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Evolution of Performance-Based Design in the Canadian Highway Bridge Design Code, CSA S6:25

Marc Gérin[1*], Don Kennedy[2], Sepideh Ashtari[3] and Jimmy Fortier[4]

[1]Senior Engineer, Gerin Seismic Design, Ottawa, ON, Canada
[2]Associated Engineering, Vancouver, BC, Canada
[3]Bridge Engineer and Seismic Specialist, TYLin International, Vancouver, BC, Canada
[4]Bridge Engineer, Parsons, Montréal, QC, Canada
[*]marcgerin@gmail.com (Corresponding Author)

ABSTRACT

Performance-Based Design (PBD) was introduced in the 2014 edition of the CSA S6 Canadian Highway Bridge Design Code (CHBDC) as the design philosophy to be used for the majority of new bridges and retrofit of existing bridges. Force-Based Design (FBD), using ductility-based R-factors, was retained from previous versions of the Code for use with certain bridges. Although there were benefits to retaining much of the previous code unchanged, this resulted in the appearance of a choice between two alternative design paths, PBD or FBD. Further complicating this dichotomy was that an elastic strength-based design approach can fit into both PBD and FBD, and that various common prescriptive requirements are specified for both paths. In 2020, a task group was formed to review the organization of the seismic provisions of CSA S6 and propose ways to improve clarity, simplicity and usability of the Section. A key focus was on clarifying the philosophy and code framework around PBD.

For the 2025 edition of CSA S6, PBD will be defined as the overarching seismic design philosophy. It will then be the framework under which all the design methods – Displacement-Based Design (DBD), FBD, elastic design, isolation design, capacity protection – are defined. The DBD approach will be explicitly defined; the role of FBD relative to PBD will be clarified, removing the ambiguity around which requirements are applicable to each approach; the elastic design approach, alone or in combination with other methods, will be defined in the context of PBD; and seismic design requirements for low-seismic regions can be defined within the framework of PBD, rather than as exceptions to it. These revisions truly define CSA S6 as a performance-based seismic code.

Keywords: Bridges, Seismic Design, Performance-Based Design, Canadian Highway Bridge Design Code

INTRODUCTION

Performance-Based Design (PBD) was introduced in the 2014 edition of the CSA S6 Canadian Highway Bridge Design Code (CHBDC) as the design philosophy to be used for the majority of new bridges and retrofit of existing bridges. Force-Based Design (FBD), using ductility-based R-factors, was retained from previous versions of the Code for use with certain bridges. Although there were benefits to retaining much of the previous code as-is, this resulted in the appearance of a choice between two alternative design paths, PBD or FBD. Further complicating this dichotomy is that an elastic strength-based design approach can fit into both PBD and FBD, and that various common prescriptive requirements are specified for both paths. In 2020, a task group was formed to review the organization of the seismic provisions in Section 4 of CSA S6 and propose ways to improve clarity, simplicity and usability of the Section. A key focus was on clarifying the philosophy and code framework around PBD.

BACKGROUND

The first comprehensive seismic provisions were included in Section 4 of the 2000 edition of the S6 Code (S6:00) [1] and were based on the 1994 American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Bridge Design Specifications. For the next iteration of the code published in 2006 (S6:06) [2], the seismic analysis and design provisions were refined based on evolving seismic methods and the 2005 AASHTO LRFD Bridge Design Specifications. The code used a Force-Based Design (FBD) approach with response modification factors (R-factors) to account for the expected non-linear response. Capacity design was required but was defined as the lower of demands from plastic mechanisms or elastic demands.

The seismic design provisions of S6:06 were developed using the general principles that: (a) structural components remain essentially elastic during low to moderate levels of earthquake shaking; and (b) high levels of earthquake shaking should not cause collapse of the bridge. While the commentary to the code listed various performance objectives for three levels of ground shaking and three bridge importance categories (lifeline, emergency-route, other), the actual design requirements only considered ground motions with a 475-year return period. The design objective for regular bridges was to prevent collapse (i.e. life safety) when subjected to the design earthquake. Importance factors were used to modify the design forces for emergency-route and lifeline bridges to achieve more stringent performance objectives; however, the code did not require explicit determination that the performance objectives were met.

In 2005, the Geological Survey of Canada (GSC) published spectral accelerations for different hazard levels (100-, 475-, 975- and 2475-year return periods). GSC also changed from an empirical design spectrum based on PGA to a Uniform Hazard Spectrum. At the same time, the National Building Code of Canada changed from a 475- to a 2475-year return period design earthquake.

