Comparative Analysis of Design Codes for Timber Bridges in Canada, the United States, and Europe

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The United States recently completed its transition from the allowable stress design code to the load and resistance factor design (LRFD) reliability-based code for the design of most highway bridges. For an international perspective on the LRFD-based bridge codes, a comparative analysis is presented: a study addressed national codes of the United States, Canada, and Europe. The study focused on codes related to timber bridges and involved the following parameters: organization format, superstructure types, loads, materials, design for bending, design for shear, deflection criteria, and durability requirements. The investigation found many similarities and some distinctive differences between the three bridge codes. Although the United States and Canada have different design load configurations, these result in similar bending moments and shear effects over a typical span range. However, the design load configuration in the European code produces bending moment and shear effects that are two to three times greater than the U.S. and Canadian levels. The comparative design of a glulam girder bridge revealed that the smallest beam size was required by the Canadian code and the largest was required by the European code.

The Canadian bridge design code was one of the first to adopt the limit-states design philosophy several years ago. In the United States, significant changes related to timber bridges recently have been adopted into the *AASHTO-LRFD Bridge Design Specifications* (*1*). In addition, FHWA has required the load and resistance factor design (LRFD) code for all new bridges in the United States since 2007. In Europe, the LRFD-based Eurocode for bridge design is scheduled for implementation in 2010. This paper presents an overview of the Canadian, U.S., and European bridge design codes, highlighting similarities and differences that relate to the design of timber highway bridges.

COMPARISON PARAMETERS

The analysis used the fourth edition of the *AASHTO-LRFD Bridge Design Specifications* (*1*) for the United States and the 10th edition of the Canadian Highway Bridge Design Code CAN/CSA S6-06 (*2*) and its companion code commentary (*3*) for Canada. For Europe, several design standards were used, including EN 1995-1-1 Eurocode 5, Design of Timber Structures, Part 1-1: General—Common Rules and Rules for Buildings; EN 1995-1-2 Eurocode 5, Design of Timber Structures, Part 2: Bridges; EN 1990:2002 Eurocode, Basis of Structural Design; and EN1990:2002/A1 Eurocode, Basis of Structural Design/Amendment A1, Annex A2: Application to Bridges.

Design Philosophy

Canada, the United States, and the European Union all have unique structural codes for the design of timber highway bridges. The Canadians adopted the limit states design (LSD) approach many years ago, and the United States recently transitioned to the LSD format for its bridge design code. The Eurocode was scheduled to convert to the LSD format in early 2010. The U.S. and the European Union LSD design codes use a calibration coefficient to convert from tabulated strength properties in allowable stress design (ASD) to reference design values in LRFD.

All codes use the same basic structural equations for flexure and shear, but they use different adjustment factors to modify reference design values or specified strength values. All three codes consider the ultimate limit states (ULS) and service limit states (SLS) but do not require fatigue limit states (FLS) to be considered for the design of timber bridges.

Organizational Format

All three codes have dedicated sections for each type of material (wood, steel, and concrete, including resistance values) and design factors (loads, load factors, and analysis methods). In Europe, however, information on the design of timber structures is located in a separate code, Eurocode 5. The Canadian code is the only one of the three with a section dedicated to fiber-reinforced-plastic (FRP) materials. The AASHTO code includes companion versions in metric and customary units, whereas the Canadian code uses only metric units. The AASHTO code includes commentary in a side-by-side, two-column format; Canada and Europe include their code commentary in companion publications. The Eurocode is available in many languages but is based solely on metric units.

The Canadian code includes the evaluation (load rating) of bridges within their bridge design code; this topic is covered in a separate publication in the United States code. The *Manual for Condition Evaluation and Load and Resistance Factor Rating (LRFR) of Highway*

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Bridges is in use by engineers to evaluate and load rate bridges in the United States (*4*). In a unique aspect of the Eurocode, each country can produce a national annex that includes nationally determined parameters (NDPs) that modify EN 1995-2 with respect to load duration, partial factors for material properties, deflection limits, damping ratios, and other geographically specific data (i.e., climate, snow loads). Although several states in the United States have design requirements that are more stringent than those given by AASHTO, the requirements must exceed the minimum requirements set by AASHTO. However, European countries have more latitude for setting their NDPs above or below Eurocode design recommendations.

