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A REVIEW OF PERFORMANCE REQUIREMENTS FOR BRIDGES

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ABSTRACT

It has been recognized for some time that performance objectives need to be well defined in terms of engineering parameters. Ideally they should be consistent with the Limit States approach which is the foundation of current bridge design codes. This is necessary to allow a seamless integration of Performance Based Earthquake Engineering (PBEE) and explicit performance requirements into the design of bridges. Performance objectives should also be selected to meet the various stakeholders' objectives. Given the flexibility in seismic hazard definition, there is no need to fit performance objectives to arbitrary hazard levels. The desired performance objectives should be defined first, then appropriate return periods can be assigned to achieve the desired risk. The return period can be varied as a function of the importance of the structure.

Introduction

Performance requirements for bridges subjected to earthquake shaking were part of ATC-6 *Seismic Design Guidelines for Highway Bridges*, written in 1981 (ATC 1981). The same performance requirements are found underlying the seismic provisions of the current Canadian and American bridge design codes, CAN/CSA S6-06 (CSA 2006) and AASHTO LRFD 4th Edition (AASHTO 2007) respectively. These performance requirements are implicit rather than explicit, i.e., the code provisions do not include verification of the performance of the structure during or after the earthquake. When ATC-6 was written, the seismic hazard associated with the performance requirements was characterized in terms of peak ground acceleration for a single return period. Since then, the definition of seismic hazard has evolved considerably and is commonly calculated for multiple return periods; however, the same performance requirements remain in the codes today.

Over the last 15 years, there have been ongoing efforts to develop Performance Based Earthquake Engineering (PBEE), where explicit performance requirements are used to direct the design. Some of the expected benefits of PBEE are explicit verification of performance of the structure as a whole, which leads to better information for decision making, and less prescriptive requirements, which provides greater flexibility for innovation. The focus of PBEE development

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for bridges has been to characterize the response of structures to ground motions and relate – generally probabilistically – ground motions to damage and repair costs. This provides quantitative tools to determine the reliability of performance requirements specified in design codes. Unfortunately, the trend has been to retain existing performance requirements and make them explicit, without ensuring they can be defined in terms of engineering design parameters. There is a need to evaluate performance requirements in conjunction with current hazard assessments, the PBEE framework, and specifically for integration into the design process.

Performance requirements used for design consist of two parts: the performance objectives and the seismic hazard levels. The latter are defined either as the probability of exceedance or as the return period of the seismic ground motions for which the performance objectives should be satisfied.

Selection of Performance Objectives for Design

Current Bridge Design Codes

Canadian and U.S. bridge design codes and a selection of projects aimed at revising code provisions are reviewed to illustrate the current use of performance objectives in the design of highway bridges in North America.

AASHTO LRFD 4th Edition and CAN/CSA S6-06

The current national bridge design codes in the U.S. and Canada are AASHTO *LRFD Bridge Design Specifications*, 4th Edition and CAN/CSA S6-06 *Canadian Highway Bridge Design Code*. Seismic design provisions in both codes 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 (Commentary to AASHTO 2007, Commentary to CSA 2006). The commentary to each code lists the performance objectives shown in Table 1. These are not design requirements, instead they are assumed satisfied by following the prescribed seismic design requirements. The codes, however, do not require calculation of expected damage or evaluation of functionality.

Table 1. AASHTO LRFD 4th Ed. and CAN/CSA S6-06 performance objectives (AASHTO 2007 commentary, CSA 2006 commentary)

	Bridge Importance Category (AASHTO / S6-06)		
	Critical / Lifeline	**Essential / Emergency-route**	**Other / Other**
Small to moderate earthquake*	All traffic Immediate use	All traffic Immediate use	All traffic Immediate use
Design earthquake*	All traffic Immediate use	Emergency vehicles Immediate use	Repairable damage
Large earthquake*	Emergency vehicles Immediate use	Repairable damage	No collapse

* Both codes use the term “earthquake” rather than ground motions

In AASHTO LRFD the design requirements are adjusted as a function of the bridge importance category by specifying different Response Modification Factors (also called Force Reduction Factors), which are used to reduce the seismic forces. In CAN/CSA S6-06, different importance factors are applied to the calculation of seismic forces. In both cases, the objective is to reduce the expected damage for more important structures by increasing the design forces. Structural capacities, on the other hand, are calculated using the same Ultimate Limit States (ULS) equations regardless of importance category. In effect, both codes increase the return period of the design earthquake for more important structures; however, since an arbitrary factor is used, the resulting return period is unknown and varies between locations.