This opened the door for design to multiple performance objectives using different hazard levels. Starting with the Golden Ears Bridge Project in 2005, Translink and the BC Ministry of Transportation and Infrastructure (BC MoTI) adopted multi-level performance objectives for their major projects. The performance objectives were defined in terms of Service levels and accompanying Damage levels. Table 1 summarizes the performance objectives defined for the Port Mann/Hwy 1 (2008) and the South Fraser Perimeter Road (2009) projects.

Table 1. BC MoTI Seismic Performance Requirements: Port Mann/Hwy 1 (2008) and South Fraser Perimeter Road (2009).

Return period	***Lifeline bridges***		***Economic Sustainability Route bridges***	
	Service	**Damage**	**Service**	**Damage**
475-year	Immediate	No Damage	Limited	Repairable
975-year	Limited	Repairable	Significantly Limited	Significant/No Collapse
2,475-year	Service Disruption	Significant /No Collapse	Service Disruption	Significant Damage (Loss of span prevention)

These requirements essentially made explicit the objectives described in the Commentary to S6:06. Although the desired objectives were defined, it was left to the design engineers to select engineering design parameters (e.g., concrete and reinforcement strain) and associated limits to demonstrate the objectives were met.

The change from single-level force-based design to multiple-level performance-based design represented a significant shift in seismic design philosophy: it was a recognition that designers can do better than simple collapse prevention. It also recognized the importance of bridges in post-earthquake response and recovery and reflected advances in our understanding of the seismic behaviour of bridges and the tools to control it.

CSA S6:14 – INTRODUCTION OF PERFORMANCE-BASED DESIGN TO THE CHBDC

PBD was formalized in S6:14 [3] as the design philosophy to be used for the majority of new bridges and retrofit of existing bridges. Its principles had been described in the commentary to S6:00, where it was considered an implicit underpinning to FBD. The latter using ductility-based R-factors, was retained from previous versions of the Code for use with certain bridges.

Performance Objectives

In defining PBD, S6:14 included service and damage performance objectives for each of the three importance categories and three hazard levels (Table 2). Intermediate levels for Major-Route and Other bridges were designated as optional (at the discretion of the owners). The main factor for selecting the applicable performance objectives is the Importance Category of the bridge: Lifeline, Major-Route (replaced Emergency-Route), or Other.

Table 2. CSA S6:14 Seismic Performance Requirements [3].

Return period	***Lifeline bridges***		***Major-Route bridges***		***Other bridges***	
	Service	**Damage**	**Service**	**Damage**	**Service**	**Damage**
475-year	Immediate	No Damage	Immediate	Minimal	Service Limited	Repairable
975-year	Immediate	Minimal	Service Limited*	Repairable*	Service Disruption*	Extensive*
2,475-year	Service Limited	Repairable	Service Disruption	Extensive	Life Safety	Probable Replacement

* Optional requirement

Seismic Performance Category

The Seismic Performance Category (SPC) is a parameter that governs the implementation of seismic design within S6. The main determinants of SPC are the intensity of the seismic hazard at the bridge site, as captured using spectral acceleration, and the importance category of the bridge itself. In CSA S6:14 there were three SPC levels: SPC 1, SPC 2 and SPC 3, with increasing seismic shaking from levels 1 to 3. Along with the Importance Category, SPC influences the adoption and implementation of the seismic design methods within the performance-based design framework in accordance with Table 4.11 of S6:14, as seen in Table 3.

Table 3. *Performance vs force-based design within S6:19 [4].*

Seismic performance category	Lifeline bridges		Major-route bridges		Other bridges	
	Irregular	Regular	Irregular	Regular	Irregular	Regular
1	No seismic analysis required					
2	PBD	PBD	PBD	FBD	FBD	FBD
3	PBD	PBD	PBD	FBD*	PBD	FBD

**PBD might be required by the Regulatory Authority.*

Section 4 Structure

The overall structure of Section 4 is summarized in Figure 1, showing the dichotomy between PBD and FBD that was created by the selection of one design approach vs another.

