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ASSESSMENT OF TEMPERATURE EFFECTS ON SEISMIC RESPONSE OF BASE-ISOLATED BRIDGES IN EASTERN AND WESTERN CANADA

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ABSTRACT: Seismic base-isolation of bridges is a very effective alternative to the conventional design approach, based on the capacity design principle. It is gaining an increasing interest, since almost two decades, in Canada and being used on many completed and in progress bridge projects. However, practically all the common seismic isolation systems are sensitive are sensitive to many external and inherent effects especially low temperature ones. In fact, under cold temperatures, they typically show an important increase of their stiffness and yield or characteristic strength. Despite relatively known effects of low temperature on base isolation systems characteristics, the impact of low temperature on base isolated bridges response and seismic demand in cold regions remain not enough studied and well understood by researchers and practicing engineers, especially within the recent Canadian seismic context, introduced by the NBCC and being adopted in the CSA-S6-14 code. The actual practice uses a bounding analysis approach through a set of property modification factors, initially recommended by the AASHTO.

This paper presents the assessment of impact of typical hysteresis features changes, notably because of temperature, on the seismic response of isolated bridges in Canada. Analyses results show that such changes cause substantial to important changes on seismic response of isolated bridges and that this effect differs significantly for eastern from western Canada.

Preliminary tendencies and findings, relating temperature and hysteretic variations to bridge seismic response main parameters are pointed out.

1. Introduction

Past major earthquakes, during the last 45 years, have demonstrated that bridges are particularly vulnerable to such events everywhere in the world (Mitchel et al. 1995, Wang and Lee 2009, Kawashima 2012). However, the lessons learned from real performance of bridges during past earthquakes, the development of powerful analytical and experimental tools as well as the availability of innovative materials and technologies greatly contributed to evolution of bridge design codes and practice during the last decades toward more reliable structures. Modern seismic design approaches generally adopt one of two distinct alternatives to face earthquakes: (1) the "conventional" fixed base design and, (2) the seismic base isolated design. The further relies essentially on the capacity of the bridge to resist the earthquake forces and /or to absorb the seismic input energy through inelastic ductile mechanisms that are created at preselected and carefully detailed locations within the structure. Seismic base isolation relies on lengthening considerably the fundamental period, through use of flexible devices at its base, instead of fixed base, resulting in a drastic reduction of the seismic forces transferred to the structure. As the lengthening of the structure period results in increased displacement demand, modern seismic isolation systems incorporate dissipative energy features to control seismic displacements at acceptable levels.

Seismic base isolation offers an attractive and increasingly popular design alternative to the fixed base approach in Eastern and Western Canada during the last two decades. Its popularity is mainly due to the fact that it allows reduction of the elastic seismic forces which make it easy to design the bridge to respond elastically during the design earthquake, preserving thereby its functionality and easily accomplishing a performance level comparable to what is intended for lifeline bridges (Moradiankhabiri et al. 2015). Seismic isolation hysteretic features such as characteristic strength, Q_d, and post-elastic stiffness, k_d, are of capital importance and govern the seismic response and consequently the performance of base isolated bridges.

However, the characteristic features of common seismic isolation systems are known to be sensitive to many factors such as the level of stress, velocity, temperature, and aging. The last factor is particularly relevant for Canadian applications as the main seismic regions are located within zones of sustained low temperatures. Many researchers (Murray and Detenber (1961), Roeder et al. (1990), Yakut (2000), Constantinou et al. (2007)) carried out extensive experimental tests on a series of seismic isolation bearings and found out that mechanical characteristics of these devices are highly affected by low temperatures especially when it drops to extreme levels.

On the other side, actually the Canadian standard CSA-S6-06 (CSA 2006) does not give combination rules of temperature with earthquake. However, without specifying a load combination including the earthquake with temperature, the just released edition of the Canadian standard CSA-S6-14 (CSA 2014) specify combining rules of thermal movements with earthquake displacements and recommends the approach of bounding analysis proposed by the AASHTO (AASHTO 2010), on the basis of Constantinou's work (Buckle et al. 2006, Constantinou 1999). This approach, already in use during the last decade, is based on modification factors, λ, applied to the main hysteretic features of the isolation system and on analysis of the bridge under two bounding conditions: (1) nominal condition with minimal values of λ, all applied simultaneously, giving rise to a lower bound in terms of seismic forces and an upper bound in terms of displacement and , (2) extreme condition with maximum values of λ, all applied simultaneously, giving rise to the maximum demand in terms of seismic forces and a lower bound of displacement.

