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SEISMIC UPGRADE OF EXISTING STRUCTURES WITH SUPPLEMENTAL DAMPING AND ISOLATION SYSTEMS IN CANADA

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ABSTRACT

Supplemental damping and seismic isolation are now well-accepted and recognized as effective approaches to mitigating seismic risk. Their implementation in deficient existing structures presents additional challenges when compared to their use in new structures, as the design approach must consider the inherent limitations of such structures. As part of the Canadian Seismic Research Network, a group of researchers is working on developing effective means for the use of advanced technologies such as supplemental damping and isolation systems for buildings and bridges. The focus of the work is set to first develop an optimal spectral approach that allows engineers to rapidly decide on the most suitable strategy using a combination of strength, stiffness, ductility and supplemental damping and then to elaborate on a full design approach that is compatible with the characteristics for the Canadian seismic environment. In addition, new retrofit strategies are also being developed to allow for a higher seismic performance by transforming existing structures into rocking systems. Through extensive time-history analyses the differences between eastern and western earthquakes is also being considered for the development of performance criteria for supplemental damping and isolation systems. Finally, an overview of the work that is underway to develop design guidelines for the seismic upgrade of existing bridges using isolation systems as well as supplemental damping is also presented.

Introduction

A considerable number of supplemental damping and isolation devices have been developed and successfully implemented in real structures to enhance their seismic protection over the past 20 years (e.g. Christopoulos and Filiatrault, 2006). Extensive research on the performance of these devices as well as on the dynamic response of structures incorporating these devices has been carried out and has formed the basis for guidelines that have been developed and used for their implementation in structures.

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Despite these significant developments, and the fact that the use of supplemental damping and isolation devices offers efficient means for retrofitting structures, the use of these technologies in practice has been somewhat limited. In addition, much of the focus on implementing damping devices has been set on new structures or structures capable of undergoing considerable deformations without considerable loss of strength and stiffness. Implementing these devices in structures that have been designed using older seismic codes that may not have the ability to undergo significant deformations prior to sustaining serious damage presents additional challenges that must be taken into account in order to effectively design a suitable retrofit strategy.

As part of the Canadian Research Network (CSRN) on “Reducing Urban Seismic Risk” a team of researchers is currently working towards the development of new design guidelines, intended for practicing engineers, to enable the wider use of supplemental damping and base isolation systems for the seismic upgrade of existing structures. In this paper, the goals of this research group are outlined and the work that is currently in progress and of new cost effective methods to achieve higher seismic performance. The primary goal of this thrust area of the CSRN 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.

In this paper, a summary of the characteristics of the Canadian seismic environment is first presented in order to highlight the differences that are expected in the response of upgraded structures in eastern and in western Canada. An overview of the work that is currently underway in this thrust area of the CSRN to develop a design procedure that is suitable for deficient existing RC and steel structures is first presented. New approaches to transform existing structures into rocking systems are also discussed. Finally, a brief outline of the work that is being carried out to develop guidelines for the isolation of existing bridges is also outlined

Characteristics of the Canadian Seismic Environment

Canadian seismicity is defined by the three seismic hazard zones posing high risk to major populated areas in Canada: earthquakes expected in Eastern North America, essentially along the St-Lawrence and Ottawa River valleys, crustal and sub-crustal earthquakes that occur west of the Rockies, along the Pacific West Coast of Canada, and ground motions generated by Cascadia subduction earthquakes that are anticipated off the west coast of the Vancouver Island.

Ground motions of the second type are similar to those recorded elsewhere in seismic active regions along the Pacific Ocean boundary. Due to their greater recurrence and the large number of available records, past studies have focused on the effects of these ground motions alone and seismic design provisions in current North America codes are essentially based on findings from these studies.