Superstructure Types

All three codes include design specifications for a variety of bridge superstructures that use timber structural components. The longitudinal deck systems included in all codes are spike-laminated, glued–laminated (glulam), and stress-laminated superstructures. The transverse deck systems on beam girders included in both codes are planks, nail-laminated, glulam panels, and concrete slabs. Specific differences in the design of each superstructure systems in the various countries include the following:

- The U.S. and Canadian codes do not permit longitudinal (continuous) nail-laminated decks but do allow panelized nail-laminated decks, commonly referred to as spike-laminated decks.
- The Canadian code includes a composite nail-laminated concrete longitudinal deck system and permits mechanically spliced, butt-jointed deck laminations.
- The Canadian code permits the use of FRP prestressing strands for stress-laminated decks.
- The Eurocode contains design provisions for cross-laminated slab bridge designs consisting of several (flatwise) lamination layers that are glued or mechanically fastened into deck slabs with each layer having a different grain direction (crosswise or at different angles).

Loads

AASHTO and the Canadian code have dedicated chapters for load and load effects within their specifications. The Eurocode has separate documents for bridge loadings with associated load factors provided in national annexes. These sections cover load combinations for ULS, SLS, and FLS. The load factors and load combinations for the Canadian code are typically less than those in AASHTO. AASHTO has seven ULS load combinations, which it refers to as Strengths I through V and Extremes I and II, whereas the Canadians have nine ULS load combinations. AASHTO has four SLS load combinations, and the Canadians have two. The Eurocode has four ULS—equilibrium (EQU), strength (STR), geotechnical, and fatigue—and has two SLS—vibration and deformation. For the design of timber bridge superstructures via Eurocode, the ultimate limit states for EQU and STR and the service limit states for vibration and deformation are usually checked. Load factors for dead load and (bridges) live load are provided in Eurocode by each member country in its National Annex 2 to EN 1995-2.

Both codes have tables for permanent load factors that give the maximum and minimum values used to produce the more critical combinations for design loads. Only one load combination is discussed here, the main load combination for all codes, ULS Combination 1

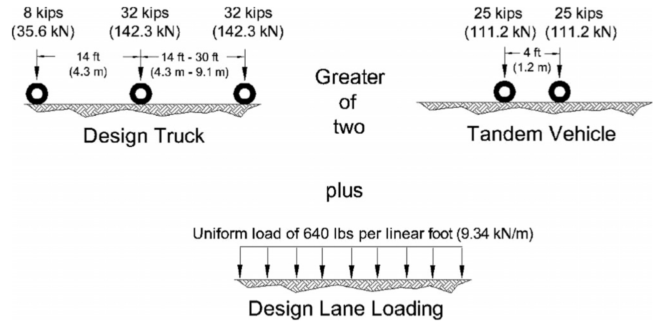

FIGURE 1 Bridge design loading configuration used in United States.

(Canada), Strength I (United States), and Strength (European Union). The basic load combinations used for the normal design vehicle and a dead load without wind follow:

Canada:

$$Q = 1.2 * \text{dead\_load} + 1.7 * \text{live\_load}$$

United States:

$$Q = 1.25 * \text{dead\_load} + 1.75 * \text{live\_load}$$

The design live loading for each code has different vehicle and uniform distributed load configurations. The AASHTO code uses an HL-93 design load (Figure 1), the Canadian code uses the CL-625 design load (Figure 2), and the Eurocode uses Load Model One (LM1; Figure 3) for the design vehicle or uniform distributed load combinations. At first glance, the U.S. and Canadian design vehicles look quite different because of their wheel spacing and axle loads. Despite these differences, they yield about the same design moments and shear (Figure 4). The Canadian design vehicle (CL-625) has a gross weight of about 70 tons (625 kN). The AASHTO design vehicle (HL-93) plus its lane load for a 50-ft bridge has a combined weight of 52 tons (463 kN). The Eurocode (LM1) design loading has a combined weight of approximately 135 tons (600 kN) evenly spread over two axles for spans of less than 10 m with the dual axles replaced with a single axle for spans greater than 10 m. A superimposed uniform distributed load of 9 kN/m^2 is applied simultaneously.

