AASHTO Load Rating of Concrete Bridges

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A bridge is designed only once but is typically load-rated multiple times throughout its life. Bridge load rating is done mainly for a couple of reasons: for maintaining the up to date record of its design load carrying capacity (Inventory Rating) and for evaluating bridge's capacity to safely carry overloads (Operating Rating). Inventory rating is performed immediately after the initial design and at least every two years to update the National Bridge Inventory data. Operating rating, on the other hand, is performed quite frequently, sometimes several times a day, to issue permits for trucks carrying loads in excess of the design load.

Since October 2008, all bridges receiving federal funding have been mandated to be designed per the AASHTO LRFD Bridge Design Specifications. In 2008 AASHTO published the first edition of the Manual for Bridge Evaluation which is consistent in philosophy and approach to the AASHTO LRFD Bridge Design Specifications. The current bridge inventory includes bridges designed by both specifications: Standard (LFD) and LRFD. The rating may be performed per LRFR or sometimes per LFR specifications. Although the LRFR specifications are somewhat similar to the LRFD design specifications, they differ in several aspects including loads and load factors. Therefore, a bridge that is designed by LRFD Specification may be deemed unsafe by LRFR and/or LFD rating procedures. This paper compares the requirements of LFD, and LRFR/LRFD. It provides a comprehensive comparison of rating factors for precast, prestressed concrete girder and CIP post-tensioned concrete box girder bridges in various span configurations to provide an understanding of the level of differences that can be expected from using different specifications.

Keyword: Bridge rating, bridge evaluation, rating, LRFR, LFR, LRFD, LFD, precast/prestressed conrete girder, cast-in-place post-tensioned concrete box girders, overload permit.

1. The content of this paper reflects the opinion of the author only and is not necessarily a reflection of Caltrans policies or practices.

INTRODUCTION

Load rating of bridges is an important activity and is routinely performed for several reasons: (A) to assess the safe load carrying capacity of bridges based on existing structural conditions, (B) to post bridges, if necessary, and (C) to issue permits for the passage of overweight trucks. Bridge owners are also required to submit the bridge ratings for inclusion in the National Bridge Inventory (NBI). Federal Highway Administration uses the NBI data to allocate federal bridge funding for rehab and reconstruction to various states. This paper deals with superstructure rating, specifically rating of prestressed, pretensioned concrete and cast-in-place post-tensioned box girder bridges.

In the past, the Allowable Stress Rating (ASR) and Load Factor Rating (LFR) of bridges designed per Allowable Stress Design method and Load Factor Design method, respectively, as specified in the AASHTO *Standard Specifications for Highway Bridges* was performed per the *Manual for Condition Evaluation of Bridges*. After the introduction of the *LRFD Bridge Design Specifications* in 1998, a new *Guide Manual for Condition Evaluation and Load and Resistance Factor Rating (LRFR) of Highway Bridges* was published in 2003. In 2008 AASHTO published the first Edition of *The Manual for Bridge Evaluation,* which compiled all rating methods, ASR, LFR, and LRFR into one reference.

AASHTO conducted a survey of the State Bridge Engineers in 2008. One of the reasons for this survey was to gain insight into the rating practices of various states with respect to LRFR. Forty states responded and the key results are noted below:

- 21 states had not rated any state-owned bridges using LRFR, 19 states had rated less than 10%, none more than 10%
- Most states (31 out of 38) indicated that no local-agency-owned bridges were rated using LRFR; the rest (7 out of 38) had less than 10% rated using LRFR.
- In almost half of the states the bridges that were rated with LRFR were mostly old bridges (less than 10% new), and in the other half they were all new bridges. In other words, very few states are rating both new and old bridges using LRFR.
- In close to 90% of the states, less than 10% of the bridges rated with LRFR were bridges that were re-rated using LRFR. In other words, in all cases the LRFR ratings are new ratings, either on new or old bridges.
- Most states (23 out of 38) indicated that they welcome guidelines for criteria to evaluate and rate prestressed or post-tensioned concrete bridges.