Furthermore, the effect of variation of the hysteretic characteristics of seismic isolation systems and notably those attributed to temperature effects are still not well understood, especially within the context on the introduction of new uniform seismic hazard maps and design spectra proposed by the NBCC 2010 and the similar seismic design spectra being adopted in the S6-14, which is based on the next coming NBCC 2015 uniform seismic hazard values. The NBC2010 design spectra are more appropriate, than the S6-06 spectra, to represent the seismic context of Canada and better takes into account differences between seismicity of Eastern Canada, characterized by a rich content of high frequencies, and that of Western Canada. The S6-06 design code did not recognize such a difference and, for example, the design spectrum for Montreal is exactly the same as the one used for Vancouver and both are based on the American West Coast spectra (California) proposed by the AASHTO (AASHTO 2010).

To assess the effect of variation of hysteretic characteristics of seismic isolation systems, especially with temperature, this paper presents preliminary results and tendencies derived from a series of nonlinear time history analyses on a simplified model of base isolated bridge. To account for the particularities of the seismicity in Eastern and Western Canada, we compared results obtained from earthquakes calibrated on NBCC 2010 uniform hazard spectra for Montreal and Vancouver with those for earthquakes calibrated on S6-06 design spectra. Starting from a typical reference design, the temperature effects are taken into account through modification of the post-elastic stiffness k_d and the characteristic strength Q_d in proportions typical of what was measured by earlier experiments on common systems.

2. Survey of past experiment work results on low temperature effects

The most common Seismic base isolation systems can be classified into two families: (1) Elastomer based systems such as the well-known lead rubber seismic isolator and; (2) Sliding/friction based systems such as the widely used friction pendulum seismic isolator.

Elastomers pertain to polymers family whose chemical structures are composed of very large sequences of monomers interlinked by Van der Waals interactions. The number of polymers can vary from some hundreds to about thousand hundreds (Marchal, 2006). Elastomers have two principle branches, which are natural rubber (polyisoprène) and synthetic rubber (polychloroprène). As the chemical composition is complex, they are vulnerable to several factors that affect the chemical, physical and mechanical properties and thus lead to substantial changes in seismic behavior. As well as elastomer compounds, main factors affecting the response are scragging, aging, pressure, wear and travel, strain rates, contamination and temperature. Elastomers are viscoelastic materials; they are subject to two low-temperature stiffness raises depending on time and temperature of exposure: (1) instantaneous stiffening and; (2) time-temperature depending stiffening (Roeder et al. 1989, Murray and Detenber, 1961). Constantinou et al. (2006) pointed out that low temperature is accompanied with increasing in mechanical parameters like stiffness and characteristic strength of elastomeric bearings and friction coefficient of sliding apparatus. Table 1 presents few published experimental results illustrating low temperature effects on the hysteretic properties of elastomeric seismic isolators.

Furthermore, many researchers reported that low temperatures have an important effect on the properties of sliding bearings. The friction coefficient as well as the stiffness increase with decrease of temperature and with velocity (up to a certain value) and decrease with the excreted pressure on the interface (Buckle et al. 2006). Private testing done in Quebec during the last decade on sliding bearing isolators confirms these findings and showed a typical increase by 40 to 60% of the friction coefficient of carbon filled PTFE-stainless steel interfaces when temperature drops from room temperature (+/- 20°C) to -30°C.

Table 1 – Temperature effects on elastomeric seismic isolation devices properties.

