Isolation and Damping Mitigation Strategies for Bridges in Western and Eastern North America

V.Koval & C. Christopoulos
University of Toronto, Toronto, Ontario, Canada

R. Tremblay
École Polytechnique de Montréal, Montreal, Quebec, Canada

SUMMARY:
The seismic design provisions of the CSA-S6 Canadian Highway Bridge Design Code and the AASHTO LRFD Seismic Bridge Design Specifications have been developed primarily based on historical earthquake events that have occurred along the North American west coast. For the design of seismic isolation systems, the simplified equivalent analysis and design method included in these codes relies on an equivalent effective linearization of the nonlinear isolated structures and a response reduction factor, or damping coefficient, B which takes into account the effect of the equivalent added damping. The appropriateness of the damping coefficient B for western and eastern North American ground motions is investigated in this paper. Results from a series of time-history analyses performed for a set of linear equivalent and nonlinear structural systems covering a wide range of isolated and damped bridge configurations are presented. It is found that there is a need to adjust existing design guidelines to better capture the expected nonlinear response of isolated bridges, especially for earthquakes expected in eastern North America.

Keywords: seismic design, seismic isolation and supplemental damping, rehabilitation and strengthening

1.INTRODUCTION

The seismic design of bridge structures is regulated by different construction codes worldwide, with the CSA-S6 Canadian Highway Bridge Design Code (CAN/CSA-S6-06) and the AASHTO LRFD Seismic Bridge Design Specifications being two examples of such codes in North America. Seismic provisions in these two codes have been developed based on historical events that have occurred along the North American west coast and are therefore calibrated to these ground motions.

Seismic protection techniques incorporating isolation and damping devices are becoming increasingly attractive for reducing seismic demands on bridges and achieving more cost efficient designs. The simplified equivalent design method for isolated bridges that has been adopted as the basis for the analysis and design methods that are included in these codes relies on an equivalent effective linearization of the isolated structure and the damping coefficient, or response reduction factor, B, that takes into account the effect of the equivalent added damping of the linearized effective structure. The same damping coefficient is used to determine the statically equivalent seismic force and the displacement across the isolation bearing as a function of the spectral acceleration (S_A) and pseudo displacement (PS_D), respectively. This factor does not vary either with the effective period of the linear equivalent system.

The appropriateness of current damping coefficient values for both western and eastern North American ground motions has been questioned in past studies (Taylor, 1999; Naumoski, 2000) and is further investigated in this paper. In addition, the correctness of using the same B factor for reducing force and displacement responses is examined. This study also confirms the dependency of B factors on the effective period that has already been identified by other researchers (Atkinson and Pierre, 2004 and Hatzigeorgiou, 2010). The simplified design procedure adopted by the Canadian CSA-S6-06 code, which is similar to the one presented by AASHTO, is first outlined. The methodology that was used to assess the damping coefficient, which required for simplified isolated bridge analysis, is introduced. Damping coefficients that resulted from series of time-history analyses performed on both linear equivalent and nonlinear structural systems covering a wide range of isolated and damped bridge configurations are then presented.

2. CODE DESIGN PHILOSOPHY

The seismic design philosophy based on the use of damped elastic response spectra, which are represented today by Unified Hazard Spectra (UHS), was introduced in North America in the late 1970's. In particular, the Applied Technology Council (ATC) adopted spectral parameters based on an earthquake return period of 475 years with the primary goal of achieving the life safety performance level (ATC, 1978). The ATC-3 provisions accounted for the effect of equivalent hysteretic damping associated to inelastic response of structures through force response modification factors.

In the early 1980's, seismic protection techniques incorporating isolation and damping devices started to draw increased attention as a possible effective means of reducing seismic demands and enhancing the seismic protection of structures. Guidelines for the design of seismic isolation systems were published by the Structural Engineers Association of Northern California (SEAONC, 1986). Later, a revised and expanded version of this document was incorporated into the 1991 Uniform Building Code (UBC) (ICBO, 1991). The damping coefficient, B, which is explicitly related to the amount of dissipated energy, appeared first in the 1991 UBC for base-isolated buildings (Naeim et Kircher, 2001). Damping coefficient values from the 1994 Uniform Building Code were adopted in the 1999 AASHTO LRFD Guide Specifications for Seismic Isolation Design (AASHTO, 1999). These values were also incorporated in the 2000 edition of the Canadian code CSA-S6 and are still in force in the CSA-S6-06.