LOAD FACTOR RATING

Nearly all existing bridges have been designed in accordance with the *AASHTO Standard Specifications for Highway Bridges*, most according to older editions of the specifications.

Two types of LFR ratings are typically performed: Inventory Rating and Operating Rating. The inventory rating represents the fraction of the nominal design live loads that can be carried safely for an indefinite period of time. Operating load rating represents the maximum live load the structure can safely carry.

The basic rating factor equations for flexure and shear are as follows:

Strength:

$$RF_{Inventory} = \frac{\phi R_n - 1.3D}{2.17L(1+I)}$$

$$RF_{Operating} = \frac{\phi R_n - 1.3D}{1.3L(1+I)}$$

Where:

ϕR_n = nominal strength of section.
D = unfactored dead load moment or shear
L = unfactored live load moment or shear
I = impact factor

Allowable Stresses:
For concrete compression and tension,

$$RF_{Inventory} = \frac{6\sqrt{f_c^{'}} - \left(F_d + F_p\right)}{F_l} \quad \text{Concrete Tension}$$

$$RF_{Inventory} = \frac{0.6 f_c^{'} - \left(F_d + F_p\right)}{F_l} \quad \text{Concrete Compression}$$

$$RF_{Inventory} = \frac{0.4 f_c^{'} - \tfrac{1}{2}\left(F_d + F_p\right)}{F_l} \quad \text{Concrete Compression}$$

Where:

$6\sqrt{f_c^{'}}$ = allowable concrete tensile stress (variable)
F_d = unfactored dead load stress
F_p = unfactored stress due to prestess after all losses
F_l = unfactored live load stress

LOAD AND RESISTANCE FACTOR RATING

The principal benefit of the new LRFD and LRFR methodologies is that the load and resistance factors have been calibrated based upon structural reliability theory to provide a uniform target reliability for all bridges at the Strength Limit State. The service Limit States are not calibrated based on reliability theory to achieve a target reliability but are based on past practice.

Bridge design and rating, though similar in overall approach, differ in important aspects. Although bridge safety is the primary concern, economics plays a major role in specifying minimum design and rating standards. Design is based on a higher reliability index (3.5), whereas rating specifications are based on a reduced reliability index of approximately 2.5. The reduced value reflects the reduced exposure period, consideration of site realities, and the economic considerations of rating vs. design.

The methodology for the load and resistance factor rating of bridges is comprised of three distinct procedures: 1) Design Load Rating, 2) Legal Load Rating, and 3) Permit Load Rating.

DESIGN LOAD RATING
Design load rating is a first-level assessment of bridges based on the HL-93 loading. The rating is performed for both the Strength and Service Limit States. Bridges that do not pass the Design Load Rating (RF < 1) should be load rated for legal loads.

LEGAL LOAD RATING
This second level rating refers to AASHTO and State legal loads. Live load factors are selected based on the truck traffic conditions at the site. Strength is the primary limit state for load rating; service limit states are selectively applied. Bridges that do not pass the Legal Load Rating (RF < 1) should be load posted or targeted fro strengthening.

PERMIT LOAD RATING
This third level rating is performed to allow the passage of overloads – loads greater than the legal loads. Permit Load Rating is also performed for bridges that do not pass the Legal Load Rating, but have sufficient capacity for AASHTO legal loads. Calibrated load factors by permit type and traffic conditions at the site are specified for checking the load effects induced by the passage of the overweight truck.

The methodology for the load and resistance factor rating of bridges is comprised of systematic evaluation of the design load rating factors, and if necessary the legal and permit load rating factors, as shown in the flowchart adopted from the MBE manual as shown in Figure 1 below.

