges" of the CSA Standard S6 "Canadian Highway Bridge Design Code" (CSA 2006) to provide a method for performance-based evaluation and retrofit of bridges.

Theme 3 – Mitigation (Theme Leader: Murat Saatcioglu)

The projects in this theme are:

Project 3.1 – Seismic Upgrade with Supplemental Damping Devices (Project Leader: C. Christopoulos)

This project will focus on developing methods for the design and implementation of supplemental damping systems for the seismic upgrading of deficient reinforced concrete and steel frame structures. The types of supplemental devices that will be investigated include hysteretic systems such as buckling restrained systems, steel yielding devices, viscous devices as well as self-centering braces. The main deliverable of this project will be a design guideline that will allow practising engineers to apply a true performance-based design approach to the retrofit of existing reinforced concrete and steel frame buildings to achieve higher seismic performance.

Project 3.2 – Seismic Upgrade with Added Stiffness (Project Leaders: R. Tremblay and P. Adebar)

One very effective method for the retrofit of existing buildings is to add key lateral load elements to the structure such that the vulnerable, more brittle elements are protected. This protection arises from the added stiffness and reduction of interstory drifts. This technique is particularly useful for deficient concrete frame and steel structures (see Fig. 6).

(a)Adding concrete shear walls to Ste-Justine Hospital, Montréal, 2007

(b) Adding steel bracing to Lions' Gate Hospital, North Vancouver, 2006

Figure 6. Upgrading with added stiffness.

Project 3.3 – Seismic Upgrade Using Innovative Materials (Project Leader: M. Saatcioglu)

Fibre Reinforced Polymers (FRP):

The use of FRP to seismically upgrade infilled masonry walls and unreinforced masonry walls will be investigated. Preliminary studies show promise for the use of FRP sheets and FRP strips for upgrading (Saatcioglu et al 2005). The researchers will also investigate the beneficial effects of using FRP wraps to aid in the confinement of reinforced concrete bridge columns.

Diagonal Prestressing for Lateral Bracing:

The use of diagonal prestressing provides an effective lateral bracing technique for the retrofit of non-ductile reinforced concrete frames. The high-strength prestressing strands and initial prestressing forces are designed to provide sufficient lateral bracing. As the frame sways the prestressed bracing develops additional tensile stresses along the "tension" diagonal, while relieving tension along the "compression" diagonal.

Fibre-Reinforced Concrete:

Fibre-reinforced concrete in conjunction with normal reinforcement can be used for reinforced concrete jacketing of deficient reinforced concrete elements. This type of retrofit is particularly applicable to the seismic retrofit of bridge columns in eastern Canada with the severe exposure conditions due to freeze-thaw cycles and the use of deicing salts. These severe exposure conditions, together with the fact that some existing bridge columns are suffering from alkali-silica reaction (ASR) has resulted in premature spalling of the concrete cover and corrosion of the reinforcing steel. The fibre reinforced concrete, with its ability to control cracking, provides additional protection of these critical members.

Project 3.4 – Seismic Upgrade with Base Isolators (Project Leader: C. Christopoulos)

Buildings:

The experimental phase of the program will include full-scale dynamic component tests on lead-rubber and sliding friction devices. Ground motions determined in Theme 1 for west coast and east coast earthquakes will provide the necessary input motions for testing and analysis. The analytical phase of the program will look at the vulnerability of existing structures to assess what level of seismic isolation is necessary to avoid any intervention or limit the intervention) to the superstructure while assuring that the system achieves the desired high performance levels.

Bridges:

The research carried out on base isolation of buildings will also be adapted for the seismic retrofit of bridges. The combination of using seismic base isolation, together with more realistic assessment of the expected range of ground motions will permit performance-based techniques to be applied to assess the improved seismic response of existing bridges. The research will result in the development of provisions for using seismic base isolation in the Canadian Highway Bridge Design code (CSA 2006). The Commentary to this code will reflect the performance based design techniques developed in this Network.

Project 3.5 – Seismic Upgrade of Operational and Functional Components: Project Leader: C. Ventura)

This project is aimed at replacing deficient supports for Operational and Functional Components (OFCs) in critical buildings (e.g., hospitals and schools). The methodology adopted will link the capacity and ductility of OFC support connections to their seismic vulnerability level. A performance-based approach will be applied to the assessment of retrofit techniques.

The Research Team

The names of members of the multi-disciplinary research team members are given in Table 1. The researchers have expertise in the following areas: engineering seismology and seismic hazard; geotechnical engineering; structural behavior and design (steel, concrete, masonry, energy dissipating devices, dynamic analysis, evaluation, retrofit); risk and reliability engineering; public policy; disaster management; and information technology.

Table 1. The Multi-Disciplinary Network Team

McGill University, Montréal	Denis Mitchell, Luc Chouinard, Ghyslaine McClure, Colin Rogers
University of Sherbrooke, Sherbrooke	Patrick Paultre, Jean Proulx, Frédéric Légeron
École Polytechnique, Montréal	Robert Tremblay, Pierre Léger, Najib Bouaanani, Sanda Koboevic, Bruno Massicotte
University of Ottawa, Ottawa	Murat Saatcioglu, Dan Palermo
Carleton University, Ottawa	David Lau, Dariush Motazedian
University of Toronto, Toronto	Constantin Christopoulos
University of Western Ontario, London	Gail Atkinson, Krity Tiampo, Gordon McBean
University of British Columbia, Vancouver	Ken Elwood, Carlos Ventura, Terje. Haukaas, Liam Finn, Perry Adebar, Stephanie Chang

Partner Organizations

Thirty-three Partner Organizations interact with the researchers and graduate students of the Network. These Partner Organizations represent the following sectors: federal government agencies; provincial government agencies; municipalities; consulting engineering firms; utilities and Industry; and emergency preparedness agencies.

Acknowledgments

The researchers of the Canadian Seismic Research Network gratefully acknowledge the financial support of the Natural Sciences and Engineering Research Council of Canada under the Strategic Research Networks program.

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