These provisions have been developed on the basis of work carried out by Newmark and Hall (1982). In these early studies, the researchers computed spectrum amplification factors for different damping levels using the elastic SDOF response to the May 18, 1940, El Centro earthquake record. These spectrum amplification factors were evaluated for three period ranges denoting regions of constant acceleration (A region), constant velocity (V region) and constant displacement (D region). These three period ranges respectively correspond to 0.2-0.5 s, 0.5-3.33 s and periods longer than 3.33 s. The damping coefficients specified in different seismic provisions are presented in Table 1.The damping reduction coefficients in the current CSA-S6-06 bridge code are based on Newmark's amplification factors for the period range associated with the constant velocity region and damping ratios ranging from 2% to 20%. The third edition of the AASHTO Guide Specification for Seismic Isolation Design (2010) proposes the following exponential equation for the value of B as a function of β_{eff} which no longer requires interpolation between tabulated values:

$$B_{Code} = \left(\frac{\beta_{eff}}{5\%} \right)^n \tag{2.1}$$

where the exponent n is set to 0.3.

These response reduction factors are also defined as independent of the structure's natural period. The B factors are equal to unity for 5% equivalent damping in all codes, which means that the spectral response for any given value of damping is obtained by dividing the 5% damped spectral response by the B factor corresponding to the level of equivalent damping in the system, β.

Table 1: High Damping Reduction Factor, *B* given in Different Codes

β	CSA-S6 (2006) AASHTO (1994)	AASHTO (2009)	EUROCODE 8	FEMA 273 (1997) FEMA 356 (2000)		UBC (1994)	ATC-40 (1996)		Newmark & Hall (1982)	
(%)	B	B	1/η	B_s	B_1	B	B_s	B_1	A Region	V Region
2	0.8	0.76	0.84	0.8	0.8				0.77	0.81
5	1.0	1.00	1.00	1.0	1.0	1.00	1.00	1.00	1.00	1.00
10	1.2	1.23	1.22	1.3	1.2	1.19	1.30	1.22	1.29	1.20
20	1.5	1.52	1.58	1.8	1.5	1.56	1.82	1.54	1.81	1.53
30	1.7	1.71	1.87	2.3	1.7	1.89	2.38	1.82		
40	1.9	1.87	2.12	2.7	1.9		3.03	2.08		
50	2.0	2.0	2.35	3.0	2.0					

Current codes include an equivalent static force method to compute the seismic response of isolated bridges and displacements across isolation bearings. Both of these design parameters are function of 5% damped spectral accelerations. In CSA-S6-06, the horizontal force, *F*, and the displacement, d_i, for an isolated structure are given as:

$$F = C'_{sm} \cdot W = \frac{A \cdot S_i}{B \cdot T_e} \cdot W \tag{2.2}$$

$$d_i = \frac{250 \cdot A \cdot S_i \cdot T_e}{B} \; (mm) \tag{2.3}$$

where C'_{sm} is the elastic seismic response coefficient, W is the total dead load of the structure, *A* is the zonal acceleration ratio, S_i is the site coefficient, and T_e is the effective period of the isolated structure. These design parameters are obtained from the site-specific 5% damped spectral acceleration, including site effects, S_A, given by:

$$S_A\,(5\%) = \frac{A \cdot S_i}{T_e}\, g \tag{2.4}$$

where g is the acceleration due to gravity. The force response in equation 2.2 is computed by simply multiplying the spectral acceleration of equation 2.4 by the weight of the structure whereas the displacement across the isolation bearings, d_i, is determined using the spectral pseudo displacement relationship ($PS_D = S_A / \omega^2$), where ω is the effective frequency of the isolated system. To account for the effect of added damping, β, for both design parameters, the spectral acceleration, S_A (5%) is reduced by the factor B. Equation 2.3 for the spectral displacement response of the isolated structure, $PS_D\,(\beta)$, is then:

$$PS_D\,(\beta) = \frac{S_A\,(\beta)}{\omega^2} = \frac{S_A\,(5\%)}{\omega^2 B} = \frac{T_e^2}{4 \cdot \pi^2} \frac{A \cdot S_i}{B \cdot T_e} \cdot g = \frac{249 \cdot A \cdot S_i \cdot T_e}{B} \; (mm) \tag{2.5}$$

The code simplified equivalent force method can be summarized in the following three main steps:

1) Determination of spectral quantities associated with the effective period of the isolated structure.
2) Evaluation of a level of equivalent damping, *β*, to determine a damping reduction factor, *B*.
3) Evaluation of the structure's force and displacement response using equations (2.2) and (2.3).

This simplified method for estimating the response of an isolated bridge is iterative because the values of the effective period and equivalent damping used in Steps 1 and 2 depend on the displacement response which, in turn, is evaluated in Step 3. Figure 1 summarizes the effects of isolation and damping mechanisms on the response of seismically isolated bridges.