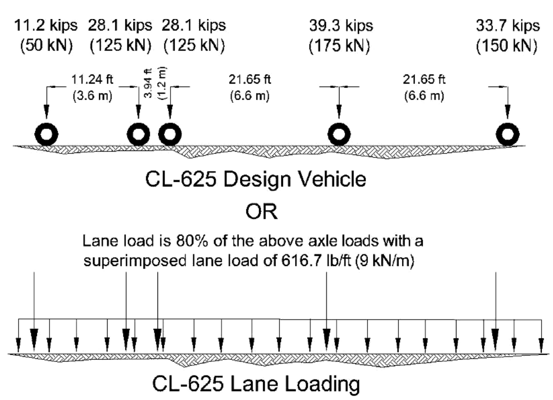

FIGURE 2 Bridge design loading configuration used in Canada.

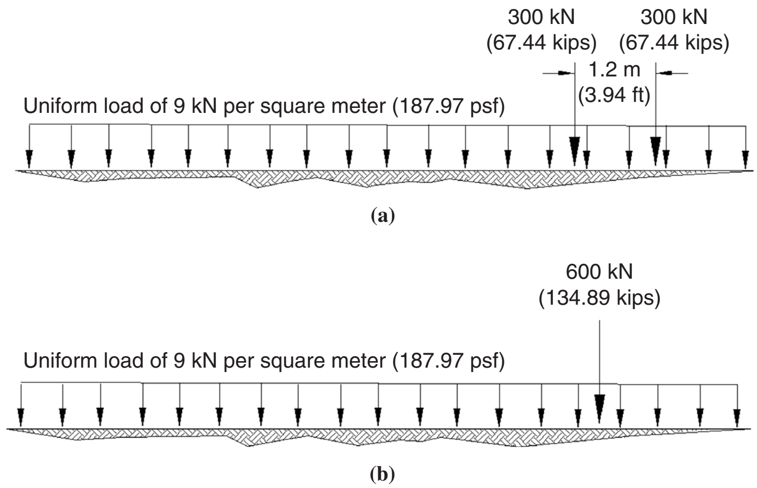

FIGURE 3 Bridge design loading configuration used in Europe: (*a*) spans of less than 10 m and (*b*) spans of 10 m or more.

Although the AASHTO design vehicle weighs less than the Canadian design vehicle, the variable wheel spacing of the AASHTO design truck develops more concentrated load than does the Canadian design vehicle. The Eurocode (LM1) design loading is significantly higher (by a factor of 2 to 3) than its U.S. and Canadian counterparts.

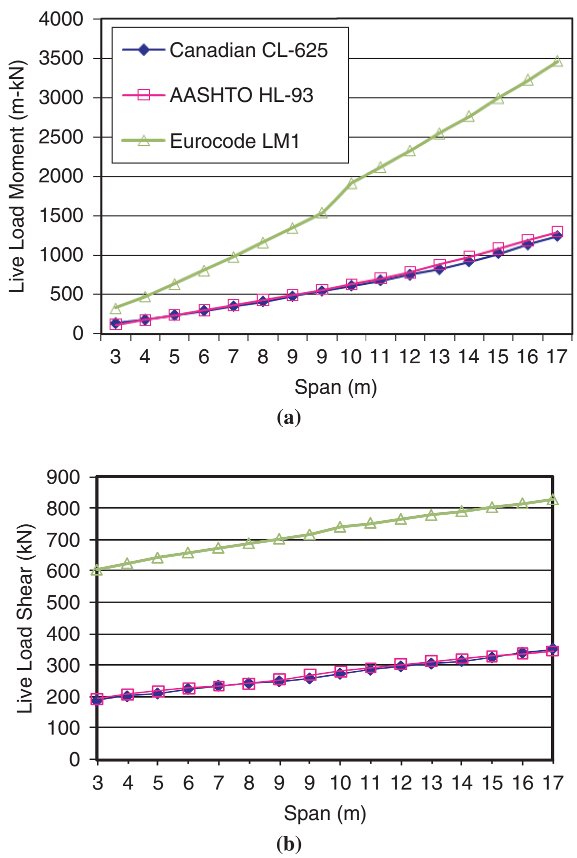

FIGURE 4 Comparison for unfactored design loads: (*a*) live load moment and (*b*) live load shear. (Note: Graphs designed based on 3-ft span intervals and then converted to metric scale. Duplicate number 9 in each *x*-axis is due to round-off error.)