Conversely, little attention has been given to eastern and Cascadia ground motion effects, partly due to the lack of seismic data from past seismic events. Ground motions in eastern Canada have most of their energy in the high frequency range, resulting in limited structural displacement demand but high accelerations and large forces for stiff structures. Cascadia subduction earthquakes are large magnitude (M9.0) events capable of producing ground motion with very long (1-2 minute) strong motion durations in large cities such a Victoria and Vancouver in British Columbia. Although of moderate amplitude, these long lasting shaking can lead to high inelastic cumulative damage levels and occurrences of low-cycle fracture of structural members or connections (Tremblay, 1998; Wang and Clark, 1999; Tremblay and Atkinson, 2001). Ensembles of representative simulated ground motions have recently been developed for these two earthquake hazards (Atkinson 2009; Atkinson and Macias 2009) and comprehensive numerical studies can now be carried out to develop specific design guidelines with the objective of achieving uniform level of protection against earthquakes across the country. In Figure 1, the 2% in 50 year 2005 NBCC Design Spectra are shown for the cities of Vancouver, BC, in western Canada, and Montreal, QC, in eastern Canada for soil classes C and E. Higher accelerations at low frequencies, but considerably lower displacement demands at longer periods can be observed by comparing the spectra for these two sites.

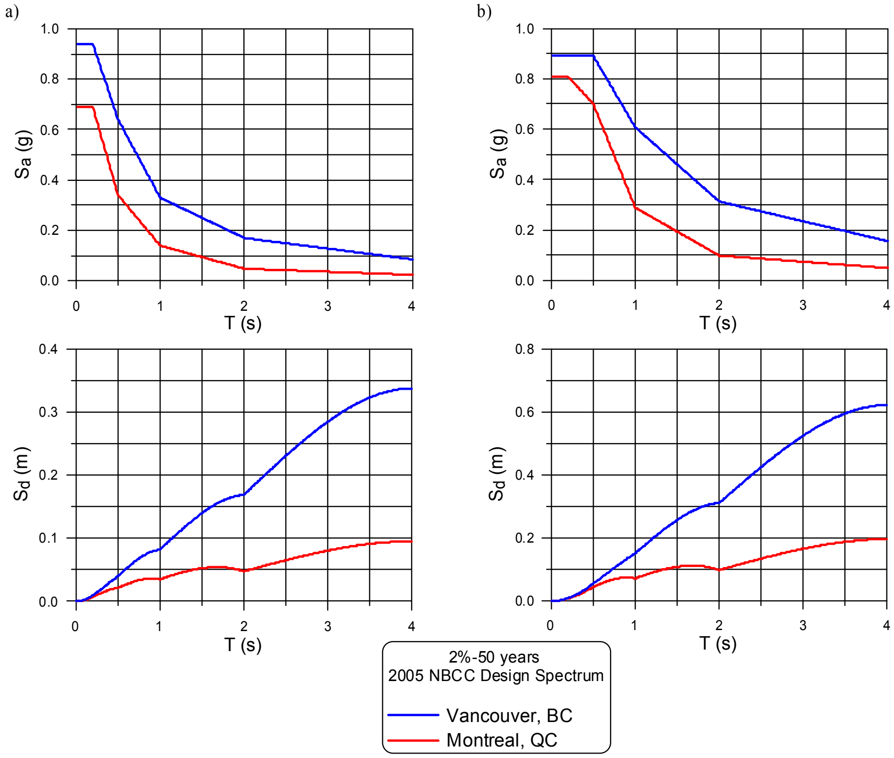

Figure 1. 2% in 50 year 2005 NBCC Design Spectra for Vancouver, BC, and Montreal, QC for a) Site Class C; b) Site Class E. Note: $S_d = S_a/(2\pi/T)^2$

For site-specific studies, ground motions time histories can be selected for earthquake magnitude-distance scenarios that dominate the hazard at the site, as obtained from a deaggregation of the seismic hazard (Halchuk and Adams, 2004). Typical simulated ground motions for crustal and sub-crustal earthquakes in eastern and western Canada are illustrated in Figure 2. The marked difference between the two types of ground motions can be seen, especially in terms of frequency content for the eastern ground motion. Long duration subduction earthquake ground motion for Victoria, BC is also illustrated in the figure. Although such earthquakes are expected to have lower ground motion amplitudes, because of the long duration of the strong ground motion a much larger number of inelastic cycles are expected under such excitations.