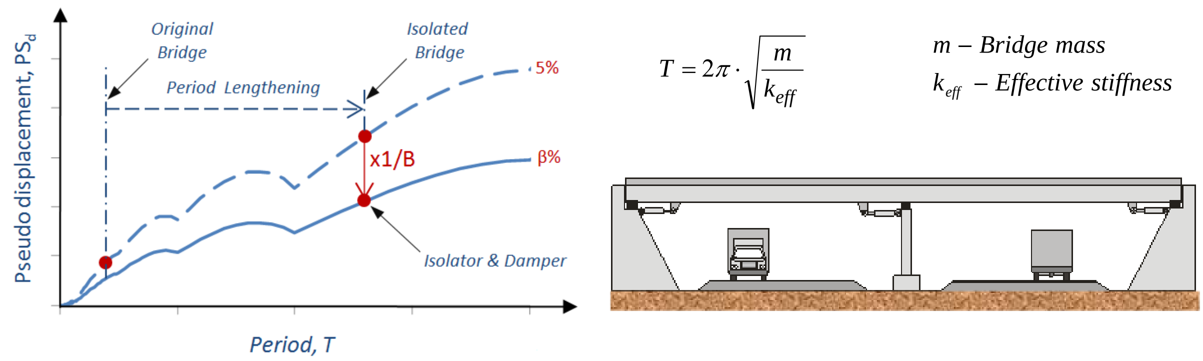

Figure 1: Effect of isolation and damping on the response of seismically isolated bridges

3. ASSESSMENT OF DAMPING COEFFICIENTS, *B*

Figure 2 summarizes the matrix of analyses that were carried out in this project to evaluate the damping coefficients and compare them with those currently specified in the CSA-S6 code. When the damping coefficient computed in the analyses is greater than the *B*-coefficient prescribed in the code, the use of the simplified code method is deemed to be conservative and the corresponding code coefficient, B , is considered acceptable (denoted "Ok" in Figure 2). These results are discussed later. Primarily, this study focused on the comparison of the *B*-factors obtained from the time-history analyses of isolated and damped bridges subjected to earthquakes characterizing western North America (WNA) and eastern North America (ENA) seismic hazards. The results for both regions are compared with respect to the code provisions. The comparison is carried out both for linear (LTHA) and nonlinear (NLTHA) time-history analyses. As shown in Figure 2, the LTH analyses were performed to obtain both spectral displacements, S_D and spectral accelerations, S_A.

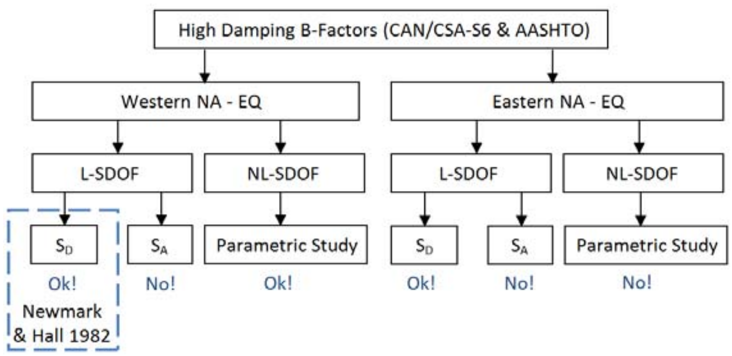

Figure 2: Flowchart of analyses for evaluating and comparing damping coefficients, *B*.

3.1 Selection of ground motions for time-history analyses

In this study, due to the scarcity of ground motions corresponding to historical events occurred in ENA, sets of eastern artificial (Atkinson, 2009) and hybrid (McGuire et al., 2001) ground motions were adopted for the ENA regions. To establish the same comparative basis between ENA and WNA, only the set of artificial western records (Atkinson, 2009) was analysed. Each of these ground-motions sets were comprised of twenty records that were selected according to the site-specific likely earthquakes scenarios. To build seismic hazard scenarios representing a high level of risk for both ground motion types, two densely populated Canadian cities were chosen: Montreal, Quebec, for eastern Canada, and Vancouver, British Columbia, for western Canada. For each location, earthquake scenarios were based on the de-aggregation of the seismic hazard in terms of magnitude and distance. The de-aggregation plots were produced for a probability of exceedance of 2% in 50 years and NBCC site class C (Halchuk and Adams, 2004; Halchuk, 2009). Consequently, three suites of twenty ground-motion records, denoted as artificial ENA (ATK-E), hybrid ENA (MCG-CEUS) and artificial WNA (ATK-W), were linearly scaled to the corresponding NBCC design spectrum (NBCC, 2005).

3.2 Linear time-history analyses

The simplified equivalent design method for isolated bridges relies on an equivalent effective linearization where the ordinate of the linear 5% damped spectra is divided by the damping coefficient *B* to obtain the resulting reduced response, as was originally proposed in the work of Newmark and Hall (1982) who compared linear damped spectra. To verify the effectiveness of the *B*-factors to accurately capture the spectral response reduction as a function of the effective damping, the results of the LTH analyses are first presented. Such analyses are representative for linear systems for which the response reduction effect is mainly influenced by the velocity-dependant viscous damping. Furthermore, as indicated in equations 2.2 to 2.5, the same damping coefficient *B* is used to determine both the statically equivalent seismic force and the displacement across the isolation bearings as a function of the spectral acceleration, S_A and pseudo displacement, PS_D, respectively. The validity of using this same *B*-factor for both these calculations is verified and discussed in this section.