Reference	Test conditions	Q_d	K_d	K_{eff}
Feng et al., 2004	LRB[1] with 300 mm width layers, Temperature drops from 20°C to -10°C, Temperature rises from 20°C to 40°C.	+25% -13%	-	+5% -2%
Constantinou et al., 1999	Velocity = 250 mm/s, Shear strain = 60%, Axial force = 1100 kN, Elastomer thickness = 195 mm, Natural rubber grade 3 shore A 45 Duro. For LRB, lead plug with 70 mm ø, Temperature drops from 20°C to -26°C,	-	-	-
	i. EB[2]	+100%	-	+50%
	ii. LRB[1]	+ 42%	-	+ ~42%
Kim et al., 1996	* Frequency=0,1 Hz, Elastomer thickness = 195 mm, Rubber grade 3 shore A 50±10 duro. *Temperature drops from 20°C to -48°C.	-	-	-
	i. EB[2] : Axial force = 356 kN, Shear strain = 50%.	+600%	-	+ 200%
	ii. LRB[1] : Axial force = 90 kN, Shear strain = 25, 50, 75 & 100%.	+80%	+40%	-

[1] LRB : Lead Rubber Bearing; [2] EB : Elastomeric Bearing

3. Objectives and methodology

The main objective of this study is to assess the effect of varying the hysteretic characteristics of the seismic isolation, due to temperature and other causes, on the seismic response of base isolated bridges located in Montreal and Vancouver sites, representative of the Eastern and Western Canada seismic regions respectively.

At this stage, the study focused on the variation of the hysteretic characteristics of the isolation system. Therefore, the used model is a nonlinear Single Degree Of Freedom (SDOF) with a bilinear hysteresis, represented on figure 1 was used. Such model neglects the foundations units' stiffness, soil and bidirectional effects. Nevertheless, isolated bridges have their dynamic response mainly lumped in their fundamental mode and such a model represents with sufficient precision a large proportion of practical isolated bridges. The characteristic features of the isolation system are the initial stiffness k_u, the post-elastic stiffness k_d and the characteristic strength Q_d as defined on figure 2.

A reference base isolated bridge with a weight of 10 000 kN and an isolation system selected to have an equivalent linear system with a period of 2 seconds and an equivalent viscous damping of 20%, using the design spectrum of the CSA-S6-06 for Montreal and Vancouver was considered. Its restoring system stiffness, $k_{d,}$, was set to the minimum value required by the AASHTO guide specifications for seismic isolation that is the difference between the force at the design displacement and the force at half the design displacement is equal to 1.25% of the weight. Note that the CSA-S6-06 requires a minimum restoring stiffness equal to twice-such stiffness (2.5% W) but the just released edition of the standard (CSA-S6-14) adopts the AASHTO requirement regarding the minimum restoring system stiffness.

The hysteresis properties, k_d, Q_d, of the reference system were varied, up and down, to generate a set of isolated bridge models simulating the effects of temperature and other sources of variation. Table 2 presents the hysteresis properties of the reference system and all the other cases studied. The characteristic strength Q_d and the post elastic stiffness k_d had varied between 20% and 200% of the reference values through 5 levels as indicated in table 2. Only three (3) levels of the characteristic strength are considered in this paper.

Table 2: Hysteresis properties variations considered.

Char. strength, Q_d (kN)	-80% 42kN (0.42%W)	-50% 105kN (1.05%W)	Q_d Reference 210kN (2.1%W)	+40% 295kN (2.95%W)	+100% 420kN (4.2%W)
Post-elastic stiff., k_d (kN/m)	-80% 1370	-50% 3425	K_d Reference 6850	+40% 9590	+100% 13700

Nonlinear time history analyses were then undertaken using a selection of 18 historical ground motions registered in eastern and western North America and scaled to match the design spectra of the CAN-CSA-S6-06 and the NBCC 2010 codes for both sites (Montreal and Vancouver). In total, 900 nonlinear time history analyses were carried out. This paper presents summary and partial results of only 540 of them. The obtained seismic responses are examined here in terms of the maximum seismic force and maximum displacement demand to bring out the principal effects of the seismic isolation hysteresis variation, due notably to temperature effects, on the seismic responses in Eastern and Western Canadian seismic regions.

