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BRIEF HISTORY OF EARTHQUAKE ENGINEERING RESEARCH AT CANADIAN UNIVERSITIES

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ABSTRACT

Canadian universities have long been involved in research related to earthquake engineering. This research embraces many different fields related to earthquakes and their impact including seismology, earthquake hazard and risk, geotechnical engineering, structural engineering, and societal issues. The present paper focuses on the history of research in structural engineering aspects of the mitigation of earthquake risk. A number of research groups and individual faculty have carried out analytical and experimental research in the area covering a broad spectrum of issues such as structural analysis and design, component and system response, material behaviour and system isolation. The research has had significant impact on the seismic design provisions of the National Building Code of Canada. The major groups working on the structural aspects of earthquake engineering are located at École Polytechnique and McGill University in Montreal, University of Sherbrooke, University of Ottawa and Carleton University in Ottawa, University of Toronto, McMaster University in Hamilton, and the University of British Columbia in Vancouver. The Canadian Association of Earthquake Engineering actively promotes earthquake engineering research and has an ongoing project to maintain a database of such research at Canadian universities.

Introduction

The history of earthquake engineering in Canada can be traced back to 1897 when the first Canadian seismogram was recorded on an instrument at McGill University. Finn (2004) provides an interesting account of the early years of earthquake engineering activity in Canada and relates the history of such activity until 2004. Research in the structural aspects perhaps began in the mid 50s with the publication of the first seismic design provisions in the National Building Code of Canada in 1953. The mid 60s saw a marked growth in such research and the establishment of graduate programs in the area at several universities. Since then university research in earthquake engineering has made great strides; several advanced experimental facilities have been established and organized research groups and networks of research have been formed. The investment at Canadian universities in seismic research infrastructure is

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estimated at a total of $80 million.

Quebec Universities

Three major universities located in Quebec, McGill University and École Polytechnique in Montreal, and the University of Sherbrooke, have collaborated extensively in earthquake related research. The three universities have established a joint research centre called Quebec Inter-university Major Infrastructure Center (CISMIQ). The Centre has one of the largest concentrations of specialized infrastructure for research in earthquake engineering. Many of the research projects have been carried out jointly under the supervision of faculty members from two or all three universities.

McGill University

McGill has a long history of earthquake engineering research. In fact, the first Canadian symposium on design for earthquake loadings was held at McGill in September 1966 and the first Master's thesis in a related area was completed in 1968. Ever since, McGill researchers have actively participated in earthquake engineering research and in developing code provisions for seismic design. The research focus at McGill covers a wide range of areas from concrete elements and structures including retrofitting, steel structures, cold formed steel structures, post-critical building functionality, system identification with ambient noise measurements, telecommunication structures, and risk and vulnerability analysis for individual buildings as well as for urban regions.

Laboratory test facilities at McGill include a 11.4 MN MTS structural testing machine, MTS dynamic loading rams, test frames for shear wall-coupling beam (Figs. 1 and 2), wall panels, reversed cyclic loading, and a structural testing strong floor.

Figure 1. Frame for testing wall panels, McGill

École Polytechnique de Montréal

Research at École Polytechnique is focused on steel and concrete structures and seismic response of dams and earth structures. Experimental studies over the past 10 years have included seismic testing of reinforced concrete shear walls (Figure 3), tests on timber shear walls made of plywood sheathing screwed to cold formed studs, dynamic testing of steel roof diaphragms (Figure 4) and multi axial testing of bridge columns (Figure 5) (Tremblay et al 2009).