The response of a linear single-degree-of-freedom (L-SDOF) system subjected to twenty time-history records, referred to as linear "exact", was averaged for each of the three ground-motion suites. The mean response spectra for the twenty records were constructed for six levels of viscous damping, β (5%, 10%, 20%, 30%, 40%, and 50% of critical) for both spectral acceleration, $S_A(\beta)$, and spectral displacement, $S_D(\beta)$. Accordingly, the damping factors, *B*, were computed by dividing the corresponding site-specific 5% damped response spectra by the response of the L-SDOF system having an increased level of viscous damping, β:

$$B(S_A) = \frac{S_A(5\%)}{S_A(\beta)} \quad \text{and} \quad B(S_D) = \frac{S_D(5\%)}{S_D(\beta)} \tag{3.1}$$

Values of $B(S_A)$ and $B(S_D)$ are plotted in Figure 3 as a function of β. The average values over a period range of 0.2 s to 4.0 s are shown. These values are compared to the damping coefficients specified in CSA-S6-06 code. It is noted that in CSA-S6-06, the same values are used to determine the statically equivalent seismic force and the displacement across the isolation bearing as a function of the spectral acceleration, S_A and pseudo displacement, PS_D, respectively, as both parameters are obtained from the site spectral acceleration reduced by the single factor *B*.

The results show that $B(S_D)$ determined from damped spectral displacements, $S_D(\beta)$, is higher than the *B*-factors specified in CSA-S6-06, indicating that the code values result in conservative displacement predictions for all levels of damping and for all three record suites. This approach agrees well with the original method proposed by Newmark and Hall which compares $S_D(\beta)$ rather than $S_A(\beta)$. Contrary to the results of $B(S_D)$, the $B(S_A)$ values determined from damped spectral accelerations are smaller than the code values, which indicates that the use of the code damping coefficients will results in underestimated (unsafe) force demand on isolated structures.

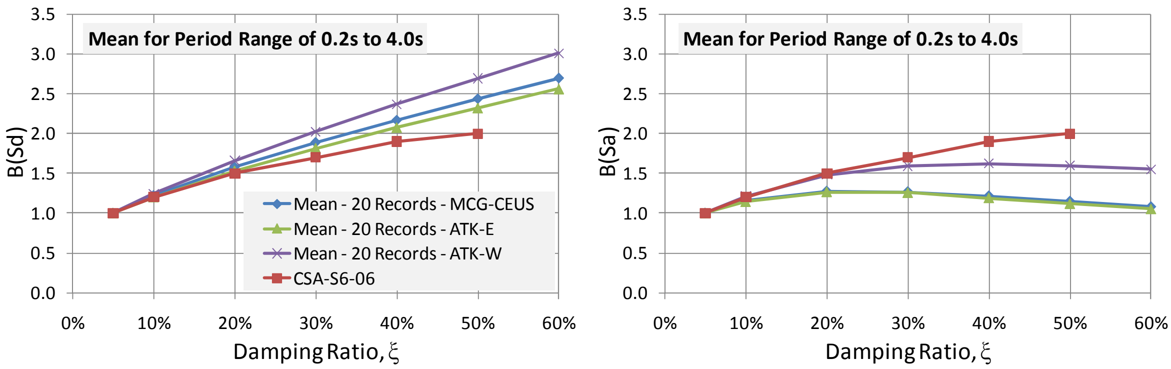

Figure 3: Comparison of damping coefficients B for the 0.2 s - 4.0 s period range.

The *B*-factors specified in the current CSA S6 code are assumed independent of the effective period of the linear equivalent system. However, the period-dependant nature of damping coefficients has already been pointed out in past studies (Atkinson and Pierre, 2004 and Hatzigeorgiou, 2010). The analysis results obtained in this study are used to verify this dependency. The effective period of an isolated structure varies from one ground motion to another and may therefore belong to different period ranges. In Figure 4, the average damping coefficients are evaluated separately for five smaller period ranges: 0-0.2 s, 0.2-0.5 s, 0.5-1.0 s, 1.0-2.0 s and 2.0-4.0 s. These period ranges correspond to the linear segments defining the 2005 NBCC design spectrum adopted in this study.

The damping coefficients $B(S_D)$ determined from the spectral displacement responses are examined first on the left-hand side of Figure 4. For the very short period range (0-0.2 s), the reduction effect of damping for the WNA records is significantly lower with respect to the other period ranges which, in turn, are reasonably close to each other. Much more pronounced discrepancy as a function of the period range is observed for the ENA suite of records. The maximum reduction effect of damping for mitigating the seismic response is observed between periods of 0.2 s and 1.0 s, which can be explained by the highest level of spectral velocities frequently found at these periods. In turn, the coefficients computed for the very short period (0-0.2 s) and long period (2.0-4.0 s) ranges point out the lowest contribution of viscous damping due to the low-velocity responses.