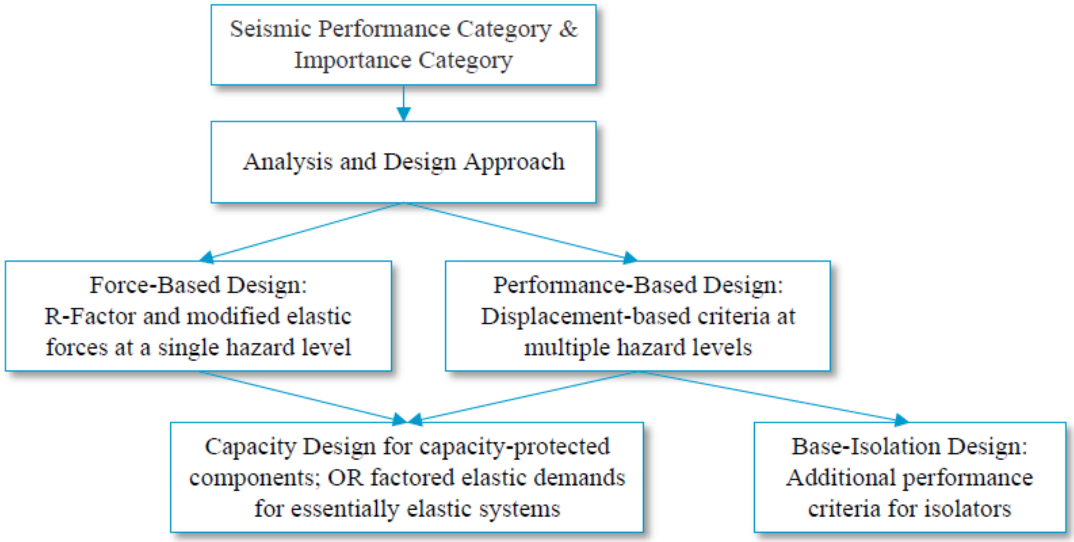

Figure 1. Design flow within S6:14 (S6:19 similar)

Although maintaining previous provisions largely unchanged was the best way to introduce new concepts to the code, this resulted in the appearance of a choice between two alternative design paths, PBD or FBD. Further complicating this dichotomy is that an elastic strength-based design approach can fit into both PBD and FBD, and that various common prescriptive requirements are specified for both paths.

S6:19 – FURTHER DEVELOPMENT OF PERFORMANCE OBJECTIVES

The next edition of the Code, S6:19, sought primarily to improve on the definition of the performance objectives and associated damage criteria, and provide some additional clarifications on the application of PBD. Based on experience with S6:14, it was found that the requirements for meeting the "No Damage" performance level were too onerous and thus were eliminated. Intermediate levels were found to contribute little to the design as they didn't govern; they were therefore eliminated and the requirements were simplified to 2 levels for each importance category (Table 4).

Table 4. CAN/CSA-S6:19 Seismic Performance Requirements [4].

Return period	***Lifeline bridges***		***Major-Route bridges***		***Other bridges***	
	Service	**Damage**	**Service**	**Damage**	**Service**	**Damage**
475-year	-	-	Immediate	Minimal	Service Limited	Repairable
975-year	Immediate	Minimal	-	-	-	-
2,475-year	Service Limited	Repairable	Service Disruption	Extensive	Life Safety	Probable Replacement

Seismic Performance Category

SPC values were adjusted in S6:19 to lower the SPC from 2 to 1 for Lifeline bridges in low hazard regions of Canada, as shown in Table 5.

Table 5. SPC Values from CSA S6:19 [4].

		Seismic performance category	
For T < 0.5 s	For $T \geq$ 0.5 s	Lifeline bridges	Major-route and other bridges
$S(0.2) < 0.20$	$S(1.0) < 0.10$	1	1
$0.2 \leq S(0.2) \leq 0.35$	$0.10 \leq S(1.0) \leq 0.30$	3	2
$S(0.2) \geq 0.35$	$S(1.0) \geq 0.30$	3	3

Parameters affecting the selection of SPC value included:

- Spectral acceleration from the uniform hazard spectra (UHS) for a 2% in 50 year seismic hazard as obtained from the Earthquakes Canada website. The uniform hazard spectra are defined for each soil and site classification, and for the site's soil conditions the reference site Class C (firm soil) is modified by an F factor to account for site-specific amplification.
- The UHS for the soil conditions was modified by a damping modification factor to account for damping different from the baseline 5% of critical damping for which the UHS is provided.
- The soil and damping-modified spectral values were determined at either 0.2 or 1.0 seconds of the first mode structural period of vibration. Thus, the structure and foundation system used was an essential input to SPC. For a structural period less than 0.5 seconds, the spectral acceleration at 0.2 second was used, and for structural period of 0.5 seconds or greater the spectral acceleration at 1.0 second was used. The greater of SPC value from two orthogonal directions would govern the SPC value.
- The importance of the structure and route to post-earthquake response and recovery.