AASHTO does not require a dynamic load allowance for timber bridges on the assumption that wood is stronger for short-duration loads than it is for long-duration loads. This increase in strength cancels the increase in force of dynamic loads. Canada requires a dynamic load allowance for wood, but that allowance is only 70% of the allowance required for steel and concrete bridges. It is not yet clear whether individual countries will provide dynamic load allowance as part of their Eurocode national determined parameters.

The multiple presence factor (United States) and multilane loading (Canada) are included in the codes to account for the probability of more than one lane being loaded at a time (Table 1). The Eurocode uses a different approach to multiple-lane loading, whereby truck axle loads and uniform distributed loads are reduced in the second and third lanes, with remaining areas having a 2.5 kN/m^2 uniform distributed load applied as well. For the U.S. code, the multiple presence factors are integrated into the approximate equations for distribution factors for bending and shear.

Materials

All three bridge codes base their strength and design values on other referenced codes. AASHTO references the 2005 National Design Specification for Wood Construction for sawn-lumber reference design values and the American Institute of Timber Construction's 117-2004: Standard Specifications for Structural Glued Laminated Timber of Softwood Species for glulam timber reference design

TABLE 1 Comparison of Factors

Number of Lanes Loaded	U.S. Multiple Presence Factors	Canadian Multilane Loading Factors
1	1.2	1.0
2	1.0	0.9
3	.85	0.8
4	.65	0.7
5	.65	0.6
6 or more	.65	0.55

values. The design values in the AASHTO code are based on ASD values, at 19% maximum moisture content with a 10-year load duration. The Canadians reference CAN/CSA-086 for sawn lumber and CSA 0177 for glulam timber. The design values in the Canadian code are based on LSD values at >20% moisture content with a 1-month load duration. The Eurocode references EN 14081-1:2005 for sawn lumber and EN 14080:2005 for glulam timber. The design values in the Eurocode are based on ASD values at approximately 12% moisture content with a 5-min load duration.

The number of sawn lumber species covered by the codes varies from 11 in the AASHTO code to eight (four species combination groups) in the Canadian code. The Eurocode contains timber strength classes instead of individual species groups (12 classes for softwoods and six classes for hardwoods). The Canadians use only Douglas fir for glulam timbers and have specified strength values for four combinations in bending, one combination in compression, and one combination in tension. AASHTO lists five species of trees and includes reference design values for 21 combinations for bending and 15 combinations for compression and tension. The Eurocode includes both European lumber species and imported species from Central America, the United States, and Canada.

Design for Bending

The approach of both the U.S. and the Canadian codes to bending strength design is very similar. They both use reference design or specified strength values and multiply them by adjustment factors to calculate an adjusted design value. This adjusted value is used to calculate a nominal flexural resistance value, which is modified by the resistance factor to yield the factored flexural resistance value. The factored flexural resistance value must be larger than the total factor load for the beam in bending.

The AASHTO code uses the following equations to determine factored flexural resistance:

AASHTO 8.4.4.1-1:

$$F_b = F_{bo} * C_{kf} * C_M * (C_F \text{ or } C_V) * C_{fu} * C_i * C_d * C_\lambda$$

AASHTO 8.6.2-1:

$$M_n = F_b * S * C_L$$

AASHTO 8.6.1-1:

$$M_r = \phi * M_n$$

The Canadian code uses a single equation to determine factored flexural resistance:

$$M = \phi * k_d * k_{ls} * k_m * k_{sb} * f_{bu} * S$$

The Eurocode also uses a single equation to determine the flexural resistance:

$$f_{m,y/z,d} = k_{\text{mod}} \cdot k_{\text{sys}} \cdot k_h \cdot k_{m,k}$$

The equations' terms for design values and adjustment factors are similar. The design values for AASHTO are F_{bo} for the reference design value and F_b for the adjusted design value. The reference design value can be compared to specified bending strength, f_{bu}, for the Canadian code. The resistance factor is ϕ for both codes, but AASHTO uses a resistance factor of 0.85 for flexure whereas the Canadians use a resistance factor of 0.9. Four adjustment factors are common to both codes: beam stability factor, C_L and k_{ls}; time-effect factor or load duration factor, C_λ and k_d; size-effect factor for sawn lumber or volume factor, C_F or C_V and k_{sb}; and the deck factor or load-sharing factor, C_d and k_m. AASHTO uses a few more adjustment factors such as C_{kf} for the format conversion factor to convert from ASD to LRFD, C_M for the wet-service factor, C_{fu} for the flat use factor, and C_i for the incising factor.