In moving to performance based design, the trend has been to take existing objectives, such as Table 1, and specify them as explicit design requirement. This then requires engineering design parameters (EDPs) for full access, emergency vehicle access, repairable damage, and no collapse. Current codes only include design provisions for no collapse (ULS), thus requiring three more sets of design requirements. This also presupposes that damage levels and functionality can be finely controlled in the design for earthquake loads. A better approach, already implied in Table 1, would be to use one set of design provisions (e.g., no collapse) and vary the design ground motions according to the importance category of the bridge.

California - Caltrans

In California, seismic design follows the methodology outlined in Caltrans' *Memo to Designers 20-1* (Caltrans 1999). *Memo to Designers 20-1* and the accompanying *Seismic Design Criteria* (Caltrans 2006) include a number of recommendations from ATC-32 *Improved Seismic Design Criteria for California Bridges: Provisional Recommendations* (ATC 1996), such as the two-level design approach shown in Table 2. Performance objectives are specified for two levels of ground motion: Functional Evaluation, which are ground motions that have a reasonable probability of not being exceeded during the useful life of the bridge, and Safety-Evaluation, which are ground motions associated with the Maximum Credible Earthquake. Similar to AASHTO LRFD and CAN/CSA S6-06, the performance objectives vary with the importance of the bridge and they are assumed satisfied by following the prescribed seismic design requirements.

Table 2. Caltrans seismic performance objectives (Caltrans 1999)

	Post Earthquake Service and Damage Level	
	Important Bridge	**Ordinary Bridge**
Functional Evaluation Ground Motion	Immediate service Minimal damage	Immediate service Repairable damage
Safety-Evaluation Ground Motion	Immediate service Repairable damage	Limited service Significant damage

Memo to Designers 20-1 (Caltrans 1999) includes separate definitions for the service and damage levels listed in Table 2. Combining these to match the table entries gives the following requirements:

Immediate service/Minimal damage: Full access almost immediately following the earthquake; essentially elastic performance.

Immediate service/Repairable damage: Full access almost immediately following the earthquake; damage that can be repaired with a minimum risk of losing functionality.

Limited service/Significant damage: Limited access (e.g., reduced lanes, light emergency traffic) possible within days of the earthquake; full service restorable within months; a minimum risk of collapse, but damage that would require closure to repair.

In definition a), the service and damage expectations seem well aligned. In definitions b) and c), the allowable damage seems too extensive to provide access almost immediately or within days. The implication is that the damage is well controlled or repairs are carried out promptly; however, damage requirements are not defined sufficiently to ensure the former, and designers have no control over the latter.

MCEER/ATC-49 and AASHTO Guide Specifications

Project MCEER/ATC-49 *Recommended LRFD Guidelines for the Seismic Design of Highway Bridges* (ATC/MCEER 2003) was conducted to develop the next generation of AASHTO seismic requirements. The performance objectives proposed in MCEER/ATC-49 are shown in Table 3. MCEER/ATC-49 does not classify bridges by importance category; instead, either the Life Safety (no collapse) or the Operational (functional after MCE) objective is assigned to the bridge. Partial functionality and repairable damage are not used. The service and damage expectations are similar to Caltrans definitions a) and c) above. Like Caltrans/ATC-32, MCEER/ATC-49 proposed to design for two levels of ground motions. The benefit of two levels is the ability to explicitly satisfy two different objectives.