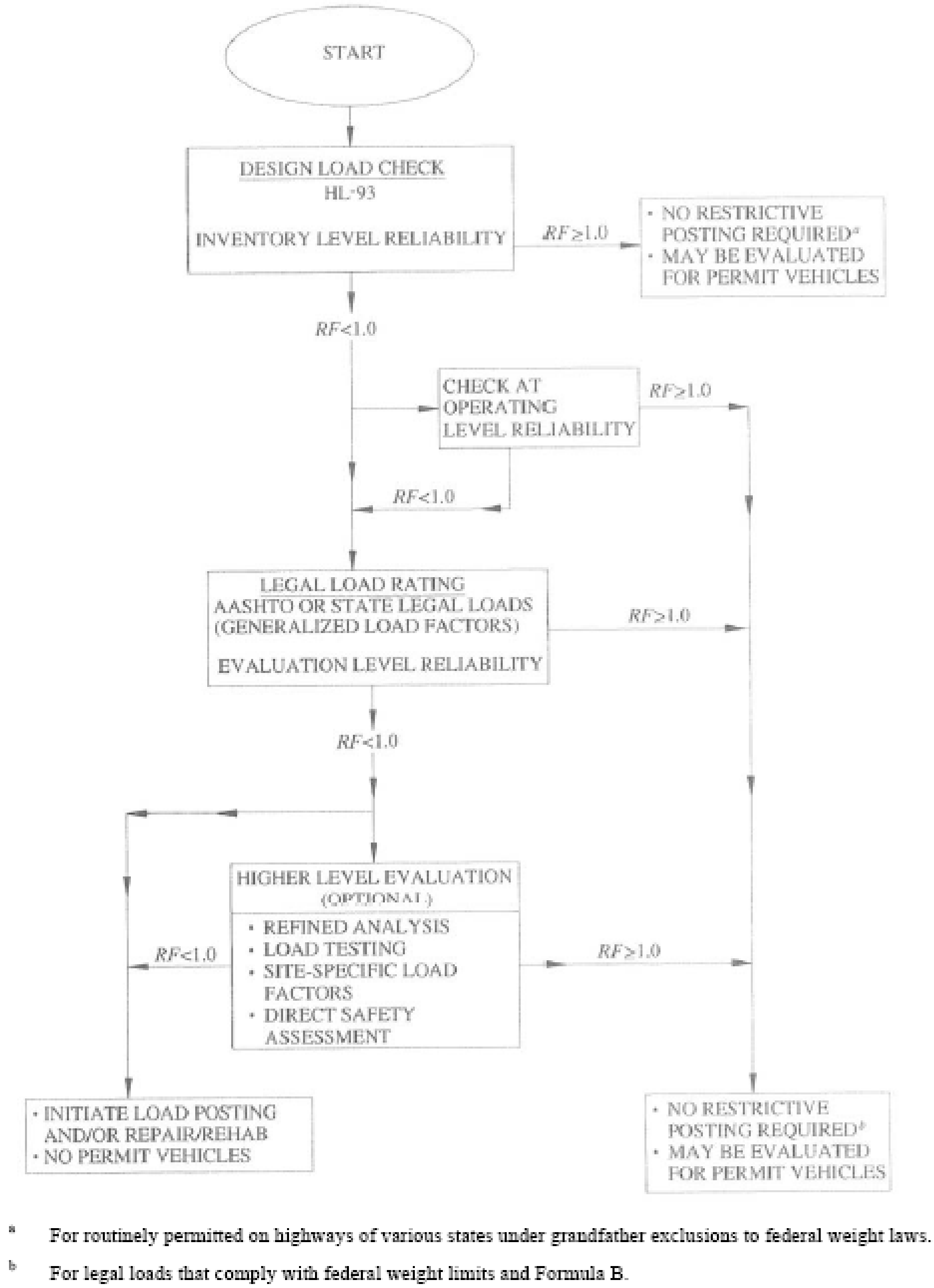


Figure 1: Flow Chart for Load and Resistance Factor Rating

The general load rating equation in LRFR is as follows:

$$RF = \frac{C - (\gamma_{DC})(DC) - (\gamma_{DW})(DW) \pm (\gamma_P)(P)}{(\gamma_{LL})(LL + IM)}$$

Where:

where:

RF = Rating factor
C = Capacity
f_R = Allowable stress specified in the LRFD code
R_n = Nominal member resistance (as inspected)
DC = Dead load effect due to structural components and attachments
DW = Dead load effect due to wearing surface and utilities
P = Permanent loads other than dead loads
LL = Live load effect
IM = Dynamic load allowance
γ_{DC} = LRFD load factor for structural components and attachments

The load rating procedures in LRFD in general consider more parameters, such as the traffic volumes (ADTT), structural condition of members (φ_c), system factors (φ_s), in all phases of the rating process. These load ratings provide a more consistent reliability as compared to the standard specification load rating process.