Figure 2. Steel sheathed old-formed steel framed shear wall test at McGill

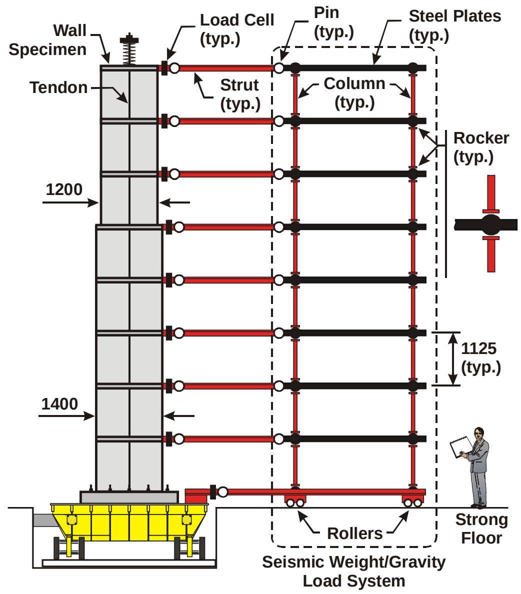

Figure 3. Test on multistory concrete shear wall at Ecole Polytechnique

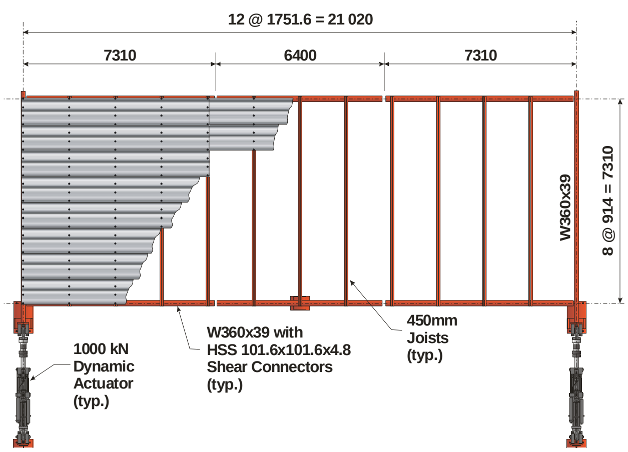

Figure 4. Dynamic tests on steel deck diaphragm at École Polytechnique

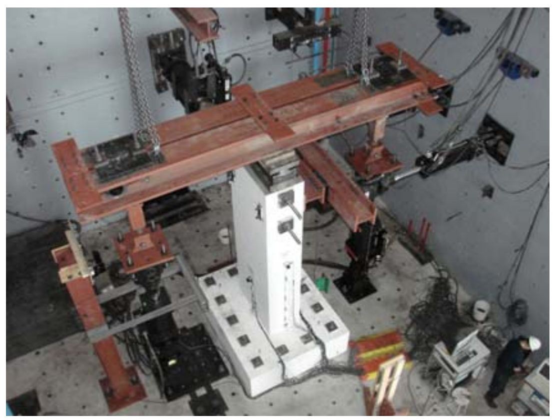

Figure 5. Testing of bridge column under bi-directional loading at École Polytechnique

École Polytechnique has a uniaxial earthquake simulator with a payload capacity of 15 tons and 3.4 m x 3.4 m plan dimensions. The multi-cellular shake table box is mounted on four frictionless linear hydrostatic bearings. The bearings are designed with high vertical capacity resulting in a large overturning moment capacity for the table. The system features a fully digital MTS 469 three-variable control system with delta pressure stabilization, amplitude phase control, online iteration, and adaptive inverse control capabilities. The actuator is powered by a hydraulic power supply with a total flow capacity of 1400 l/min. The frequency range is 0-50 Hz and the system can achieve peak displacements of ± 125 mm, peak velocities of 1.0 m/s and peak accelerations ranging between 3.0 g (table empty) and 1.0 g (at full payload capacity).

Other testing equipment at the Polytechnique includes dynamic hydraulic jacks ranging in capacity from 100 to 250 kN and stroke from 250 mm to 750 mm, a compression tension testing facility with a capacity of 12 MN and an L shaped 10 m tall reaction wall. Each wing of the wall is 12m long.

University of Sherbrooke

Earthquake engineering research started at University of Sherbrooke around 1975. A small shaking table, 1.2x1.2 m in size, was built at that time. Today, the structural laboratory at university is one of the largest laboratory dedicated to earthquake engineering in Canada. The laboratory consist of two facilities, of which the older one is centered around a 20x10 m strong floor with a large-capacity 4x10x7 m three-cell reaction wall at one end and a 3x3 m 10 ton MTS shaking table at the other. The uniaxial shaking table is fully controlled by an MTS 469DU three-variable control system with delta pressure stabilization, amplitude phase control, online iteration, adaptive harmonic cancellation, and adaptive inverse control capabilities. Pseudo dynamic and hybrid tests can be performed with three MTS 8-channels controllers and a wide range of MTS dynamic-rated hydraulic jacks with capacities ranging from 100 kN to 2300 kN. The other facility is centered around a 9x20 m strong floor with two 12 m high reaction walls at a right angle. A 12 MN press is positionned in the center of the strong floor.