Table 3. MCEER/ATC-49 performance objectives (ATC/MCEER 2003)

	Performance Objective	
	Operational	**Life Safety**
Expected Earthquake	Immediate service Minimal to no damage	Immediate service Minimal damage
Maximum Credible Earthquake	Immediate Service Minimal damage	Significant disruption to service Significant damage

Project NCHRP 20-7/Task 193 *Updating "Recommended LRFD Guidelines for the Seismic Design of Highway Bridges"* re-examined the performance requirements and seismic hazard to be used for design by AASHTO (NCHRP 2006). The performance requirements of NCHRP 20-7 were then incorporated into the AASHTO *Guide Specifications for LRFD Seismic Bridge Design* (AASHTO 2009). The 2009 AASHTO Guide Specifications are intended for conventional bridges only and consider only one hazard level, as shown in Table 4. The assumption, based on case studies, is that limited damage and partial functionality will be available following smaller ground motions.

Table 4. AASHTO Guide Specifications performance objectives (AASHTO 2009)

	Importance Category	
	Critical	**Conventional**
Maximum Credible Earthquake	(Define project-specific requirement)	Significant disruption to service Significant damage

Stakeholder Requirements

The goal of performance objectives is to guide the design such that stakeholder requirements are met. For most bridges, stakeholders are the owner (transportation agency), design engineers, emergency managers, and the public. Unlike for buildings, bridge owners are usually the government agencies involved in specifying the design requirements, either through code committees or project-specific requirements.

All stakeholders share the requirement to prevent loss-of-life, which is the current minimum requirement specified for all bridges. PBEE, with multiple hazard/risk levels, enables the design to explicitly meet additional performance objectives. Even if they have no impact on the design, additional objectives can be used to satisfy additional stakeholder requirements. Additional stakeholder requirements are outlined below.

Owners have a broad set of requirements: they need to balance capital costs, post-earthquake repair costs, and service levels following an earthquake. Transportation agencies focus both on individual bridges and on a network of bridges as a whole.

Design engineers require that the specified performance objectives translate into well defined engineering design parameters (EDPs) with measurable criteria. For example, emergency vehicle access has been discussed for over 15 years, yet the authors are not aware of a single instance where this has been defined in terms of live load parameters. Designers also cannot take into account post-earthquake conditions over which they have no control. For example, they cannot determine availability of materials or labour for repairable damage.

To provide an effective response, emergency managers may require access over or under the bridge, that key utilities carried by the bridge remain intact, or that adjacent facilities are not damaged by the bridge shaking. If the bridge performance can be reliably characterized (e.g., probability of damage and of collapse), then the bridge can be included in emergency response plans. Emergency managers' requirements need to be considered when determining the importance classification of a particular bridge.

After no loss-of-life, the public's main concern is access: to get home immediately after the earthquake, to receive aid, or to regain a normal life. A survey conducted in Japan following the Kobe earthquake indicated the public has much higher expectations regarding functionality than is currently specified in codes (Kawashima and Miyaji 2006).

Reliability

Performance objectives should be evaluated and selected based on their reliability or probability of success. The usefulness of a performance objective is a function of its chance of being achieved in reality after an earthquake has occurred, taking into account all parameters. This means ground motion probabilities should be combined with structural performance probabilities (the structural design), and post-earthquake conditions should be considered. The principal driver for this broader context is improved information for decision making, which is one of the most touted benefits of PBEE.

A number of researchers have been developing probabilistic methods for implementing PBEE (e.g., Fajfar and Krawinkler 2004, Jalayer and Cornell 2003, Mackie and Wong 2008). A key component of these methods is a probabilistic assessment of EDPs in terms of variability and correlation with performance objectives (e.g., Berry and Eberhard 2008, Lee and Mosalam 2006). This research provides tools for a quantitative evaluation and comparison of performance objectives. Coupled with probabilistic seismic hazard assessments, these tools can be used to determine the probability of meeting performance objectives. This can be formulated as a reliability index, as per the Limit States (or Load and Resistance Factor Design) methodology.

The likelihood of achieving a desired outcome is a function of how well the performance objective is defined. The more ambiguity in the definition, the less confidence there is that the bridge will achieve the desired performance, and thus the less useful the performance objective becomes for decision making. To improve reliability, performance objectives should ideally be defined in terms of quantifiable EDPs. They must also be essentially independent of post-earthquake conditions. The three most common performance objectives are compared below based on these criteria.