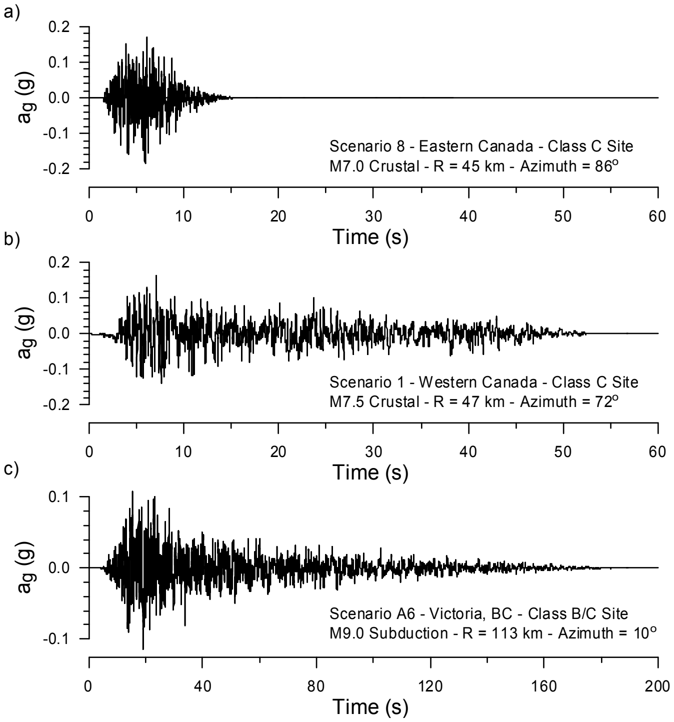

Figure 2. Simulated ground motion time histories for: a) M7.0 at 45 km for Eastern Canada; b) Crustal M7.5 at 47 km for western Canada; and c) M9.0 Cascadia earthquake at 113 km (Victoria, BC). (Source: http://www.seismotoolbox.ca/)

Methodology for Optimal Retrofits with Supplemental Damping Systems

A significant number of researchers have proposed different approaches to retrofit or design new structures with supplemental damping devices. Currently in North America, the most widely accepted approach to designs of buildings with passive damping technology is to follow the procedure outlined developed by Whittaker et al. (2003) and included in chapter 15 of the FEMA450 guideline (BSCC 2003). The method described in FEMA450 can be seen as an extension to the traditional seismic design method which makes use of R, C_d and Ω_o factors to account for inelastic behaviour of the seismic force resisting system (SFRS). By introducing additional effective damping into the system, the damped structure's responses can be evaluated using simple methods such as modal superposition and design can then be carried out based on these computed response quantities.

While such approaches are fully compatible with typical seismic design techniques familiar to most practicing engineers, devising an original with the right initial design largely relies on past experience as limited guidance is provided on this aspect. Because of this, many possible alternative designs which combine added strength, stiffness and damping, in different proportions can be overlooked. Although this is less critical for new structures, it may lead to an inefficient retrofit strategy when considering an existing deficient existing structure. As such, this methodology can be labeled as being more of a “simplified analysis method” that is used iteratively to converge to one feasible solution rather than a full design approach that allows the designer to consider a number of possible solutions.

One of the main goals of the CSRN research on the mitigation of seismic damage using passive control technology is to develop a versatile and practical design guideline for retrofitting currently deficient steel and concrete structures that allows the designer to target a performance level while considering the inherent constraints in such structures. An important constituent of such an approach is the development of a performance spectra-based design method for buildings with passive supplemental damping for both the Eastern and Western Canadian seismic hazard environments.

The concept of performance spectral-based design has been explored by various researchers such as Filiatrault and Cherry (1990), Fu and Cherry (1999), Kasai et al. (2003) and Mansour and Christopoulos (2005). The biggest advantage of such approaches is that they allow the designer to quickly assess the performance of not one but multiple design alternatives at the initial stage of design. Such performance spectra, which are usually graphical tools, provide estimates of a wide range of different response quantities using equivalent SDOF representations of the damped structure. Through the modal transformation of MDOF structures into an equivalent SDOFs, it becomes possible to perform approximate analyses and to approximate the seismic response of highly complex systems.