Limit States and Load Factors for Load Rating

Bridge Type	Limit State*	Dead Load		Design Load	
				Inventory	Operating
		γ_{DC}	γ_{DW}	γ_{LL}	γ_{LL}
Reinforced Concrete	Strength I	1.25	1.5	1.75	1.35
	Strength II	1.25	1.5	-	-
	Service I	1.0	1.0	-	-
Prestressed Concrete	Strength I	1.25	1.5	1.75	1.35
	Strength II	1.25	1.5	-	-
	Service III	1.00	1.00	0.80	-
	Service I	1.00	1.00	-	-

Table 1: Limit States and Load Factors for Load Rating (Adapted from MBE)
* Defined in the AASHTO LRFD Bridge Design Specifications
Notes:

- Service I is used to check the 0.9Fy stress limit in reinforcing steel.
- Load factor for DW at the strength limit state may be taken as 1.25 where thickness has been field measured.

PARAMETRIC STUDY

The current U.S. bridge inventory includes bridges designed by both specifications: Standard (LFD) and LRFD. The rating of these bridges may be performed per LRFR or sometimes per LFR specifications. Although the LRFR specifications are somewhat similar to the LRFD design specifications, they differ in several aspects including loads and load factors. Therefore, a bridge that is designed by LRFD Specification may be deemed unsafe by LRFR and/or LFD rating procedures. A parametric study was undertaken to study the level of differences that can be expected from using different specifications. A set of precast, prestressed concrete girder and CIP post-tensioned concrete box girder bridges in various span configurations as shown in Table 2 was selected for the study. Bentley's LEAP CONSPAN and LEAP CONBOX bridge design software was used for performing the designs and ratings.

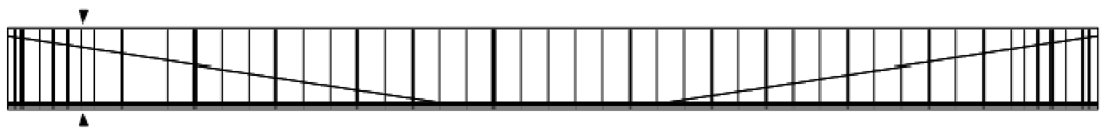
Bridge Type	Girder Types	Spans	Bridge Width	Strand/Tendon Type	Rated for	Specifications
Precast, Prestressed Concrete Girder	BT-54	Simple Span 80 ft.	60 ft.	0.5 in/ 0.6-in diameter	Flexure Strength	LFD/LFR
	BT-63	Simple Span 100 ft.		7-wire strand	Shear Strength Beta-Theta Method	LRFD/LRFR
	BT-72			270 ksi GUTS	Concrete Compressive Stress	
				Straight	Concrete Tensile Stress	
CIP PT Girder	Four-Cell Box	120'-120' Two-Span Continuous with Integral Piers	60 ft.	0.6-in diameter	Flexure Strength	LFD/LFR
	Six-Cell Box	200'-200' Two-Span Continuous with Integral Piers		7-wire strand bundle	Shear Strength Beta-Theta Method	LRFD/LRFR
				Long-term loss = 25 ksi lump sum	Concrete Compressive Stress	
					Concrete Tensile Stress	