Fig. 6: Pseudo dynamic test at Sherbrooke on a 3-storey Steel frame with Chevron bracing

Fig. 7: Test on a large fiber-reinforced concrete beam, 12m high reaction walls are in the background

The earthquake engineering research activities at the university have included dynamic testing of dams, bridges, and buildings under forced and ambient vibrations, modeling of the dynamic behavior of structures, seismic analysis of structures, and pseudo-dynamic testing with wall reaction (Figs. 6 to 9). Notable on-site test projects include Bustards 3 and Beauharnois 3 gravity dams, Emosson arch dam in Switzerland, several bridges and other structures such as the mast of the Montreal Olympic Stadium.

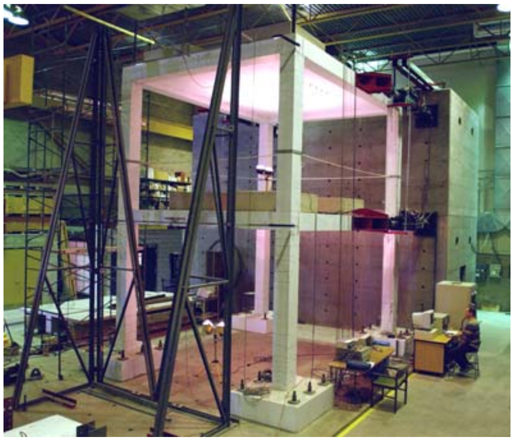

Fig. 8: Pseudo dynamic test on a full size two-story high-strength concrete frame.

Fig. 9: Pseudo dynamic substructure test of 1/3 scale three-columns bridge pier.

Ottawa-Carleton Earthquake Engineering Research Centre

The two universities in Ottawa, Carleton University and the University of Ottawa, also collaborate on earthquake engineering research. The collaboration is facilitated by the presence of a joint research centre named Ottawa-Carleton Earthquake Engineering Research Centre. The Centre has two Structures Laboratories, one at the University of Ottawa and the other at Carleton University, both capable of testing full-scale structural components under reversed cyclic loading. Both laboratories are equipped with servo-computer controlled testing capability to conduct simulated seismic testing under slow load reversals. The experimental research at the centre is complemented by analytical research, involving dynamic analysis of concrete and steel structures, response history analysis of building and bridges, and the development of new analytical tools, including hysteretic models for inelastic time history analysis.

Carleton University

The first PhD in the area of earthquake engineering was awarded at Carleton University in the early 1970s. Since then seismic research in the structural area has focused on studies related to earthquake codes and standards and analytical studies on seismic response of buildings, lifeline structures, and dams. Experimental studies have included cyclic load testing of steel concrete composite beams and concrete shear walls strengthened with polymer fibres (Figure 10).

In 2004 a collaborative program between the National Center for Research on Earthquake Engineering (NCREE) and National Taiwan University (NTU) in Taiwan and Carleton

University (CU) in Canada was established to perform internet based multi-site pseudo-dynamic experiments to simulate the response of a multi-span bridge to a series of bi-directional ground motions. The bridge piers were made of two concentric circular thin steel tubes with concrete filled in between, an innovative system developed in Taiwan for tall bridge pier construction in environmentally sensitive seismic regions. A substructure consisting of 1/5 scale bridge pier was tested at Carleton (Figure 11). One of the objectives of the collaborative program was to develop a standardized protocol and the associated software for such testing.

The state of the art structures laboratory at Carleton has a strong floor that measures 11m x 27 m with a clear height of 11 m, high capacity testing machines, modern data acquisition systems, and hydraulic actuators and frames.

Figure10. Test on concrete shear wall strengthened with carbon fiber

Figure 11. Hybrid multi-site test on bridge column

University of Ottawa

University of Ottawa has a Structures Laboratory with a 13 m by 22 m strong floor and a 10-ton overhead crane. The laboratory is equipped with a full-scale multi-degree-of-freedom pseudo-dynamic testing facility, which includes MTS servo controller and four 1000-ton MTS actuators. In addition, the Laboratory has a uni-directional shaking table and a large number of hydraulic loading devices and meccano sets suitable for quasi-static seismic testing.