Figure 3 shows a general flow chart of the methodology that is currently being developed. Once the design parameters that are applicable to the type of structure that is being retrofitted are defined, through an in depth understanding of the structure’s deficiencies, the multi-performance criteria spectra are used to examine a number of possible solutions. These consist of various combinations of strength, stiffness and damping, as well as targeted structural upgrades to enhance the ductility or displacement capacity of the main structure. Once the target design is identified, approaches similar to the FEMA 450 method are used to carry out a full design.

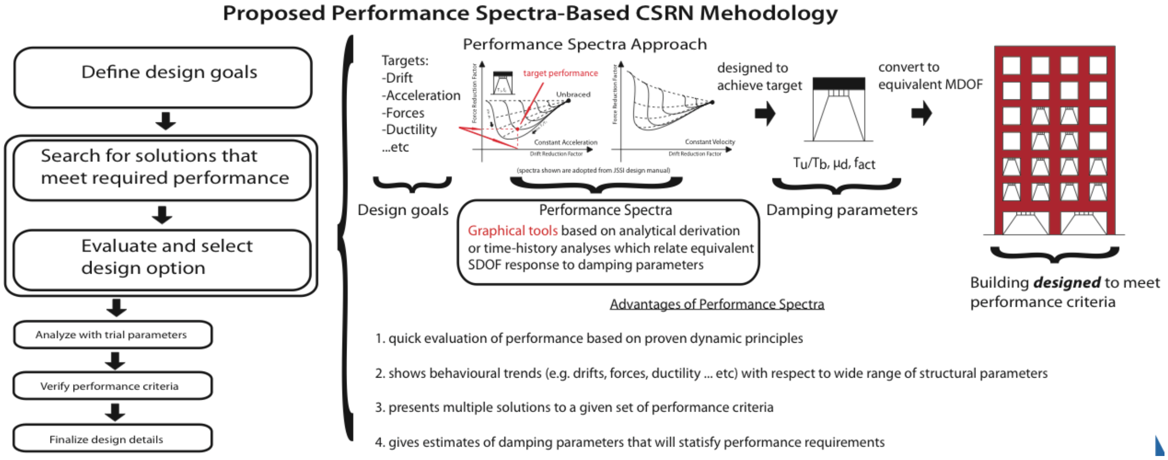

Figure 3. Flowchart of Proposed Optimal Design Approach for Structures with Supplemental Damping Systems

The optimal design spectra will be developed using the ground motions that are defined in the CSRN for all three seismic hazard environments in Canada and in close collaboration with CSRN researchers working on the assessment of deficient steel and concrete structures.

A large number of numerical analyses of typical upgraded structures will also be carried out using the ground motions that will be developed by the CSRN members for the different seismic regions in Canada to define realistic protocols for prototype and production testing of supplemental damping and isolation devices that adequately represent the frequency content and displacement amplitude of the loading that is expected to be applied in the supplemental damping systems.

High Performance Upgrade of Existing Structures with Rocking Systems

High-performance systems such as ones providing a self-centering response that achieve a stable seismic response while limiting damage to the main structural elements and while reducing residual deformations have recently been developed and used primarily for new RC and steel structures.

Among them, base-rocking systems such as concrete walls and more recently steel frames are being investigated as new seismic resistant systems that allow for a near linear response of the main structure while forming a force limiting mechanism through the rocking response at the base. The focus of this project is to develop methodologies for transforming existing deficient steel and concrete frames into base-rocking systems. This retrofit consists of disconnecting the structure at its base, and thus enabling a rocking response while carrying out targeted strengthening of the structural elements to allow them to resist the forces that are developed during the rocking response.