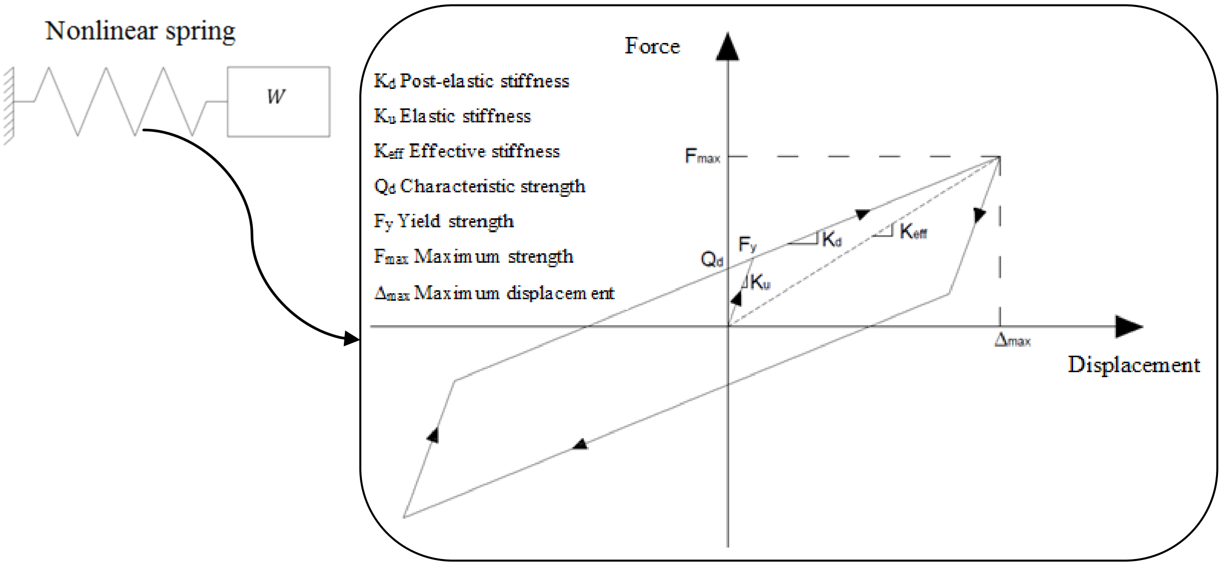

Fig. 1 – Nonlinear SDOF model of the studied isolated bridges

4. Ground motion selection and scaling

Table 2 and 3 present respectively the unscaled selected ground motion used for this study for both Montreal and Vancouver sites. These ground motions were scaled to match the target design spectra for Montreal and Vancouver as defined in the CSA-S6-06 and NBCC 2010 codes. The selected ground motions were therefore scaled to the target spectra using a spectral matching technique in the time domain (Abrahamson et al. 1992 and Hancock et al. 2006). Michaud and Léger (2014) made a comparative study between different methods of ground motion scaling and recommended the time domain spectral matching method.

This study, considers a class C soil as per NBCC 2010 classification and a class II soil as per the CSA-S6-06 classification. The latter code defines a unique spectrum for both cities as target spectrum. Figure 2 shows the target design spectra with the obtained acceleration spectra for some of the scaled ground motions used for both sites

In conformity with the specifications of the NBCC 2010 and the recommendations of the Michaud and Leger (2014), we used at least seven records for each site and we considered the mean values of the obtained maximum response variables.

Table 2 – Unscaled selected ground motions characteristics used for Montreal site.

Event	**Date**	$R(km)$	M_w	**PGA**	**PGV**
Saint-André _ EW 270°	25-Nov-1988	64	5.7	0.091	0.009
Saint-André _ NS 0°	25-Nov-1988	64	5.7	0.156	0.018
Nahanni Bettlement Creek _ N 360°	23-Dec-1985	24	6.5	0.194	0.034
Nahanni Bettlement Creek _ N 270°	23-Dec-1985	24	6.5	0.186	0.063
Saguenay Chicoutimi Nord _ N 124°	25-Nov-1988	43	5.7	0.131	0.025
Saguenay Chicoutimi Nord _ N 214°	25-Nov-1988	43	5.7	0.106	0.015
Saguenay Les Éboulements _ NS 0°	25-Nov-1988	90	5.7	0.125	0.044
Saguenay Les Éboulements _ EW 270°	25-Nov-1988	90	5.7	0.102	0.027

Table 3 – Unscaled selected ground motions characteristics used for Vancouver site.