Of note in Table 5 is the step function from SPC 1 to SPC 3 for Lifeline bridges, which occurs at a modest value of spectral acceleration. In S6:14 there was no SPC 1 value for lifeline bridges, and SPC 2 required a rigorous seismic design process for many bridges even in low seismic hazard regions across Canada. While this change solved a perceived design challenge, it also created an incentive to designate an important crossing as a "Major-route" bridge to avoid the perceived quantum step in design approach implied by an SPC 3 designation.

S6:25 - PBD AS OVERARCHING FRAMEWORK

A reorganization of Section 4 was one objective of the S6:14 edition, but was deferred to allow the Section 4 Technical Sub-committee (TSC) to focus on introducing the PBD provisions. The S6:25 cycle was lengthened to five years from four, which supported the decision to re-organize in this cycle.

In 2020, a task group was formed within the Section 4 TSC to review the organization of S6:19 Section 4 and propose ways to improve clarity, simplicity and usability of the Section. A key focus was on clarifying the philosophy and code framework around Performance-Based Design.

S6:19 requires the designer to choose between PBD and FBD early in the design process (Figure 1), which implies two alternative design paths. Choosing between PBD and FBD brings ambiguity around which requirements are applicable to each approach. For example, and as noted previously, an elastic strength-based design approach was typically used as a subset of FBD (using R=1); however, it is also a valid approach for meeting PBD objectives. There are also many requirements that are common to both design paths, such as capacity design, seat lengths or minimum forces at bearings, which has confused users.

As a philosophy, PBD is more than demonstrating strain and displacement criteria; it also requires consideration of functional parameters beyond the structural design requirements. This can be lost or unclear when a designer follows the FBD path.

To address these issues, it is proposed to define PBD as the overall seismic design philosophy at the front of the section. It will then be the framework under which all the design methods – Displacement-based Design (DBD), FBD, elastic design, isolation design, capacity protection – are defined (see Figure 2).