The $B(S_A)$ damping coefficients obtained from the acceleration response spectra are presented on the right-hand side of Figure 4. In Fig. 4b, the code values for WNA are appropriate for β up to 30% and for periods ranging between 0.2 s and 2.0 s. For ENA, in Figures 4d & f, the use of the simplified code method appears to be conservative for damping levels up to around 30% and periods ranging from 0.2 s to 1.0 s. These results confirm the code imposed upper limit of 30% imposed on the value of the effective damping for which the *B*-factor method can be used.

For a more accurate evaluation of the displacement across isolation bearings, the analysis results suggest that the code simplified method should be based on spectral displacements rather than spectral accelerations. For assessing the statically equivalent seismic force using equation (2.2), limitations on the effective period range and the effective damping ratio should also be specified. Otherwise, the use of current code provisions could result in unsafe response estimates.

In addition, it is opportune to mention that both sets of ENA ground motions yield results that are in good agreement with each other. This indicates that these suites have a reasonable level of compatibility that confirms consistency in the record selection and scaling procedures adopted for these time-history analyses.

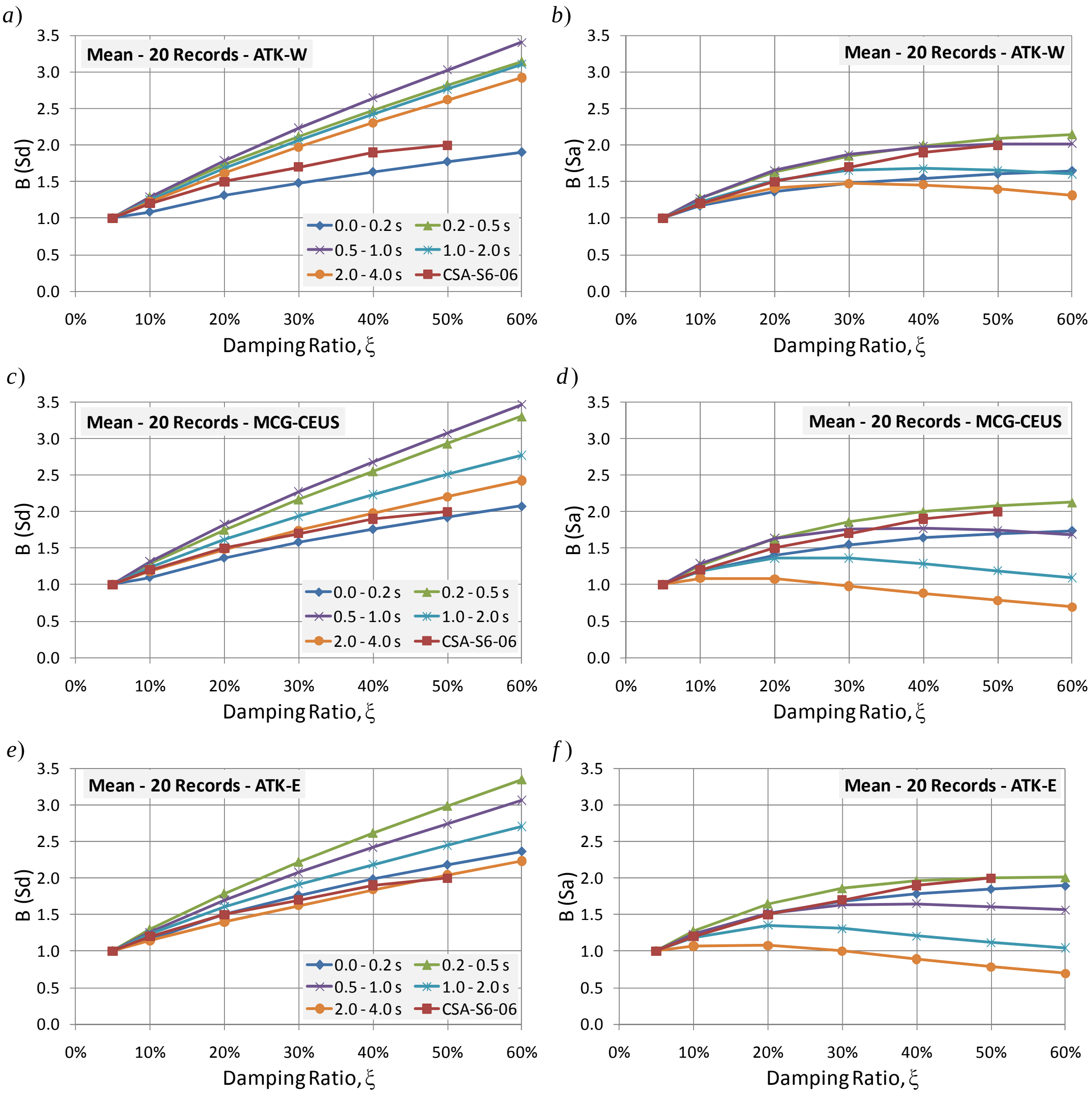

Figure 4: Variation of *B*-Factor with Damping Ratio by Period Range – Mean of 20 Records.