Event	**Date**	$R(km)$	M_w	**PGA**	**PGV**
San Ysidro Gilroy #6 EW 90°	24-Apr-1984	36	6.2	0.286	0.366
San Ysidro Gilroy #6 NS 360°	24-Apr-1984	36	6.2	0.219	0.113
Pacoima-Kagel Canyon EW 90°	01-Oct-1987	38	6.1	0.158	0.077
Pacoima-Kagel Canyon NS 0°	01-Oct-1987	38	6.1	0.155	0.074
San-Francisco-Presidio EW 90°	17-Sep-1989	98	7.0	0.199	0.335
San-Francisco-Presidio NS 0°	17-Sep-1989	98	7.0	0.100	0.133
San Pedro Palos Verdes EW 90°	17-Jan-1994	58	6.7	0.095	0.064
San Pedro Palos Verdes NS 0°	17-Jan-1994	58	6.7	0.101	0.055
Castaic - Old Ridge Route NS 360°	17-Jan-1994	41	6.7	0.514	0.526
Castaic - Old Ridge Route EW 90°	17-Jan-1994	41	6.7	0.568	0.515

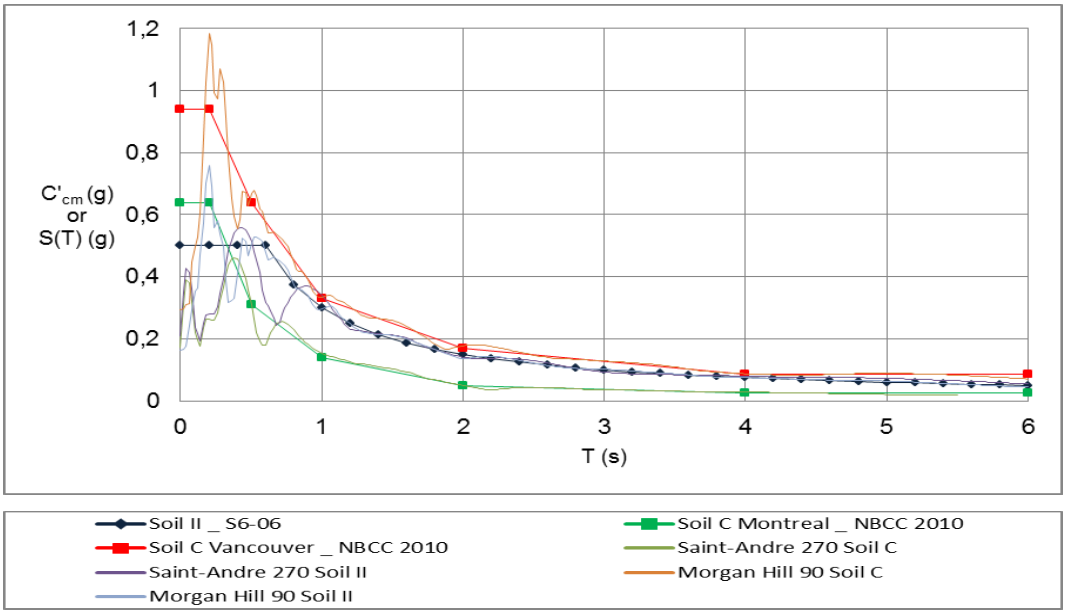

Fig. 2 – Target spectra for Montreal and Vancouver and response spectra of some scaled records.

5. Results and discussion

This section presents selected results obtained from the time history analyses for a selected set of the varying variables, for both sites (Montreal and Vancouver) and both standards spectra (S6-06 and NBCC 2010). For more generality, the seismic force demands as well as the characteristic strengths are expressed as fractions of the superstructure weight, W so they can be directly compared to a spectral acceleration or a seismic response coefficient. Similarly, the post-elastic stiffness is expressed in terms of a fraction of its restoring force correspondent to an arbitrary displacement of 100mm to the weight of the superstructure.

5.1 Seismic force demand

Figures 3 and 4 show the variation of the seismic force demand for Montreal and Vancouver respectively as a function of the hysteresis properties of the isolation system.