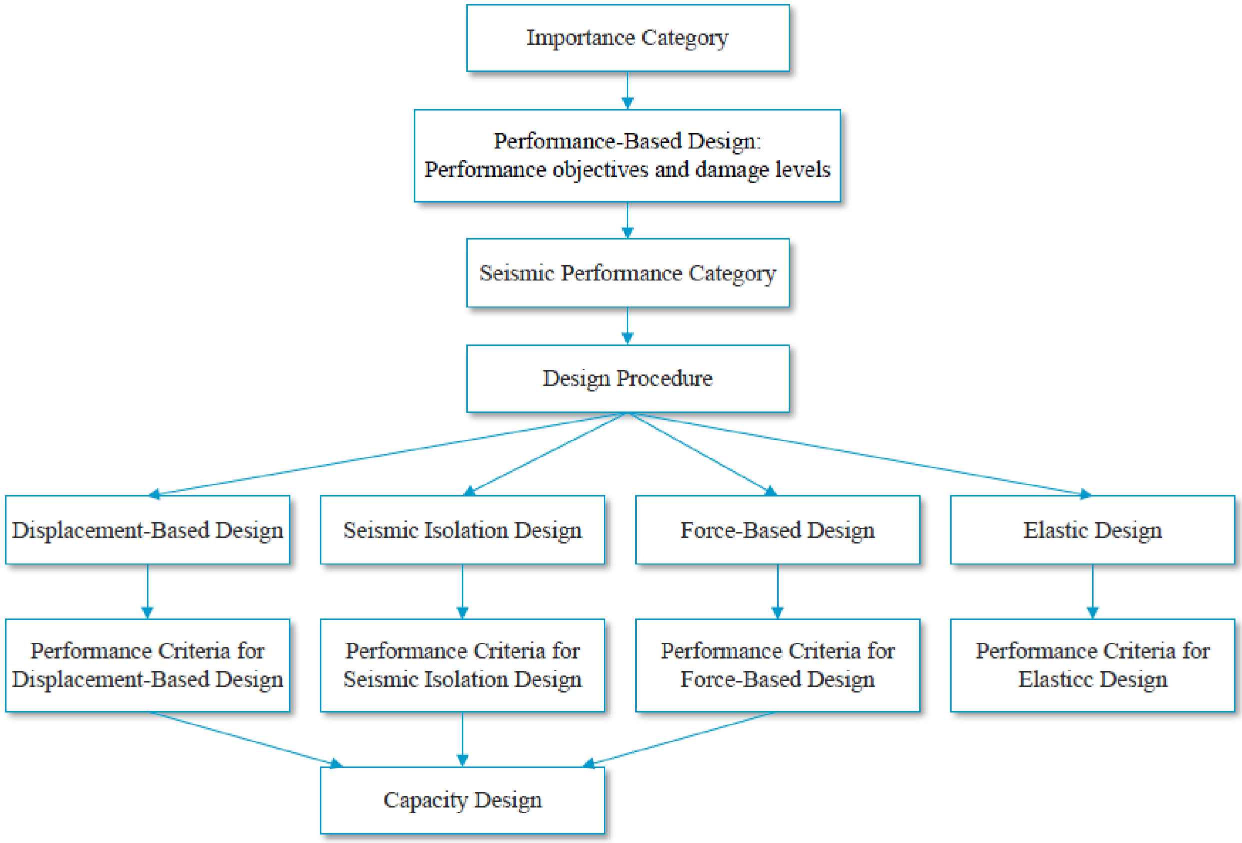

Figure 2 – S6:25 Proposed Framework

Clarifying PBD as the overarching framework and defining the different design methods within that framework provides the following benefits:

- The DBD approach can be explicitly defined. This is important because it is the design approach currently implied by the code.
- The role of FBD relative to PBD can be clarified, removing the ambiguity around which requirements are applicable to each approach; they all can be brought under one consistent framework.
- It provides a consistent framework for seismic isolation and added damping: currently isolation and added damping are defined as PBD but are set apart from the PBD clauses.
- The elastic design approach can be defined in the context of PBD, clarifying its application as a PBD design approach and eliminating confusion with FBD, R=1.
- Seismic design requirements for low-seismic regions can be defined within the framework of PBD, rather than as exceptions to it. This can include bridges for which there are no Section 4 requirements at all.
- Provide more flexibility and clarity in the definition of performance objectives and performance criteria.
- Having all design methods under the PBD framework should address the perception that PBD is always more complex than FBD and is to be avoided.
- It allows new lateral load-resisting systems to be used.
- It allows the use of new materials (e.g., high-strength steel) and harmonizes seismic design provisions for steel and reinforced concrete sub-structures.
- Other design approaches (e.g., energy-based) can be added in the future.

Performance Objectives

The performance objectives will remain unchanged from S6:19; however, they will be presented earlier in the section and apply to all design approaches, including FBD. As before, the performance objectives are a function of the importance category (Lifeline, Major-Route, Other) and the hazard level.

Seismic Performance Category

As currently proposed for S6:25, the SPC value will be a function only of the seismic hazard intensity at the site as defined by the 5% damped spectra for the soil conditions at the site. The seismic performance objectives for use within a performance-based design process will depend on bridge importance. And together the SPC value and the crossing importance will influence or govern the structural system adopted, the design approach to be used, the modeling and analyses, seismic detailing and levels of damage and acceptable repair times to return to partial or full service for the crossing.

Table 6 illustrates the proposed values of SPC for S6:25.

Table 6. SPC Values proposed for CSA S6:25 (Canadian Standards Association)

Spectral acceleration	***Seismic Performance Category***
	All bridges
$S_a(1.0) < 0.05$	0
$S_a(1.0) < 0.10$	1
$0.10 \leq S_a(1.0) < 0.30$	2
$S_a(1.0) \geq 0.30$	3

Proposed changes of note between S6:19 and the S6:25 draft include:

- An SPC = 0 is proposed for $S_a(1.0) < 0.05$ g. The purpose is to clarify that bridges in low seismic hazard regions do not have any specific seismic design provisions within this Section. No analyses (such as for seat length) or calculations are required for this determination. It is noted that there are design and detailing provisions in other sections of the CHBDC that influence concrete and steel beam and column details, structural arrangement, lateral forces (braking or impacts), minimum resistance for bearings, section capacities and system redundancy which together provide a reasonable level of seismic resilience for virtually any bridge in Canada.
- Only the spectral acceleration values at 1.0 second are used for setting SPC. The values for 0.2 seconds were removed for the purpose of setting SPC. In part this is because bridges having significant spectral values in this period range tend to require increasing levels of seismic design. As well, there are other aspects of the design process that influence requirements and design methods for analysis and design for both structural and geotechnical aspects, and which differentiate design and detailing for lifeline and major-route bridges.
- A modification for damping has been removed from the SPC process. Damping may increase or decrease and can reflect the engineer's approach to structural damping as affected by damage levels, foundation geometry, depth and stiffness, added damping and seismic isolation. These factors are believed best addressed in the analysis and design process rather than in influence site hazard and SPC.
- For soil conditions for which linear or non-linear site-specific response analyses are appropriate or required, soil-related damping can be explicitly considered, whether in a free-field or coupled soil-structure approach.

As noted, other aspects of design, including foundation and structural systems, performance objectives (damage and return to service), seismic detailing and design method all affect seismic design. Some of these are influenced by the SPC designation, but add important layers to the design process that strongly influence seismic performance.

Detailing

In S6, prescriptive detailing requirements are used to complement the performance-based design approach by ensuring robustness and resiliency regardless of the design procedure used. These requirements address uncertainty in the seismic hazard and response of the structure that may not be explicitly considered in the design.

As part of the restructuring of the seismic provisions, the seismic detailing requirements were reviewed to improve coherency and consistency with the rest of the updates to the section. Two notable changes are as follows:

- ***Potential plastic-hinge regions:*** It was identified that clarification is needed for potential plastic hinge regions when an Elastic Design approach is used. For the 2025 edition of the code, it is proposed to explicitly identify and detail the potential plastic hinge regions for lifeline and major-route bridges, when the Elastic Design approach is used. The intent of the new requirement is to ensure that adequate ductile detailing is provided in key locations across the structure where inelastic behaviour might occur under increased seismic demands or due to other sources of uncertainty.

- ***Welded or mechanical connection splices***, the 2019 edition of the code did not have adequate seismic detailing for the welded or mechanical connection splices. This is especially important if the mechanical connection splices are placed in the potential plastic hinge regions. For the 2025 edition of the code, it is proposed that these splices develop the specified tensile strength of the spliced bars and that the bar rupture occurs away from the location of the splice.

SEISMIC ISOLATION

Background

The provisions for seismic isolation were first introduced in the CHBDC in 2000 and remained mostly unchanged in S6:06. Seismic isolation was defined in its own sub-section of Section 4, where an essentially elastic design was prescribed for emergency-route and lifeline bridges and a maximum R value of 1.5 was allowed for other bridges. Consequently, the detailing requirements for isolated bridges were also relaxed. The isolation section also used different equations to define the design spectra for isolated bridges. These versions of the CHBDC only had a generic requirement to consider the cold weather performance of isolation systems in the design, nothing specific.

In S6:14, the provisions for seismic isolation were extensively revised and requirements for supplemental dampers and shock transmission units were introduced. S6-14 required isolated bridges to be designed using PBD. The substructures and foundations were designed to have factored resistances equal to or greater than the forces imposed by the isolation units. F or isolated bridges in SPC 2 and 3, the substructures were to be detailed to exhibit ductile failure modes.

Explicit requirements were also added for the design and the testing of the cold weather performance of isolation systems. In addition to the ambient temperature (20°C), two low temperatures were defined: the minimum service temperature and the minimum concomitant temperature. Both low temperatures were required to be assessed during prototype testing and S6:14 specified a minimum conditioning time of 14 days for elastomeric isolator units and 3 days for other isolation units.

The requirements for seismic isolation remained essentially unchanged in S6:19.

Feedback from the industry

Since the publication of S6:14, there was a noticeable decrease in seismic isolation projects, especially in the provinces of Quebec and Ontario. However, isolation is an important tool to achieve a rapid return to traffic following large earthquakes, which is now explicit within the code performance objectives, particularly for Lifeline bridges. To address this issue, the technical requirements were reviewed by a dedicated task group and the integration of the isolation provisions under the PBD framework was reviewed by the reorganization task group.

In preparation for S6:25, the isolation task group consulted the seismic isolation industry by sending a questionnaire to selected seismic isolation suppliers. The feedback of some design engineers and owners was also considered. The main objectives were to understand the main impediments to the implementation of seismic isolation to receive suggestions for the improvement of the current requirements and to increase the adoption of seismic isolation as a low-damage seismic system.