3.3 Nonlinear time-history analyses

The results presented in the previous section are applicable to the response of linear systems for which the response reduction effect is strongly influenced by the velocity-dependant viscous damping. For isolated bridge structures responding nonlinearly, however, the amount of equivalent damping depends on the hysteretic nature and the maximum displacement response, and the equivalent damping is no longer a direct function of the velocity. For this reason, a series of nonlinear time-history (NLTH) analyses was performed for an ensemble of bilinear SDOF systems covering a wide range of isolated and damped bridge configurations. The same suites of artificial ground-motion records that were used for the study on linear systems were also adopted for this parametric study. Table 2 presents the parameters used for defining the properties of the nonlinear SDOF systems analyzed herein which resulted in a total of 12 000 time-history analyses. In the table, five different levels of inherent damping were defined in relation to the elastic and effective periods. Both of these techniques are frequently adopted by researchers for NLTH analyses and yield comparable results for low-ductility response. However, the use of inherent damping related to the elastic period may lead to unconservative displacement response for highly nonlinear systems. In this study, these results are presented to represent the case where supplemental damping devices are used in bridges. For each suite of records, the results for the 20 records are averaged to present for each structure the mean response under a range of ground motions from site-specific earthquake scenarios.

Table 2: Structural parameters for nonlinear time-history analyses

Analysis Parameter	Eastern NA	Western NA
Strength Reduction Factor	R=[4, 16, 28, 40, 52]	R=[4, 16, 28, 40, 52]
Elastic Period	T_e=[0.25, 0.5, 0.75, 1.0 s]	T_e=[0.25, 0.5, 0.75 1.0 s]
Inherent Damping Ratio	$\xi(T_e)$= [0%, 2%, 5%]; $\xi(T_{eff})$=[2%, 5%]	$\xi(T_e)$= [0%, 2%, 5%]; $\xi(T_{eff})$=[2%, 5%]
Post-Yield Stiffness Ratio	α=[0.01, 0.05, 0.1]	α=[0.01, 0.05, 0.1]
Ground-motions Records	20 Atkinson's 2009 (ATK-E)	20 Atkinson's 2009 (ATK-W)

The damping coefficients, *B*, from NLTH analyses were assessed in two steps. In the first step, after obtaining the maximum displacement response, the effective period was evaluated as a function of this response. In the second step, the *B*-coefficient was determined by dividing the 5% damped spectral displacement corresponding to the effective period by the maximum displacement obtained from NLTH analysis. In Fig. 5, the damping coefficients computed for nonlinear SDOF systems are compared to those provided by the CSA-S6-06 code as a function of the effective damping. For WNA (Fig. 5a), the majority of the plotted dots, which represent the mean value of nonlinear responses under twenty seismic records, are above the curve that describes the code damping coefficients. This shows that the use of current code provisions results essentially in safe predictions. In contrast, for the ENA records (Fig. 5b), a significant number of dots are situated under the curve representing the code prescribed values. For eastern Canada, the unconservative predictions using the *B*-factors specified in the CSA-S6-06 code indicate that there is a need to adjust the code provisions to better predict the expected response of isolated bridges under ENA earthquake records.

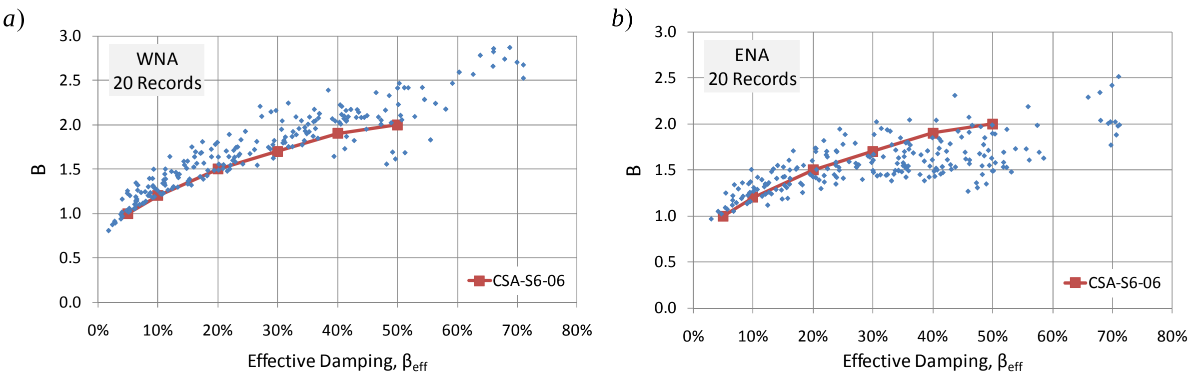

Figure 5: Comparison of computed damping coefficients, *B* with the provided by the CSA-S6 Code