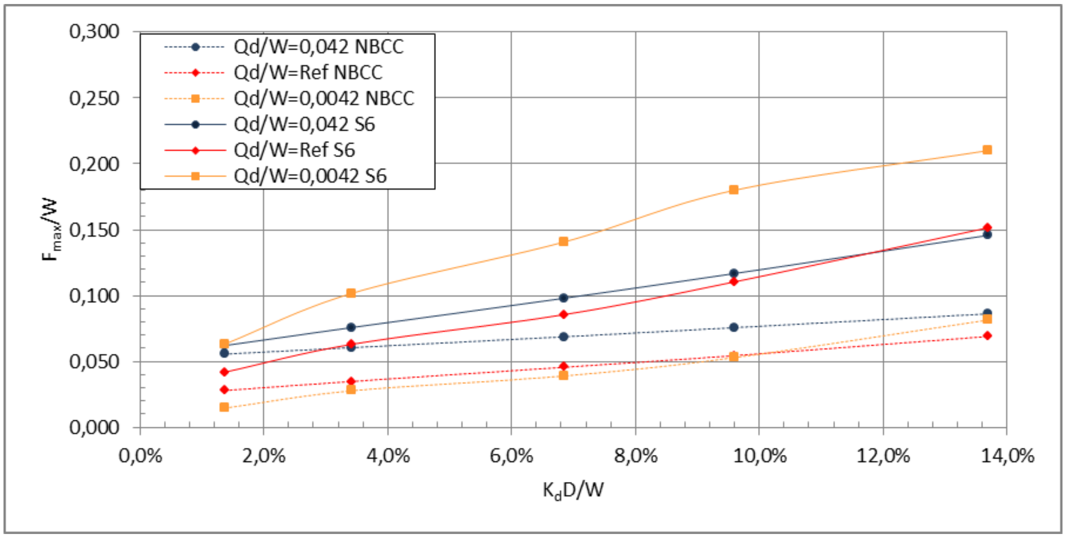

Fig. 3 – Seismic force demand variation with characteristic strength and post-elastic stiffness for Montreal site using NBCC 2010 and CSA-S6-06 design target spectra.

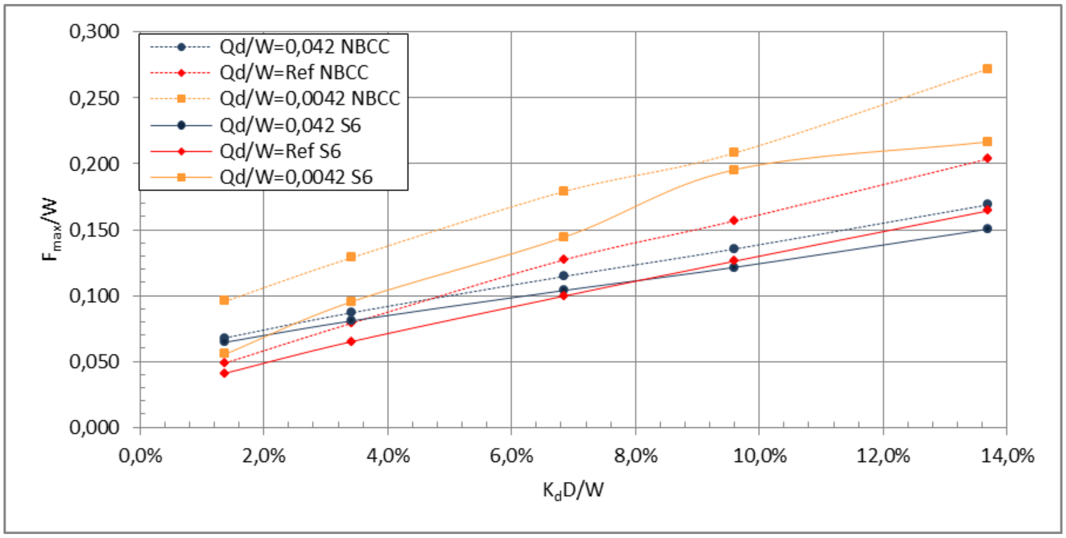

Fig. 4 – Seismic force demand variation with characteristic strength and post-elastic stiffness for Vancouver site using NBCC 2010 and CSA-S6-06 target spectra.

From figure 3, we note that the seismic force demand according to the NBCC 2010 design spectrum for Montreal is much lower (typically about 50% around the reference system) of that resulting from the CSA-S6-06 design spectrum. The reduction in the seismic demand is even more pronounced for systems with low values of characteristic strength. This indicates that adopting the NBCC seismicity has a major beneficial consequence on the efficiency of the base isolation in eastern Canada.