Functional / minimal damage

Low ambiguity: the corresponding EDP is generally taken as force or displacement at yielding of structural members. Although different definitions of yielding exist, they tend to correspond to a narrow range of displacements (Priestley 2000).

No post-earthquake requirements: the bridge is expected to be functional; therefore, no post-earthquake action is needed to achieve this objective.

Emergency vehicle access / Repairable damage

High ambiguity: these performance objectives have appeared in the literature for over 25 years, yet they remain undefined in terms of EDPs. For example, loading associated with emergency vehicles has never been specified. Repairable damage can include practically any damage, from large cracks requiring grout-injection to replacing columns while traffic is supported on temporary shoring. Although repairable damage appears in ATC-32, the authoring committee notes they could not reach consensus on its definition (ATC 1996, p. 19).

Significant post-earthquake requirements: meeting this objective depends significantly on post-earthquake conditions. The bridge may be designed such that the damage is repairable within a certain time-frame; however, time-frames for inspection, design of repairs, material procurement and execution of repairs all become highly uncertain following an earthquake. Kawashima and Miyaji (2006) give an example where, following the Kobe earthquake, it took 4 months to repair damaged bearings and 13 months to complete column strengthening and reopen the bridge. Alternatively, the bridge may be designed to a damage level which allows emergency vehicle access, but if the emergency personnel do not feel the bridge is safe, the objective will not be met. To ensure a bridge is available for emergency vehicles, it should be designed to be functional; emergency providers can then be given priority access as needed.

Significant disruption / No collapse

Low ambiguity: This damage state is typically associated with strength or ductility limits. Although it may be difficult to define the collapse point, the objective only relies on defining a safe minimum value. This objective relates well to existing Limit States design methods.

No post-earthquake requirements: since there is no expectation of functionality, this objective will be met regardless of post-earthquake conditions.

Selection of Seismic Hazard: Design Return Period

Current Return Periods for Design

Until recently, bridge codes have used the seismic hazard maps defined for building codes. With the greater flexibility in current seismic hazard calculations, this limitation is no longer necessary (see Table 5). In the U.S., building codes have adopted a 2% in 50 year probability of exceedance (2475 year return period) to define the Maximum Credible Earthquake (MCE). The design earthquake is taken as 2/3 of the MCE to reflect a safety margin inherent in the design (NEHRP 1997). For bridges, AASHTO has adopted a 7% in 75 year probability of exceedance (1033 year return period) hazard level for design. This better reflects the 75 year design life assigned to bridges; is considered to include the conservatism inherent in the design; and is considered more representative of MCE than 2% in 50 year when considering deterministic upper bound ground motions (NCHRP 2006).

Table 5. Bridge design hazard levels and return periods

Document	Probability of Exceedance	Return Period (Years)
CAN/CSA S6-06	10% in 50 years (under review)	475
AASHTO LRFD 4th Ed.	7% in 75 years	1033
Caltrans Memo to Designers 20-1	Functional Evaluation: 40% chance of being exceeded in useful life of the bridge; determined case-by-case Safety Evaluation: MCE - deterministic or probabilistic	(100 – 500) (1000 – 2000)
MCEER/ATC-49	Expected Earthquake: 50% in 75 years MCE: 3% in 75 years	108 2475
AASTHO 2009	7% in 75 years	1033

In Canada, the National Building Code has adopted the 2% in 50 year probability of exceedance ground motions as the design earthquake. In design, the forces from the design earthquake are divided by an overstrength-related force modification factor, R_o, in addition to the traditional ductility-related force modification factor (Mitchell et al. 2003). Values of R_o range from 1.3 to 1.6, thus, the effect is similar to the 2/3 factor of U.S. codes. The current Canadian bridge code is based on the previous generation seismic hazard maps for 10% in 50 year probability of exceedance. The seismic provisions are currently under review and the hazard level is expected to increase.