The Structures Laboratory has been active in Earthquake Engineering research since 1985, starting with a comprehensive project on concrete column confinement, which has led to the development of a displacement-based design procedure and a well-accepted analytical model for concrete confinement. The research on columns continued in the area of high-strength concrete columns through funding provided by the Cement Industry and matching funds provided by NSERC and the Province of Ontario. Concrete strength of 130 MPa was produced for the first time in Ottawa and was used in the Laboratory to develop seismic design procedures for high-performance concrete. The ACI Building Code adopted the results of this research program in 2005.

The research team at the University of Ottawa was the first to conduct pseudo-dynamic testing in Canada, starting with the test of a large scale masonry house model and a large scale steel bridge structure in 1990's and continuing more recently with reinforced concrete frame tests to develop seismic retrofit strategies for non-ductile frames. Small-scale shake table tests have been performed to implement earthquake resistant smart structure technology through active structural control.

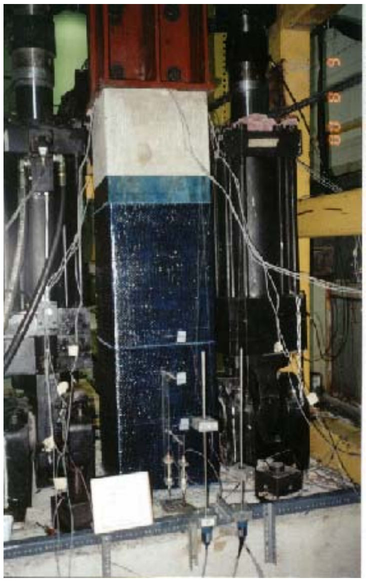

Figure12. FRP wrapped concrete column

Figure 13. Surface bonded FRP on masonry infill

An extensive experimental research program was initiated at the University of Ottawa in late 1990's. It was related to the use of fiber-reinforced plastics (FRP), both for seismic retrofitting of existing infrastructure and as reinforcement in new earthquake resistant concrete structures. Circular and square columns were externally wrapped with carbon FRP fabrics (Figure 12) to improve concrete confinement, diagonal tension capacity, and the performance of spliced reinforcement in potential plastic hinging regions of bridge and building columns. A design procedure was developed and incorporated into the CSA Standard S806-02, which is one of the few standards on FRP reinforced concrete structures in the world.

The application of FRP sheets, in the form of externally bonded retrofit material, was extended to masonry infill walls (Figure 13). Research on the use of FRP materials on new seismic earthquake structures was extended to the development of "stay-in-place FRP formwork." Tests were conducted on concrete columns cast in FRP tubes/forms, which serve the multiple function of i) formwork, ii) transverse reinforcement for improved concrete confinement and seismic shear resistance, and iii) protection against environmental and chemical attacks.

University of Toronto

From the very beginning, the structural research at the University of Toronto has had its focus on the development of National Building Code of Canada and the Concrete Design Code, and in particular on their provisions on seismic design. After the establishment of a structural laboratory, research at the University concentrated on the experimental study of the behavior of full size or nearly full size structural elements under cyclic loads simulating earthquake effects. The objective of these studies was to use the resulting data to develop mathematical models that could describe the behavior of components and structures strained well into the inelastic range.

The structures laboratories at Toronto have extensive test facilities including a 5.4 MN universal testing machine, several dynamic actuators with capacities up to 2,000 kN and stroke of ±375 mm, dynamic shell element tester with 60 actuators, column testing frame with axial load capacity of 9 MN and lateral capacity of 1,000 kN, and strong floors and wall systems. The two strong floors are, respectively, 21 x 4 m and 18 x 12 m in plan and 1.2 m deep. The strong wall is 5 m high and 5 m wide.