It has been shown that base rocking systems often have the drawback of large forces in the structure that are caused by the higher mode response above the base-rocking level (e.g., Tremblay et al., 2008). In a study by Wiebe and Christopoulos (2008), it was shown that higher modes could be controlled by allowing the structure to rock about its base and about other floor levels along its height. In Figure 4, a schematic of a multiple rocking section wall system is shown as well as the bending moment diagram along the height of the wall that illustrate the effectiveness of the added rocking sections in controlling higher mode effects. A similar technique was examined by Tremblay et al. (2004) when using buckling restrained vertical elements to form plastic hinges along the height of multi-storey braced steel frames.

This, and other higher mode mitigating approaches are currently being investigated and developed to enhance the feasibility of the seismic upgrade of existing deficient structures and to reduce the need for further strengthening of structural members when using this retrofit technique.

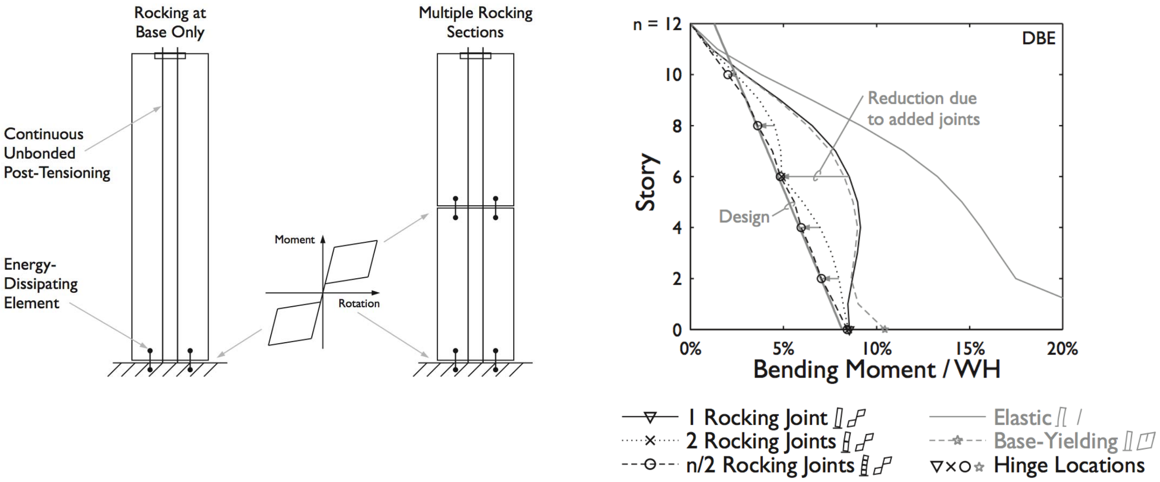

Figure 4. a) Schematic of multiple rocking section system and b) Effect of multiple rocking sections on higher mode response (after Wiebe and Christopoulos, 2009)

Implementation of Supplemental Damping Systems to Seismically Deficient Steel and RC Frame Structures constructed in Canada in the 1960s and 1970s

Although the methodology for the definition of optimal upgrades of existing structures using supplemental damping systems discussed above is of a general form and can be applied to any type of structure, the main focus is set on the retrofit of deficient steel and RC frames designed and built in the 1960s and 1970s that are believed to be some of the most vulnerable structures in Canada

In many locations across Canada, the design seismic loads have increased in the last 30-40 years and most existing structures constructed before that period of time lack lateral capacity. More importantly, these structures have not been designed and detailed to withstand seismic effects in the primary structure's nonlinear range of deformation.

For instance, capacity design for steel structures was introduced only in 1989 in Canada. Braced steel frames designed according to earlier code editions typically have slender bracing members that exhibit limited energy dissipation capacity. Brace cross-sections do not meet plastic design requirements either, which makes the braces prone to premature low-cyclic fracture under reversed inelastic loading. Brace connections do not possess the capacity to develop the full yield tensile strength of the braces, and columns and beams were not designed to resist the forces that will develop when the braces reach their probable resistance. In the 1960's and 70's, unbraced steel frames, referred to as simple framing construction, with most beam-to-column connections assumed to be flexible and designed for gravity loading only and a few selected "wind connections" that were designed to resist wind loading. In the "wind connections", the members and joints are designed to carry wind moments and are provided with sufficient inelastic rotation capacity to avoid overstress of the fasteners or welds under combined gravity and wind loading (AISC, 1969). However, these connections were not designed for seismic loading and may not be capable of accommodating the inelastic rotation demand expected from earthquakes.