We observe also that the seismic demand increases with the post elastic stiffness k_d in an almost linear trend. However, it is clear that the different lines are not parallel indicating that the effect of the variation in the post-elastic stiffness depends on the level of the characteristic strength and the design spectrum. The effect of the post elastic stiffness is more important, in terms of absolute seismic force demand change, for systems with low characteristic strengths and with the S6-06 spectra. For example, due to an increase of 100% of the characteristic strength, we observe an increase of 6.9%W in force demand for the low reference value of Q_d/W=0.42% with the S6-06 spectrum but only an increase of 1.74%W for the high reference characteristic strength of Q_d/W=4.2% with the NBCC code spectrum.

It is interesting to observe that with the S6-06 code spectrum, the highest force demand is obtained for low characteristic strengths while for the NBCC code spectrum an opposite trend is obtained, as higher force demands are associated with higher characteristic strengths, except for very stiff recentring systems associated to a very low characteristic strengths.

For the Vancouver site, results of figure 4 show a similar general trend as those for Montreal but with important differences. It can be noted that for Vancouver site, contrarily to Montreal where a drop of about 50% is observed in force demand, the NBCC 2010 force demands are generally higher (20 to 30%) than those associated to the CSA-S6-06 code.

Contrarily to the Eastern site of Montreal, it is clear that for the Western site of Vancouver increasing the characteristic strength Q_d is beneficial as it causes a decrease in the seismic force demand with both standards except for very low post-elastic stiffness. For example, considering the reference starting point, an increase by 100% of the characteristic strength causes an increase by 50% of the seismic demand in Montreal but a drop of 10% for Vancouver site. However, increasing the post-elastic stiffness by 100% causes an increase of 50% in force demand for Montreal and a similar 60% increase for Vancouver. The combined effects of an increase by 100% in both the characteristic strength and the post elastic stiffness induce an increase by 87% in force demand for Montreal site but only an increase of 29% for Vancouver.

5.2 Seismic displacement demand

Figures 5 and 6 present the maximum seismic displacement for both sites as a function of varying characteristic strength and post-elastic stiffness. Both figures present the same general trend that is the increase in post-elastic stiffness results in a decrease of the seismic displacement demand for both standard spectra and for all the characteristic strength levels. However, beyond the reference point, the curves flatten and the effect of the post-elastic stiffness is almost null except for very low characteristic strengths (Q_d/W=0.42%). Besides, major differences may be drawn from figures 5 and 6 on the displacement demands of isolated bridges in eastern and western Canada according to both standards.

Major differences may be drawn from figures 5 and 6 on the displacement demands of isolated bridges in western Canada and eastern Canada according to both standards.

For Montreal site, we observe on figure 5 that the displacement demand from the NBCC 2010 code spectrum are much lower than those associated to the CSA-S6-06 code spectrum. Typically, a reduction of 50% in displacement demand is observed when shifting from the S6-06 code spectrum to the NBCC 2010 code spectrum. For systems with low characteristic strengths, a more pronounced reduction in displacement demand (i.e.: in the range of 75% for *Qd/W*=0.42%) is obtained. For Vancouver, contrarily to Montreal, the displacement demands associated to the NBCC 2010 spectrum are higher than those resulting from the CSA-S6-06 spectrum (typically 20 to 30%).

Figures 5 and 6 show that increasing the characteristic strength from low values results in an important decrease in displacement demand but increasing already high values of the characteristic strength is less efficient specially for Vancouver with the NBCC 2010 code spectrum.

An increase of 100% of Q_d *from the reference point*, due to temperature drop, would cause a decrease of the displacement demand of the reference system by 25 mm (-24%) for Montreal with the CSA-S60-06 code spectrum but only 5.7mm (15%) with the NBCC Code spectrum. For Vancouver, the same increase in Q_d would cause a reduction of 29mm (-20%) with the CSA-S6-06 but as high as a reduction of 53mm (-33%) with the NBCC code spectrum. Effects of a similar increase of 100% of the post-elastic stiffness on the displacement reduction are much less important as we obtain almost no change for Montreal and less than 10% for Vancouver.

Finally, low temperatures affect the seismic response of isolated bridges, notably through increasing the hysteresis characteristics (characteristic strength and post-elastic stiffens) of the isolation system. This effect is found important but differs for Western sites from Eastern and for CSA-S6-06 from NBCC code (or the new S6-14) sites and depend on the initial levels of the hysteresis features.