Table 2: Description of Bridges Used in the parametric Study

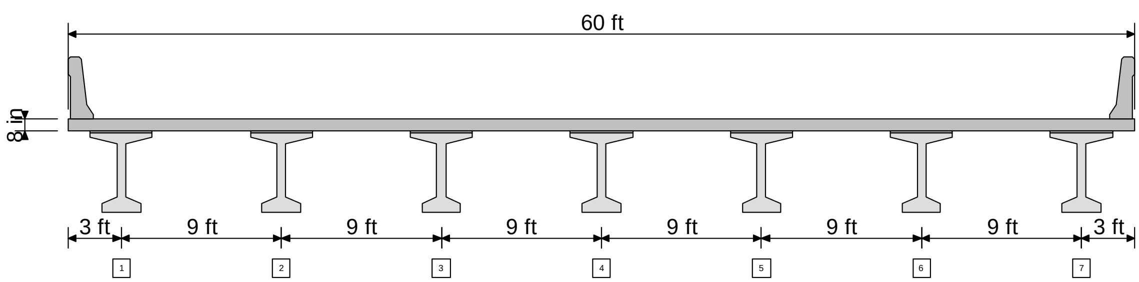
A typical cross section of the I-girder bridges is shown in Figure 2. Three girder sizes (BT-54, BT63, and BT-72) are used along with two span lengths of 80' and 100' to create a total of 6 analytical cases. All bridges are simply supported. The strands are designed based on LFD specifications and HS-20 live load to replicate the condition of the majority of the existing bridges. These bridges are rated using the LFR specifications for HS-25 truck, and the LRFR specifications for HL-93 live load. Since the bridges are rated for higher loads than their design load, it is expected that most rating factors would be below 1.0. However, what is of main interest is to compare these factors and to see if the LRFR factors are generally higher or lower than LFR. These results are discussed in the next section.