The reference design values ($f_{m,y/z,d}$) in the Eurocode are determined by multiplying the characteristic (mean) bending strength ($f_{m,k}$) of a timber component by the following three factors: k_{mod} (modification factor for moisture condition and service classes), for which a value of 0.7 is appropriate for wet-service conditions and short-term traffic loading; k_{sys}, the system strength factor; and k_h, the modification factor for member size effects. In conversion to a factored bending resistance value, the reference design value is divided by the partial coefficient for material properties (γ_M), for which a value of 1.30 is used for lumber and a value of 1.25 is used for glulam timber components.

Canada uses a true LSD, so they do not require a format conversion factor to convert from ASD to LRFD. The semiwet condition and incising factor are already included in the Canadian code's specified strength tables.

Design for Shear

Both the U.S. and the Canadian codes use a similar approach for shear strength design. Both use reference design or specified strength values and multiply them by adjustment factors to calculate an adjusted design value. This adjusted value is used to calculate a nominal shear resistance value, which is modified by the resistance factor to yield the factored shear resistance value. The factored shear resistance value must be larger than the total factor load for the beam in shear.

AASHTO uses the following equations to determine factored shear resistance:

AASHTO 8.4.4.1-2:

$$F_v = F_{vo} * C_{kf} * C_M * C_i * C_\lambda$$

AASHTO 8.7-2:

$$V_n = F_v * \frac{b * d}{1.5}$$

AASHTO 8.7-1:

$$V_r = \phi * V_n$$

The Canadian code uses a single equation to determine factored shear resistance:

$$V = \phi * k_d * k_m * k_{sv} * f_{vu} * \frac{A}{1.5}$$

The Eurocode uses a single equation to determine factored shear resistance:

$$f_{v,d} = k_{\text{mod}} \cdot k_{\text{sys}} \cdot f_{v,k}$$

The equations' terms for design values and adjustment factors are similar. The design values for AASHTO are F_{vo} for the reference design value and F_v for the adjusted design value. The AASHTO reference design value can be compared to specified shear strength, f_{vu}, for the Canadian code. The resistance factor is φ for both codes, but AASHTO uses a resistance factor of 0.75 for flexure, whereas the Canadian code uses a resistance factor of 0.9. The time effect or load duration factor, C_λ and k_d, is the only adjustment factor for shear that is common to both codes. AASHTO has a few more adjustment factors, such as C_{kf} for the format conversion factor to convert from ASD to LRFD, C_M for the wet-service factor, C_{fu} for the flat use factor, and C_i for the incising factor. The Eurocode calculates shear based on the characteristic value ($f_{v,k}$) based on the shear strength parallel to the grain, which is modified by the factor for moisture condition and service classes (k_{mod}), for which a value of 0.7 is typically used, and the system strength factor (k_{sys}).

The Canadian code uses a true LSD, so it does not require a format conversion factor to convert from ASD to LRFD. The semiwet condition and incising factor are already included in the Canadian code's specified strength tables. The last two adjustment factors, k_m, modification for load sharing, and k_{sv}, modification for size effect for shear, are found only in the Canadian code and the Eurocode.

Deflection Criteria

All three bridge design codes set limits for the amount of deflection at the SLS with the allowable deflection varying from $L/400$ for the Canadian code, $L/425$ for the AASHTO code, and $L/300$ to $L/400$ in Eurocode 5, where L equals the length of the bridge. The Eurocode uses mean values (versus fifth-percentile value for the United States and Canada) for stiffness-related properties in the service load limit state. However, each member country of the Eurocode can impose alternative deflection limits in their individual national annex document, which modifies the requirements of Eurocode EN 1995-2.