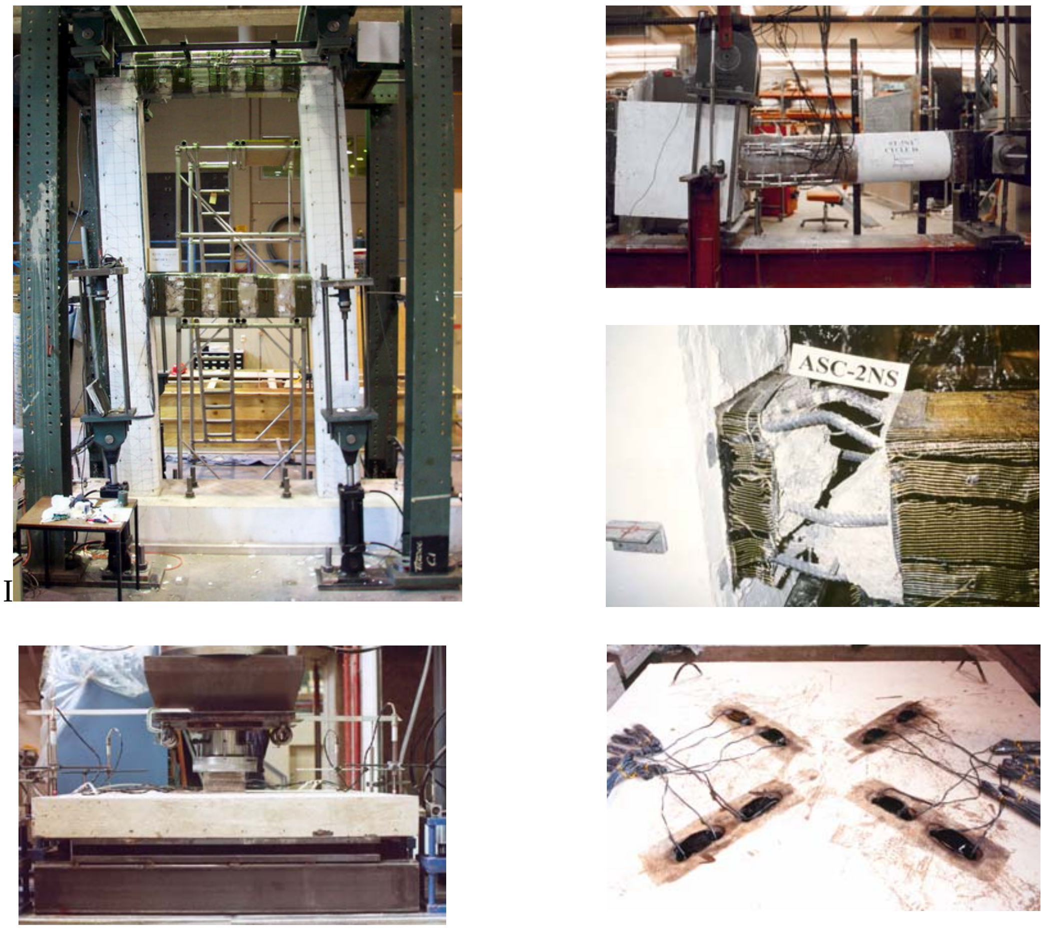

Figure 14. Recent tests program at the University of Toronto related to earthquake performance of concrete structures

In 1960's a comprehensive experimental research program was started at the University on the performance and design of reinforced concrete beam-column joints. A large number of specimens consisting of exterior joints with different configurations of joint shear reinforcement and with and without column axial load were tested. The information obtained from these tests was used to develop mathematical models that could describe the inelastic energy dissipation characteristics in R/C beams and columns. The results provided input for the ACI Committee 352 document on earthquake resistant monolithic joints.

In the 1970s, an experimental program was undertaken on the behavior of concrete specimens under cyclic shear. In the mid 1970's another experimental investigation was started, related to the study of the effect of confinement in reinforced concrete columns. In that program, large columns were tested under concentric compression to investigate the effect of steel configuration and lateral steel strength on the confinement of concrete. Mechanism of confinement using lateral steel was modeled at the fundamental level for all shapes of lateral reinforcement. The model was calibrated for columns with rectilinear confinement reinforcement. The mode has since been used extensively around the world. In 1980s, this work was further extended to deal with columns under simulated seismic loads. Large-scale circular, square and rectangular columns with concrete strength up to 115 MPa and for an array of characteristic parameters were tested. A performance-based procedure for the design of confining reinforcement was developed in 1997. This procedure and the analytical and experimental work have formed the basis of design provisions for various design codes such as the Canadian, New Zealand, Australian, Indian and European codes

In 1993, a new direction of research was initiated dealing with evaluation of concrete structures for their seismic resistance and the upgrading of such resistance with FRP. Figure 14 shows almost full-scale test specimens used in the study of retrofit of a two-storey frame, shear upgrade of beams, confinement retrofit of columns, and shear upgrade of slabs. The first field application of FRP for the upgrade of deficient highway bridge columns in Canada was carried out in 1996 based on the results from this research. This research has also resulted in the development of a performance-based design methodology for FRP confining reinforcement.