Numerous deficiencies are also inherent to existing reinforced concrete structures designed prior to the implementation of modern seismic provisions. These include a lack of transverse reinforcement for the confinement of the concrete core for the control of the buckling response of the longitudinal reinforcement in members expected to sustain large inelastic rotational demands. These structures have also been designed without any capacity design considerations to prevent column sway mechanisms in moment-resisting frames or non-ductile failure modes such as shear failures in beams, columns or walls. These structures also present deficiencies in the development lengths and lap splices of rebars.

The focus of this facet of the project is to devise optimal retrofit strategies for these structures by taking advantage of the beneficial effects of supplemental damping in conjunction with the implementation of techniques to address the inherent structural deficiencies that are being developed by other researchers in the CSRN. Some of the critical design criteria are the level of additional foundation forces that can be imposed on the structure, the deformation capacity of the members, the level of acceptable accelerations in the structure, as well as the most suitable method to transfer the forces induced by the added supplemental damping systems. Hybrid retrofit strategies involving both upgrading of key elements of the structure to eliminate the possibility of brittle failures and to enhance the global deformation capacity of the structure, and the addition of supplemental damping systems will also be investigated.

Upgrade of Bridges with Seismic Isolation

A large number of existing bridges in Canada have been identified as having severe deficiencies with respect to their seismic performance. To address this, one of the focus areas of the CSRN is to develop retrofit strategies for these bridges through seismic isolation.

The basic design spectrum specified in current CSA S6-06 Standard for the design of bridge structures in Canada (CSA, 2006) is based on the 1994 AASHTO specifications (AASHTO, 1994) and, hence, reflects seismic hazard from the Pacific west coast only. In future editions of CSA S6, it is expected that site specific Uniform Hazard Spectra (UHS) will be prescribed at various locations across the country, similar to the 2% in 50 years UHS that have been introduced in the 2005 National Building Code of Canada (NBCC) (NRCC, 2005). These spectra include variations in ground motion characteristics as illustrated in Fig. 2 which compares the 2005 NBCC elastic acceleration design spectra for Vancouver, BC, in western Canada, and Montreal, QC, in eastern Canada. Due to their higher high frequency content, ground motions in the East impose much smaller displacement demands compared to the West, which is even more attractive for the use of base isolation systems. In addition, previous version of the CSA S6 code did not include provisions for the design of bridges with supplemental damping coupled with the isolation devices.

Numerical studies are currently being conducted to determine whether such elastic spectra can be used to accurately predict the displacement demand that will actually be imposed on isolated bridge structures and to calibrate modification factors that can be used with linear elastic spectra to account for the effect of the supplemental damping provided at the isolation level of these structures. In addition, the establishment of appropriate safety factors with respect to the isolator displacement demands, especially in the East, is being carried out un order to provide a safety margin that recognizes the high uncertainty that is related with the definition of the ground motion amplitudes.

In addition, given the harsh environmental variations that are experienced to be experienced by bridges in many regions of Canada, thermal effects, which include the modification of the properties of the isolation and damping systems as well as the combination of seismic and thermal displacements are also currently being investigated.

Finally, the current study is also investigating the use of new isolation approaches which include shock transmission systems as well as various combinations of stiffness, supplemental damping and re-centering properties and optimal combinations of these properties for both eastern and western Canadian earthquakes.

Conclusions

An overview of the work that is being carried out in as part of the Canadian Seismic Research Network to develop approaches and guidelines of the seismic upgrade of non-seismically designed RC and steel structures was provided. This work is focused on the development of effective retrofit strategies that account for the deficiencies of these structures, as well as new techniques for transforming deficient systems into higher performance structures. A crucial aspect of this work is to investigate the implication of the different seismic hazard environments that are defined in Canada on the design and performance of damping and isolation protective systems.

Acknowledgments

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