Decks

The U.S. code has a separate section for decks, and the Canadian code includes decks in the wood section. The Eurocode integrates its deck design provisions within its bridge design code. The decks covered in all three codes are glulam, stress-laminated, and nail-laminated decks. The Canadian code also includes wood–concrete composite decks in its specifications. The Eurocode includes provisions for cross-laminated decks and stress-laminated decks consisting of glulam beams that are prestressed and glued at the lamination interfaces.

Durability

AASHTO and the Canadian bridge code require timber used in bridges to be treated with preservatives applied by pressure treatment. AASHTO follows the AASHTO M 133 standard for allowable treatments and retentions. The Canadian code's subsection on durability lists allowable preservatives and follows the Canadian Standards Association 080 series of standards. Both the U.S. and Canadian codes reference the American Wood Preservative Association standards. The Eurocode allows for designer choice from (*a*) sufficient flashing or sheltering details, (*b*) use of naturally durable timbers, or (*c*) preservatively pressure-treated materials. The allowable preservative treatments are similar with each providing preservative alternatives from creosote to chromate copper arsenate. All three codes require galvanized metal fasteners and hardware.

COMPARATIVE BRIDGE DESIGN

A bridge component was designed by using the different design loadings along with similar design assumptions so that a general comparison of the bridge design codes could be made. This comparative design analysis was based on a longitudinal glulam stringer bridge with a transverse glulam deck. The single-lane bridge measured 60 ft long and had a span distance of 59 ft (center-center bearings). The transverse glulam deck was 5.125 in. thick and measured 18 ft wide, providing a 16-ft roadway width. Five glulam beams spaced at 42 in. (center-center) supported the deck; these were Douglas fir with a nominal bending strength of approximately 2,400 lb/in.^{2}. Design loading was as required by each design code, and adjustments were made for wet-use exposure conditions. Live load deflection was limited to approximately L/400 for the glulam girder designs. Specific design parameters were derived from the national annex of Portugal for the Eurocode beam design.

The interior beam size required by each national bridge design code is provided in Table 2. The required beam sizes for the United States and Canada are similar with live load deflection controlling in both cases. The slightly deeper beam required in the United States was attributed to different load distribution, deflection limits, and deflection loadings. The required beam size in the Eurocode design specifications is much larger at 9.5 × 63 in. for the Class I loading level. This requirement in Europe for a wider and deeper beam was attributed to the significantly higher design loads required for Class I loading and resulted in a bending controlled design. If Class II loadings with a reduced axle and lane loading are considered, the Eurocode required beam size becomes 9.5 × 45.5 in. and is much closer in beam depth to that of the United States and Canada. Remaining differences are related to the live load distribution to the girders and safety factors between North American and European bridge design.

SUMMARY

This study performed a comparative analysis of the national codes from the United States, Canada, and Europe related to the design of timber highway bridges. The analysis found many similarities and some distinctive differences among the three bridge codes. Although

TABLE 2 Summary of Comparative Interior Beam Bridge Design Analysis

	United States	Canada	European Union[a]
Beam size	8.75 × 42 in.	8.75 × 40.5 in.	9.5 × 63 in. (Class I) 9.5 × 45.5 in. (Class II)
Deflection limit	$L/425$	$L/400$	$L/400$
Deflection loading	100% truck loads	90% truck + lane loads	100% truck + lane loads
Controlling factor	Deflection	Deflection	Bending

[a]Eurocode calculations are based on bridge design requirements in Portugal.

the United States and Canada have different design load configurations, they produce similar live load effects for bending and shear. The design load configuration of the Eurocode produces bending moment and shear effects that are significantly higher than U.S. and Canadian levels. A comparison design was performed for a 60-ft (Douglas fir) glulam beam bridge by using the design load configuration for each national design code. The largest beam size of 9.5 × 63 in. was required by the Eurocode, whereas the beam size requirements were smaller in North America. The United States required a beam size of 8.75 × 42 in., and Canada required a beam size of 8.75 × 40.5 in. The controlling design parameter was deflection in the United States and Canada, whereas bending controlled in the Eurocode (Portugal) design. The large differences noted between required glulam beam sizes in North America and Europe are most likely associated with the different design loads, live load distribution, and safety factors used in the design of timber highway bridges. Future work will focus on those key details used in each country (or national code) in designing for durability.

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