Analytical Models/Case Studies

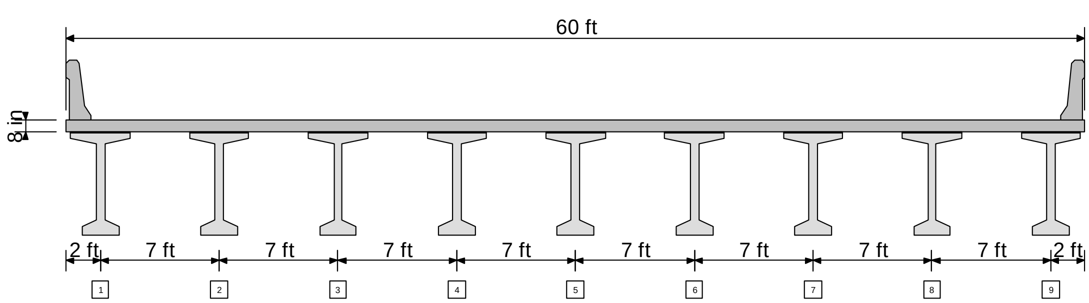
Typical Bridge Cross Section



a) Typical Elevation of the I-Girder Bridges



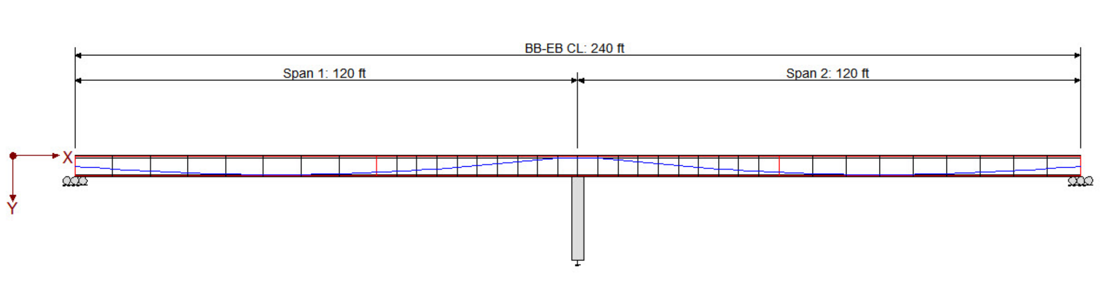
b) Cross Section of 80 ft Span Bridges



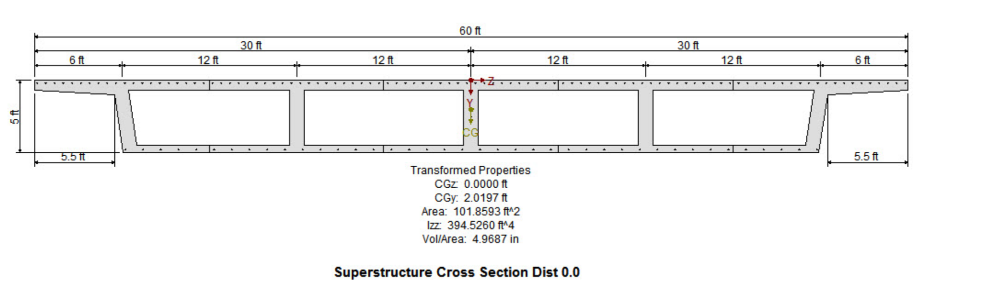
c) Cross Section of 100 ft Span Bridges

Figure 2: Typical Cross Section of I-Girder Bridges

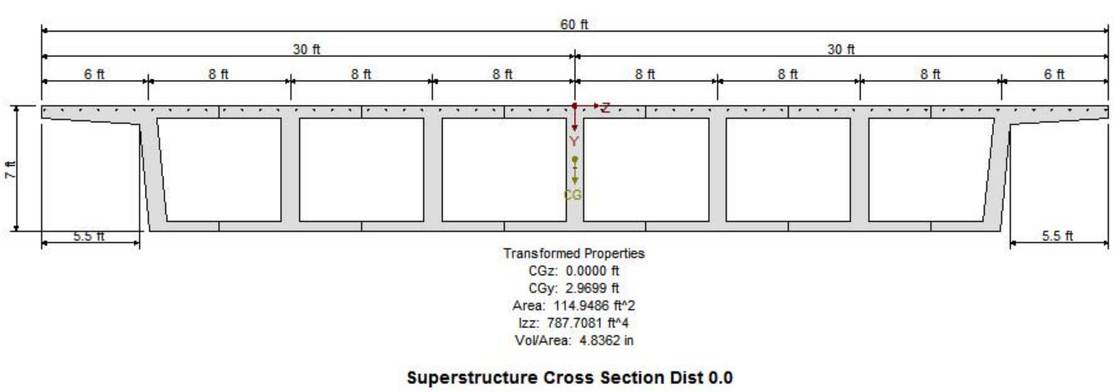
Two two-span bridges were considered for the box girder study, one with two equal spans of 120 ft, and another with two equal spans of 200 ft. In each case a four-cell and a six-cell cross section were considered. The LFD/LFR Specifications do not consider the cross section configuration in determining the live load distribution factors, while the LRFD/LRFR Specifications do. In addition, the higher moment of inertia in six-cell configuration results in lower dead and live load stresses, and thus different rating factors. Once again, due to lower design loads (HS20) compared to rating loads (HS25 or HL-93), it is expected that most rating factors would be below 1.0. The results are discussed next.



a) Typical Elevation of the Box Girder Bridges



b) Cross Section of Four-Cell Bridges



c) Cross Section of Six-Cell Bridges

Figure 3: Typical Elevation and Cross Section of Box-Girder Bridges

Results of Study

The results of the I-girder study are shown in Table 3. Inventory rating factors are calculated for flexure and shear capacity and concrete compressive and tensile stresses. Operating rating factors are calculated for flexure and shear capacities. Shear capacity is rated using the LRFD MCFT criteria included in Appendix B5 of the LRFD Specifications (noted as "Tables") and also the latest method (noted as "Equations"). Primary observations from these results are listed below.

- Inventory flexure rating is generally higher in LRFR compared to LFR/HS25. This is partly attributed to the fact that the live load factors are lower in LRFR (1.75) compared to LFR/HS25 (2.17), while the live load effect (including live load distribution factors) are somewhat less in LRFR, and the dead load factor is slightly lower as well.

- Concrete compression rating values are generally very high (greater then 5.0) and although LRFR factors are slightly less than LFR/HS25 factors, they are of no considerable consequence.

- Concrete tension rating factors are generally higher in LRFR. This is partly attributed to LRFR live load factor of 0.8, and lower live load distribution factors, while the live load factors are similar.

- Inventory shear rating governed the rating of the bridge in all cases. The LRFR rating factors are lower than LFR/HS25 in most cases when the latest code (formula) is used. The LRFR rating factors are higher than LFR./HS25 in half the cases when the older method (Beta/Theta Tables) are used. The LRFR capacity using tables was always higher than the capacity using the formulas.