Difficulty with cold weather requirements was an issue cited by industry. Other issues included lack of experience from the design engineers and owners, a lack of uniformity in the project specifications and in the CHBDC's interpretation of the seismic isolation requirements. For the cold weather requirements, the minimum conditioning time of 14 days for elastomeric isolation units was deemed unreasonable by some suppliers, as the minimum service temperature corresponds to a 50-yr return period. It was also noted that the requirement of testing both low temperatures with a conditioning time of 14 days adds time to a bridge project where testing may be on the critical path. Finally, the difficulty of having access to testing facilities with the appropriate equipment to test the bearings at the bridge natural frequency was cited. Going through universities to perform testing can take up to 6 months.

Some design engineers also mentioned the stringent requirements regarding cold-weather temperatures. Very few suppliers can provide property modification factor for the conditioning time specified in the CHBDC. Another challenge identified is the difficulty to prepare performance-based isolation specifications in conventional projects (design-bid-build) as there are important differences between different isolation types or even different suppliers of the same type. Isolation bearing detailing, testing and acceptance during procurement, i.e. after bid prices are locked in, represents a cost and schedule risk as well.

Finally, another reason why seismic isolation is used less in the provinces of Quebec and Ontario is the decrease in the seismic hazard. For example, in Montreal, the spectral acceleration for conventional bridges at 1 s and 2 s were respectively 0.24 and 0.15 in S6-06 (soil type I) whereas they were 0.15 and 0.07 in S6-14 using the 5th generation of the seismic hazard of Canada (V_{s30} =450 m/s). Therefore, in most cases, design engineers were able to achieve an economical design without the use of seismic isolation. However, the 6th generation of the uniform hazard spectra has recently been published and results in a significant increase in these regions. In Montreal for example, the spectral accelerations at 1 s and 2 s are now at 0.22 and 0.10, respectively.

Simplifications and Clarifications proposed for Isolation within S6:25

The following summarizes some of the simplifications and clarifications that are proposed for S6:25:

1) Seismic isolation will be integrated into the main body of Section 4 rather than being in a separate section. Seismic isolation can be very efficient and economical for meeting the more stringent service levels of CHBDC.

2) Whenever possible, isolated bridges should target minimal damages for a seismic event with probability of exceedance of 2% in 50 years. For these cases, the substructures and the foundations can be designed with limited detailing as the isolation units provides a fusing mechanism that limits the seismic demand. Brittle failure modes in lateral-load resisting elements shall be designed with 1.25 times the maximum forces. If minimal damages cannot be achieved, then seismic detailing as prescribed for conventional seismic approach is required.

3) Isolation units are the most important element in isolated seismic design approach and should therefore be capacity-protected. Prototype testing already verifies their performance at the total design displacement. However, current Table 4.19 suggests some damage is acceptable to the seismic isolators. It is envisioned to only accept minor damage that does not affect the performance of the isolators, with the only exception being the failure of the elastic restraint system which is acceptable.

4) Regarding the cold-weather performance, some recent Canadian studies increased the available information [5-7]. However, to our knowledge, there are yet researches that have studied the joint probability of temperature and earthquake for bridges considering both the concomitant temperature as well as the effective conditioning time. For S6:25, recent research is being used to clarify and simplify the requirements.

5) For moderate seismicity, low-damping rubber isolators are sometimes considered for new bridges or seismic retrofit. As these bearings can be considered rate independent [8], it is proposed to reduce the testing requirements to encourage their use.

CONCLUSIONS

In preparation for S6:25, a task group was formed within the Section 4 TSC to review the organization of the S6:19 Section 4 and propose ways to improve clarity, simplicity and usability of the Section. The main recommendation from the task group is to clearly define Performance-Based Design as the overall framework for the seismic design of bridges in S6. It will then be the framework under which all the design methods – displacement-based design, force-based design, elastic design, isolation design, capacity protection – are applied. Clarifying PBD as the overall framework and defining the different design methods within that framework provides the following benefits: the Displacement-Based Design (DBD) approach can be explicitly defined; the role of FBD relative to PBD can be clarified, removing the ambiguity around which requirements are applicable to each approach; it provides a consistent framework for seismic isolation and added damping; the elastic design approach can be defined in the context of PBD, clarifying its application as a PBD design approach and eliminating confusion with FBD (R=1); seismic design requirements for low-seismic regions can be defined within the framework of PBD, rather than as exceptions to it. These revisions will truly define CSA S6 as a performance-based code for seismic design.

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