A research project has been recently launched to develop supplementary damping devices, utilizing explicit performance spectra. The primary goal is to provide a framework that allows practicing engineers to select an optimal upgrade solution by selecting how much strength, stiffness and damping they can add in order to achieve a feasible solution that meets the desired performance goals.

Over the years, the experimental research program has generated extensive data from tests on comparable specimens carried out under similar conditions so as to evaluate the effect of various parameters in a rational manner. For example, over 460 column tests have been carried out under the program, of which more than 50 % were on almost full-scale specimens.

McMaster University

Earthquake engineering research at McMaster University had its beginning in 1969 with the inauguration of the state-of- the-art Applied Dynamics Laboratory. The laboratory equipment included a 1.5x1.5 m shake table facility as well as a variety of other dynamic and static testing equipment and instrumentation. Over the years, upgrades and additions were made to the equipment; they included a vertical shaking platform and table controls. The latest upgrade included the addition of strong reaction frame and four actuators, two with the capacity of 500 kN each and two of 1000 kN capacity with a stroke of ±250 mm. Two of the actuators are dynamic. An upgrade to the oil system included three modules of 113 lpm capacity with an adjustable operating pressure of 21 MPa. As the laboratory developed testing expertise, the equipment was extensively used for dynamic testing and seismic qualification of telecommunication and nuclear power plant equipment as well as in tests related to various industrial applications. In addition, McMaster University's Applied Dynamics Laboratory developed and maintained a strong-motion database, which was used quite extensively from about 1985 to the early 1990's.

Over the years, McMaster University researchers have played a prominent role in the development of the National Building Code of Canada and the Canadian Standards Association Nuclear Standards. In addition, members of the earthquake engineering research group have participated in site visits following most major recent earthquakes.

Areas of research at McMaster University included determination of design basis and seismic ground motions for critical facilities; seismic hazard and mitigation; seismic design guidelines for equipment and components of buildings; seismic qualification of components, structures and equipment; safety analysis, design and rehabilitation; rehabilitation and retrofit of structures and components; and damage assessment of structures.

Research on the seismic performance of various structural systems included highway and long span suspension and cable-stayed bridges, moment resisting frames, braced frames, structural walls, liquid containing tanks, chimneys, power transmission lines, torsion of buildings and components, primary-secondary systems response and concrete gravity dams. The development and testing of seismic rehabilitation systems for structural components addressed steel, concrete and masonry structures. The investigated structural components included beams, columns (Fig. 15), beam-column joints (Fig. 16) and walls. The materials used in retrofitting included steel, glass fiber and carbon fiber reinforced polymers, and shape memory alloys.

Figure 15. Testing of rehabilitated column at McMaster

Figure 16. Testing of beam column joint at McMaster

University of British Columbia

The first formal graduate programs in geotechnical and structural earthquake engineering at the University of British Columbia (UBC) were established in the mid-1960's, motivated by the earthquake damage caused during the 1964 earthquakes in Alaska and Niigata (Finn 2004). At that time, a medium-sized shake table was installed at UBC, with a nominal 22 kN (5,000 lb.) capacity horizontal actuator. In about 1979, a larger uni-axial shake table having an aluminum cellular structure with dimensions of 3 m x 3 m and a payload capacity of 156 kN was installed. For about twenty years, the table was used extensively for research as well as for qualification tests of equipment and structural components. The table has been converted to a 4 degree-of-freedom system.