- Operating flexure ratings are comparable and slightly lower in LRFR compared to LFR/HS25. This is attributed partly to the fact that live load factors in LRFR (1.35) are similar to the LFR live load factors (1.3)

- Operating shear rating was always higher than 1.0 using the LFR Specifications. LRFR factors were in all cases less than the LFR/HS25 values and in some cases less than 1.0

		LRFD Rating Factor		LFD HS20 Rating Factor		LFD HS25 Rating Factor	
		Inventory	Operating	Inventory	Operating	Inventory	Operating
80 ft- BT54	Moment	1.02	1.33	1.03	1.71	0.82	1.37
	Shear- Tables	0.72	0.93	1.19	1.96	0.95	1.58
	Shear-Equations	0.69	0.92	-	-	-	-
	Conc Comp 0.6fcp, CC1	8.80	-	11.38	-	9.10	-
	Conc Comp 0.4fcp, CC2	n/a	-	8.34	-	6.68	-
	Conc Tens	1.20	-	1.08	-	0.86	-
80 ft- BT63	Moment	1.06	1.37	1.10	1.84	0.88	1.47
	Shear- Tables	0.86	1.12	1.01	1.68	0.80	1.34
	Shear-Equations	0.83	1.08	-	-	-	-
	Conc Comp 0.6fcp, CC1	10.09	-	13.53	-	10.82	-
	Conc Comp 0.4fcp, CC2	n/a	-	9.67	-	7.73	-
	Conc Tens	1.37	-	1.32	-	1.06	-
80 ft- BT72	Moment	1.05	1.36	1.12	1.88	0.90	1.50
	Shear- Tables	0.95	1.23	1.27	2.12	1.01	1.69
	Shear-Equations	0.9	1.17	-	-	-	-
	Conc Comp 0.6fcp, CC1	11.27	-	15.59	-	12.47	-
	Conc Comp 0.4fcp, CC2	n/a	-	10.97	-	8.78	-
	Conc Tens	1.47	-	1.51	-	1.20	-
100 ft- BT54	Moment	1.14	1.47	1.23	1.64	0.98	2.06
	Shear- Tables	1.06	1.38	1.00	1.32	0.79	1.65
	Shear-Equations	0.7	0.91	-	-	-	-
	Conc Comp 0.6fcp, CC1	6.29	-	8.79	-	7.03	-
	Conc Comp 0.4fcp, CC2	n/a	-	6.65	-	5.32	-
	Conc Tens	1.15	-	1.06	-	0.85	-
100 ft- BT63	Moment	1.16	1.50	1.30	2.18	1.04	1.74
	Shear- Tables	1.28	1.66	1.53	2.49	1.19	1.99
	Shear-Equations	0.9	1.57	-	-	-	-
	Conc Comp 0.6fcp, CC1	7.53	-	10.93	-	8.74	-
	Conc Comp 0.4fcp, CC2	n/a	-	7.99	-	6.39	-
	Conc Tens	1.31	-	1.31	-	1.05	-
100 ft- BT72	Moment	0.90	1.16	1.03	1.71	0.82	1.37
	Shear- Tables	0.98	1.28	1.31	2.21	1.05	1.77
	Shear-Equations	0.33	0.42	-	-	-	-
	Conc Comp 0.6fcp, CC1	8.51	-	12.78	-	10.22	-
	Conc Comp 0.4fcp, CC2	n/a	-	9.20	-	7.36	-
	Conc Tens	1.10	-	1.78	-	0.95	-

Table 3: Rating Results for I-girder Bridges

The results of the box-girder study are shown in table 4. Inventory rating factors are calculated for flexure and shear capacity and concrete compressive and tensile stresses.

Operating rating factors are calculated for flexure and shear capacities. Shear capacity is rated using the older LRFD MCFT criteria using the Beta/Theta tables. Interesting observations from these results are listed below.