To better understand how the use of the code-specified *B*-coefficients may impact the response prediction, the same nonlinear structures were analysed according to the complete iterative procedure required by the CSA-S6-06 code simplified method. The ratios of the nonlinear "exact" NLTH analysis results to the corresponding values obtained when using the code coefficients, u_{NLTH}/u_{code}, are presented as a function of the effective equivalent damping, β_{eff} in Fig. 6. For ENA, a large fraction of the computed ratios are larger than 1.0, especially for systems exhibiting a low yielding stiffness ($\alpha \leq 0.05$), which provides further evidence that the current code *B*-factors need to be adjusted for ENA records.

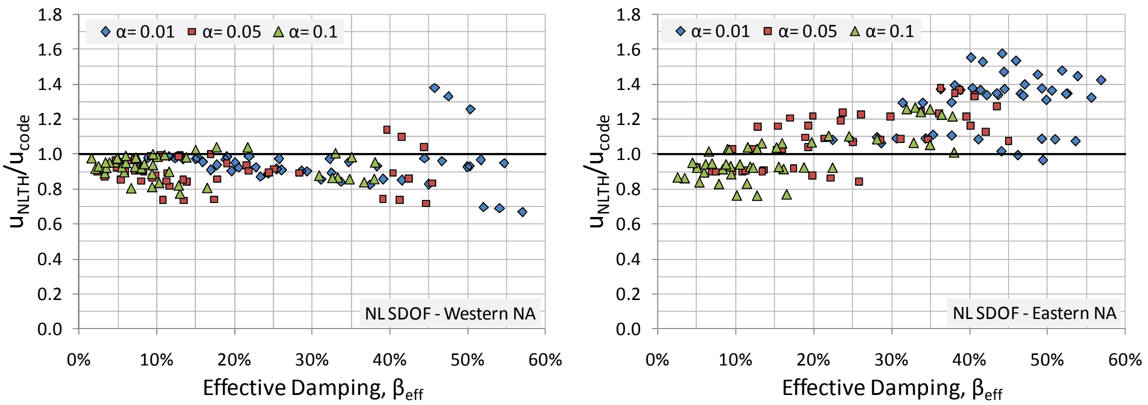

Figure 6: Ratio of NL SDOF to CSA-S6 with Effective Damping (WNA and ENA)

4. PROPOSED EQUATION FOR DAMPING COEFFICIENTS, *B*

The analysis results showed that the use of damping coefficients as specified in the CSA-S6-06 code may lead to underestimation of peak isolator displacements in eastern North America. Consequently, alternative damping coefficients are required to account for the response reduction effect of the ENA ground motions. Following the same procedure, exact values of the required damping coefficients are computed using NLTH analyses of the ensemble of nonlinear SDOF bridge systems. The results are presented in Fig. 7. As shown, it is found that a safe (lower bound) damping coefficient estimate for ENA can be obtained using equation 2.1 with an exponent n = 0.2. In Fig. 7, it is also shown that equation 2.1 with n = 0.3 gives similar damping coefficients compared to current code values. This means that equation 2.1 could be incorporated in future edition of CSA-S6 for the *B*-coefficients with two different exponent values: n = 0.2 for ENA and n = 0.3 for WNA.

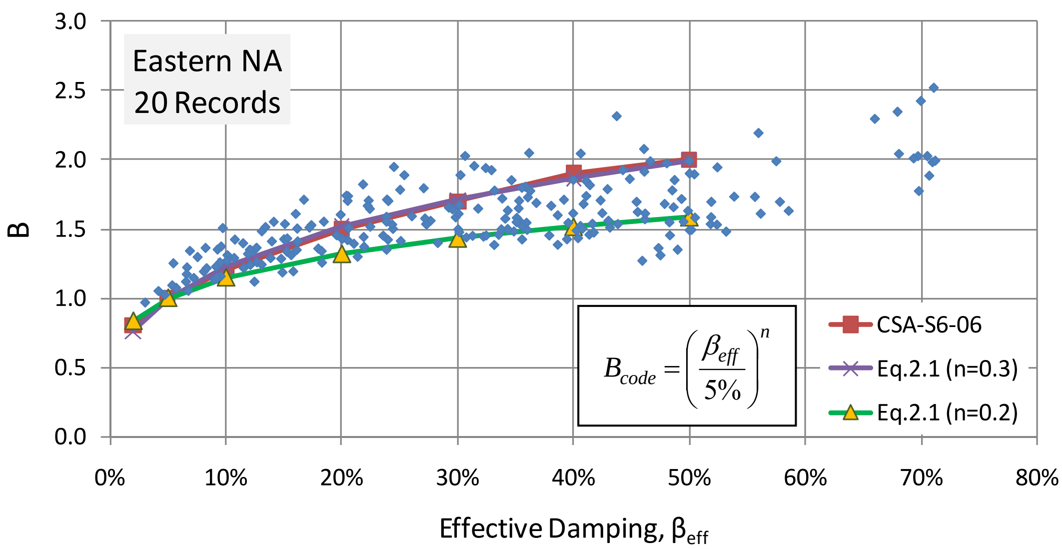

Figure 7: Comparison of proposed and computed *B* damping coefficients for ENA.