Return Periods for Performance Requirements

In Canada and the U.S., seismic hazard calculations are performed for probabilities of exceedance of 10% in 50 years, 5% in 50 years (approximately 7% in 75 years) and 2% in 50 years (approximately 3% in 75 years). In addition, complete hazard curves are relatively accessible; therefore, ground motion values can be obtained for any return period. For example, seismic design provisions for railway bridges include functions for interpolating ground accelerations at return periods between published values (AREMA 2009).

The flexibility in hazard calculations allows performance requirements to be defined by first selecting desired performance objectives and then hazard levels for design. As discussed above, accounting for the importance category of the bridge is best done through varying seismic hazard levels. This is the approach used for railway bridges in the American Railway Engineering and Maintenance-of-Way Association seismic design requirements (AREMA 2009). Table 6 shows an example based on Table 1, but varying the design return periods rather than the performance objectives.

Table 6. Example performance criteria: return period of ground motions for design (note: return periods shown are for illustrative purposes only)

Performance Objective	**Bridge Importance**		
	Critical / Lifeline	**Essential / Emergency-route**	**Other / Other**
Immediate Use	2500 year	1000 year	100 year
No Collapse	n/a	2500 year	1000 year

In a probabilistic determination of performance requirements, the return period can be selected to achieve a target reliability index. The reliability index could be similar to other Limit States design loads, such as live loads or wind loads, or it could be set higher for more important bridges. Ultimately, however, the selection of design seismic hazard involves policy decisions regarding acceptable risk (May 2007).

Implementation of Performance Requirements into Design Codes

A key component of PBEE is the relationship between performance objectives and engineering design parameters. Krawinkler (1999) identified this relationship as critical: “PBEE can not be attempted unless the performance descriptions associated with various levels of desired performance are translated into engineering limit states that can become targets for design.” Much of the development work for PBEE has focused on linking hazard levels to damage levels, and relating damage levels to repair costs. The resulting methodologies are well suited to evaluating the performance of structures already designed and provide important tools to develop explicit performance criteria for design of new structures; however, they are not of themselves targets for design.

Targets for design should be essentially pass/fail criteria. This is because the need to satisfy other requirements, such as dead and live loads, minimum reinforcement ratios, collision loads, available construction equipment, and time constraints from design and construction schedules, generally precludes optimization for seismic demands.

It should be recognized that bridges are designed using Limit States principles. Design requirements are met by satisfying the equation: Capacity ≥ Demand. To be implemented into the design process, performance objectives should be defined in terms of limit states. For example, the immediate-use objective can be defined as: yield strength ≥ force demands. Similarly, the no-collapse objective can be defined as: ultimate displacement capacity ≥ displacement demands. This approach allows PBEE to be implemented using methods familiar to design engineers.

Seismic design codes have focused on Ultimate Limit States for strength or ductility of primary seismic-force-resisting structural components. Specifying explicit performance objectives requires designers to consider the behaviour of secondary elements, such as joints, approach slabs, and bearings, which may be important for functionality. In effect, Serviceability Limit States are then included in the seismic design.

Conclusions

Performance requirements for the design of bridges have so far been implicit rather then explicit. With the trend towards Performance Based Earthquake Engineering, the performance requirements become explicit and need to be integrated into design codes or project specifications. The performance requirements consist of two parts: performance objectives and seismic hazard. Typically seismic hazard is selected first, and then performance objectives are assigned depending on the importance category of the bridge. This approach can lead to performance objectives which are poorly defined. A better approach is to first select performance objectives which can be well characterized in terms of engineering design parameters or existing limit states. Then seismic hazard levels can be assigned as a function of importance category.

Performance objectives should be evaluated on the probability of actual success, taking into account all factors, including seismic hazard probabilities, post-earthquake conditions, and stakeholder requirements. Performance objectives such as no-collapse or immediate use can be defined in terms of existing engineering design parameters and do not rely on post-earthquake conditions to be satisfied. By comparison, objectives such as emergency vehicle access and repairable damage are ambiguous and rely on post-earthquake conditions, thus their probability of success is much less certain. Explicit performance objectives can broaden the design to include serviceability aspects and provide better information for decision making.

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