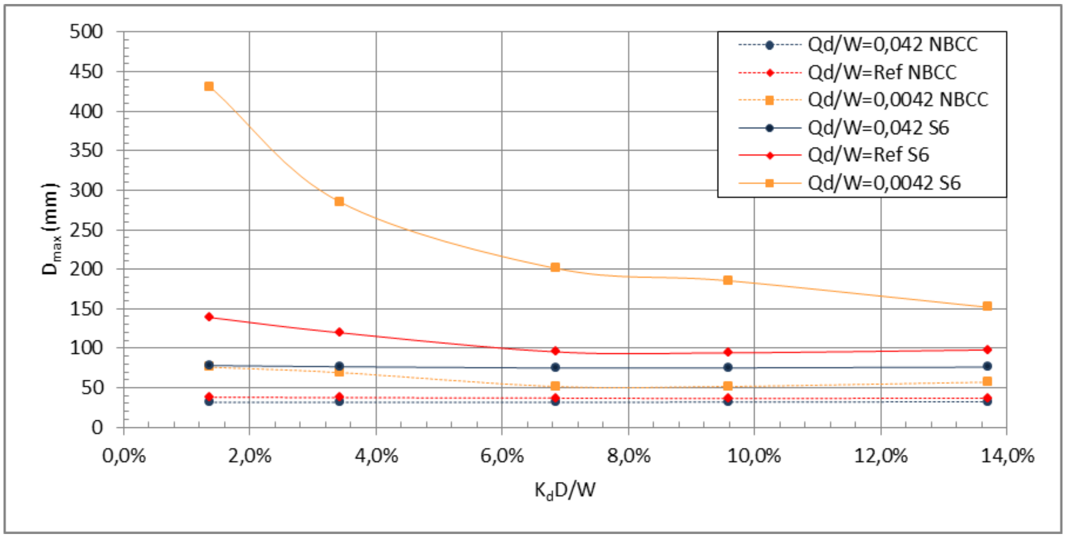

Fig. 5 – Maximum displacement as a function of the post-elastic stiffness and characteristic strength variation for Montreal site.

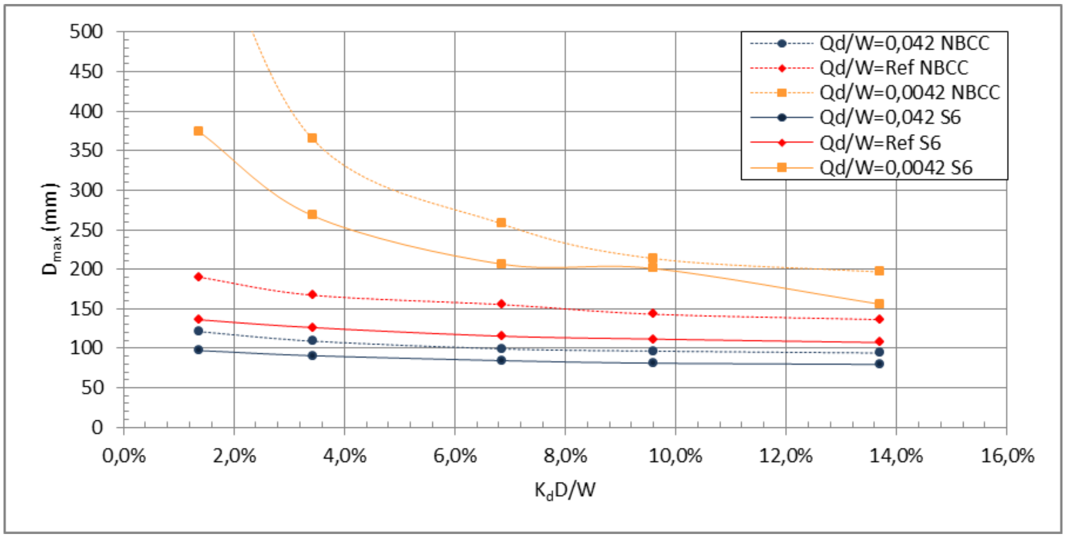

Fig. 6 – Maximum displacement as a function of the post-elastic stiffness and characteristic strength variation for Vancouver site.

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