5. CONCLUSIONS

In this paper, the effect of equivalent damping for reducing the response of isolated bridges located in eastern and western Canada was investigated under site-specific ground motions anticipated in eastern North America (ENA) and western North America (WNA), respectively. To ensure consistency in the comparison of the effects of ENA and WNA earthquakes, suites of artificial records from the same source were adopted for both locations. The responses obtained from linear and nonlinear time-history analyses were obtained and compared to those obtained with the CSA-S6-06 code when using code specified damping coefficients *B*. The following conclusions can be drawn from the analysis results:

1) The spectral displacements, rather than spectral accelerations, should be used in the simplified equivalent method proposed in the CSA-S6 code.

2) The reduction of the seismic response due to the damping depends on the effective bridge period and the differences between period ranges are more pronounced under ENA earthquakes.

3) The reduction effect of equivalent damping is lower under ENA records when compared to WNA records. The use of the damping coefficients specified in the current CSA-S6 code results in safe designs for WNA but leads to underestimated displacement demands under ENA ground motions. An equation as currently used in AASHTO specification could be used with different exponents for WNA and ENA locations to compute the B factors in future edition of the CSA-S6 code in Canada.

ACKNOWLEDGMENTS

As part of the Canadian Seismic Research Network's (CSRN) project, this work was supported by the Natural Science and Engineering Research Council of Canada (NSERC) and by the doctoral research scholarship from the Fonds de recherche du Québec – Nature et technologies (FQRNT).

REFERENCES

Adams J., Halchuk S. (2004). Fourth-generation seismic hazard maps for the 2005 national building code of Canada. *Proceedings of the 13th World Conference on Earthquake Engineering*, Vancouver, Canada, August 1-6, 2004, Paper 2502.

ATC-3 (1978). Tenative provisions for the development of seismic regulations for buildings, National Bureau of Standards, Special, Publication 510, Applied Technology Council, Washington, DC.

Atkinson G.M., Pierre JR. (2004). Ground motion response spectra in Eastern North America for different critical damping values. *Seismological Research Letters 2004* 75(4), 541–545.

Atkinson G.M. (2009). Earthquake time histories compatible with the 2005 National Building Code of Canada uniform hazard spectrum, *Can. J. Civ. Eng.* 36(6), 991-1000.

CAN/CSA-S6-06 (2006). Canadian highway bridge design code. CSA International, Toronto, Ontario, Canada.

Halchuk, S. and Adams, J. (2004). Deaggregation of seismic hazard for selected Canadian cities, *Proceedings of the 13th World Conference on Earthquake Engineering*, Vancouver, Canada, August 1-6, 2004, Paper No. 2470.

Halchuk, S. (2009). Personal Communication with R.Tremblay.

Hatzigeorgiou, G.D. (2010). Damping modification factors for SDOF systems subjected to near-fault, far-fault and artificial earthquakes, *Earthquake Engng. Struct. Dyn. 2010* 39, 1239–1258.

ICBO (1991). Uniform Building Code, International Conference of Building Officials, California, USA, 1991.

McGuire, R.K. (1995). Probabilistic seismic hazard analysis and design earthquakes: closing the loop, *Bull. Seism. Soc. Am. 1995* 85: 1275-1284.

McGuire, R.K., Silva, W.J., and Constantino, C. J. (2001). Technical basis for revision of regulatory guidance on design ground motions. Rpt. NUREG/CR-6728, U.S. Nuclear Regulatory Commission.

Naeim, F., Kircher, C.A. (2001). On the damping adjustment factors for earthquake response spectra, *The Structural Design of Tall Buildings* 10(5), 361-369.

Naumoski, N., Cheung, M.S. and Foo, S. (2000). Evaluation of the seismic response coefficient introduced in the Canadian Highway Bridge Design Code. *Can. J. Civ. Eng.* 27, 1183–1191.

Newmark, N.M. and Hall, W.J. (1982). Earthquake spectra and design. Engineering Monographs on Earthquake Criteria, Structural Design, and Strong Motion Records, Earthquake Engineering Research Institute.

NRCC (2005). National Building Code of Canada, and Commentary. National Research Council of Canada Ottawa, ON.

SEAONC (1986). Tentative Seismic Isolation Design Requirements. SEAONC: San Francisco, CA.

Taylor, P.R. (1999). Some thoughts on seismic engineering for bridges seen from a Canadian perspective. *Proceedings of the 8th Canadian Conference on Earthquake Engineering*, Vancouver, B.C., pp. 29–41.