A new Earthquake Engineering Research Facility (EERF) was opened at UBC in the fall of 2004. The EERF brings together under one roof an impressive array of test equipment for specialized research on earthquakes and their effects on structures and the soil that supports them. The 10 m high overhead area of the EERF allows the testing of large-scale structural models. Two different earthquake simulators (or shake tables) are housed in the facility. The centrepiece of the facility is the six-degrees-of-freedom shake table, with a footprint of about 4 m by 4 m and the capacity to shake 30-ton structures. The second shake table with a footprint of 6 m by 6 m has a payload capacity of about 100 tons and is used for the uni-axial testing of large-size structures. The EERF also has available to it a third, portable uniaxial, shake table for testing smaller specimens.

Other equipment in the structures laboratory includes MTS loading rams, reversed cyclic loading frame, pseudo dynamic testing system, MTS dynamic loading rams, and a structural testing strong floor measuring 9 m × 22 m.

EERF researchers have conducted ambient vibration tests on a number of bridges and buildings. Other areas of research include seismic control by passive and semi-active dampers, and base isolation of structures, pseudo-dynamic testing of large-scale concrete bridge bents, retrofit of concrete beam-column joints, seismic response of structures with steel plate or timber shear walls and timber frames, decision analysis for seismic retrofit strategies, regional damage estimation due to earthquakes, development of software for seismic risk, structural stability, and non-linear seismic response, and reliability of structures with non-rigid connections.

In the aftermath of the Northridge and Kobe earthquakes and with the newly perceived threat from a major subduction earthquake, several institutions in British Columbia became concerned about their exposure to loss. They commissioned the Earthquake Engineering Group at UBC to perform seismic risk studies in the major population centers of southwestern British Columbia to provide better estimates of potential losses at various probability levels. These loss assessments were based on a detailed categorization of the building stock, according to structural type and loss potential.

Figure 17. Retrofitted masonry wall on the shake table

Figure 18. Shake table test on a wood panel wall

Figure 17. Shake table test on a full-scale two-storey house

Recently a state-of-the-art Real-time Hybrid Testing System has been installed to connect the UBC facilities to the Network for Earthquake Engineering Simulation (NEES) in the United States. The Hybrid Testing System allows for experimental evaluation of civil engineering infrastructure on a scale that is not possible in a single laboratory. Physical specimens, all of which are parts of a single structure, can be tested at the geographically distributed laboratories, while network tools and numerical models control the input to the physical experiments based on the hybrid testing method.

Research Network

From time to time research networks involving major universities across Canada have been established to foster research in earthquake engineering. University researchers from across Canada have recently formed the Canadian Seismic Research Network (CSRN) dedicated to the development of the next-generation of methodologies and structural systems to manage and mitigate the seismic risk to Canada's urban infrastructure. A total of 26 researchers from eight universities across Canada (University of British Columbia, University of Western Ontario, University of Toronto, University of Ottawa, Carleton University, McGill University, École Polytechnique de Montréal, and Université de Sherbrooke) participate in the network.

The network will address three interacting themes, namely, hazard assessment, vulnerability assessment, and mitigation. The mitigation techniques to be studied will include on retrofit techniques that are applicable to the critical and “vulnerable” infrastructure.

Earthquake Reconnaissance

Over the years, teams of Canadian researchers and practitioners have carried out several post-earthquake reconnaissance studies to learn from past earthquakes and to identify structural systems and details that are vulnerable. These site visits included the 1976 Cotabato earthquake in Phillipines, the 1985 Mexico earthquake, the 1988 Saguenay earthquake (Québec), the 1989 Loma Prieta earthquake (California), the 1990 Manjil earthquake (Iran) the 1991 Talamanca earthquake (Costa Rica), the 1994 Northridge earthquake (California), the 1995 Hyogo-Ken Nanbu earthquake (Kobe), the 1999 Kocaeli earthquake (Turkey), the 1999 Chi-Chi earthquake (Taiwan), the 2001 Bhuj Earthquake (India) and the 2004 Sumatra earthquake and Indian ocean Tsunami.

Conclusions

Since the early sixties universities in Canada have actively pursued research in all areas related to Earthquake Engineering including its structural aspects. Over the years, such research has grown in both its scope and its sophistication. Universities now possess state-of-the art testing equipment and a large pool of well-qualified researchers. In a large measure because of this research, the country has some of the most comprehensive and modern design loading codes and material standards and a sound program of hazard mitigation.

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