- Inventory flexure rating in LRFR compared to LFR/HS25 is generally lower in the shorter bridges and higher in the longer bridges. This is partly attributed to the fact that the live load distribution factors are somewhat less in shorter bridges in LRFR compared to longer bridges.
- Concrete compression rating values are somewhat lower in LRFR compared to LFR/HS25, however, all cases are greater than 1.0.
- Concrete tension rating factors are generally higher in LRFR. This is partly attributed to LRFR live load factor of 0.8, and lower live load distribution factors, while the live load factors are similar. The only exception is the 120-ft span, four-cell bridge, which has the highest live load distribution factor in LRFR.
- Inventory shear rating governed the rating of the bridge in all cases. The LRFR rating factors are lower than LFR/HS25 in all cases. This is attributed to the lower shear capacity using the LRFR Specifications.
- Operating flexure ratings are somewhat lower in LRFR compared to LFR/HS25, in all cases except the 200-ft span six-cell bridge. This is attributed partly to the fact that live load factors in LRFR (1.35) are similar to the LFR live load factors (1.3), but the live load distribution factor varies from case to case in LRFR.
- Operating shear rating for LRFR were in all cases less than the LFR/HS25 values. The largest differences are found in shorter spans with less number of webs (cells). This is once again due to variations in LRFR live load distribution factors.

		LRFD		LFD HS20		LFD HS25	
		Rating Factor		Rating Factor		Rating Factor	
		Inventory	Operating	Inventory	Operating	Inventory	Operating
120-120-4	Moment	0.67	1.30	1.06	1.77	0.85	1.41
	Shear	**0.36**	**0.51**	**1.05**	**1.75**	**0.84**	**1.40**
	Conc Comp 0.6fcp, CC1	2.56	5.06	4.19		3.35	
	Cocn Comp 0.4fcp, CC2	1.90	8.25	3.12		2.49	
	Conc Tens	0.95	0.95	1.24		0.99	
120-120-6	Moment	0.86	1.11	1.10	1.84	0.88	1.47
	Shear	**0.69**	**0.90**	**1.09**	**1.70**	**0.87**	**1.36**
	Conc Comp 0.6fcp, CC1	3.23	6.41	4.37		3.50	
	Cocn Comp 0.4fcp, CC2	2.41	7.17	3.26		2.61	
	Conc Tens	1.17	1.17	1.26		1.01	
200-200-4	Moment	0.91	1.18	1.03	**1.72**	0.82	**1.37**
	Shear	**0.58**	**0.81**	1.04	1.74	0.83	1.39
	Conc Comp 0.6fcp, CC1	1.36	3.57	1.71		1.37	
	Cocn Comp 0.4fcp, CC2	1.23	4.54	1.55		1.24	
	Conc Tens	1.00	1.00	**1.00**		**0.80**	
200-200-6	Moment	1.23	1.60	1.09	1.82	0.87	1.46
	Shear	**0.78**	**1.07**	1.03	**1.72**	0.82	**1.37**
	Conc Comp 0.6fcp, CC1	1.72	4.58	1.78		1.43	
	Cocn Comp 0.4fcp, CC2	1.58	5.87	1.63		1.31	
	Conc Tens	1.21	1.21	**1.00**		**0.80**	

Table 4: Rating Results for Box-girder Bridges

CONCLUSIONS

Six I-girder and four multi-cell box girder bridges were designed for HS20 live load per LFD Specifications, which were then rated using LFR Specifications for HS25 truck and LRFR Specifications for HL93 live load.

For I-girder bridges the flexure rating (flexure capacity and stresses) by LRFR is generally lower or comparable to the one by LFR. The shear rating is generally lower in LRFR and this difference is more pronounced when the MCFT (Equations) method for LRFD shear designis used.

In box-girder bridges, the flexure rating (flexure capacity and stresses) by LRFR is comparable to that by LFR. The shear rating is generally lower in LRFR. There is noticeable increase in LRFR rating factors when span lengths increase or number of cells increase. This is attributed mainly to the variation in the live load distribution factors.

Looking at the ratio of the LRFR to LFR rating factors for shear and flexure, operating rating factors have a higher value than inventory rating. This is mainly due to differences in the live load factors.

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