EVALUATION OF ALLOWABLE LOADS ON A BRIDGE IN ACCORDANCE WITH AASHTO - LRFD 1998

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Abstract - The quality of bridges in Vietnam causes topical concern. When the maximum unrestricted legal loads or State routine permit loads exceed the allowable limit, the bridge must be posted or restricted. This paper provides an overview of the requirements of load rating bridges, the basic concept of structural reliability used in calibration of the Load and Resistance Factor Design (LRFD) and Rating (LRFR) method in accordance with AASHTO – LRFR.

Key words - reliability index; inventory level; legal load rating; permit load rating; design load tests: bridge rating.

1. Introduction

In the developing economies like Vietnam, particularly important development of the network of highways and modernization of the existing road network are of much concern.

One of the weakest links in the process of upgrading the existing road network is the bridge construction, which in the state of the historical development of the country are designed and built using different contrives regulations (such as France, USA, Russia, Japan and others countries). Many of these regulations do not meet the requirements in size and loads suitable for Vietnam conditions. I should add that a long period of neglected maintenance of bridges, unplanted repair and reconstruction have negative impact on the operated bridge-works. Climatic factors such as the hot tropical climate with long rainy period and the sea effects are also contributing factor. In Vietnam there is a lack of highly skilled professionals who are able to evaluate the technical condition of bridge structures, their capacity and bandwidth in a timely manner to make recommendations for repair and reconstruction.

Once a bridge is constructed, it becomes the property of the owner or the agency. The evaluation and rating of existing bridges is a continuous activity of the owner or the agency to ensure the safety of the public, especially in context of increasing heavy load pass on the bridges. Existing bridges contain many uncertain factors of material resistance, structural behaviors and operating load.

Also, the Vietnam's bridge design specifications 22TCN 272-05 current in, use is base on AASHTO-LRFD-1998. But the bridge's evaluation and verification are done in accordance with 22TCN 243-98, which is based on Russian standard. This paper research the Load and Resistant Factor Rating method in accordance with AASHTO – LRFR – 2008.

2. Structural Reliability

During the development of AASHTO LRFD Bridge Design Specifications and calibration of the LRFR load rating method [1, 3], there has been considerable research and data gathering in highway bridge loadings and component resistances.

The limit state function is defined as:

$$g = R - D \quad (1)$$

Where D and R are the load effect and resistance, respectively. Both D and R are statistically distributed with the uncertainty of their values at the time that the component is designed or evaluated. The probability of failure can be written as:

$$P_f = P[g < 0] = P[R < D] \quad (2)$$

Alternatively, one can use the reliability index, β, to measure the safety margin:

$$\beta = \frac{\bar{g}}{\sigma_g} \quad (3)$$

Where $\bar{g}$ and represent σ_g the mean and standard deviation of the random number, g. If $\bar{g}$ is large (appositive value means safe) and/or σ_g is small, the probability that g will fall below zero or that failure will occur will be small. The greater the reliability index, β, the greater the safety margin or the smaller the probability of failure.

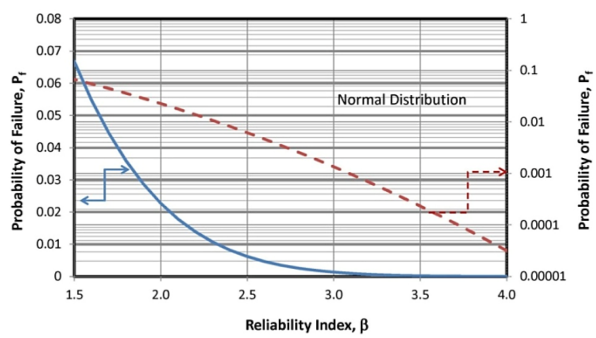


Figure 1. *Reliability index vs. Probability of failure*

The relationship between the reliability index and probability of failure is shown in Figure 1, assuming that *g* follows a normal distribution. Corresponding to a reliability index of 3.5 (target index for design), P_f < 0.00023. For legal load ratings, β and P_f are 2.5 and 0.00621, respectively. Note that the duration of exposure for design is the design life of the bridge, however, the duration for legal load ratings is the inspection cycle.

Table 1. *Target reliability indices [4]*

Evaluation Level		Reliability Index
Design		3.5
Design Load Rating	Inventory Level	3.5
	Operating Level	2.5
Legal Load Rating		2.5
Permit Load	Routine Permits	2.5

Rating	Special Permits (Single Trip, Escorted)	2.5
	Special Permits (Single or Multiple Trip, Mixed in Traffic)	3.5

If D and R are normally distributed with a mean of $\overline{D}$ and $\overline{R}$, and a standard deviation of σ_D and σ_R, g will be normally distributed too. β can be written as:

$$\overline{g} = \overline{R} - \overline{D} \quad (4)$$

$$\sigma_g = \sqrt{(\sigma_R)^2 + (\sigma_D)^2} \quad (5)$$

$$\beta = \frac{\overline{R} - \overline{D}}{\sqrt{\sigma_R^2 + \sigma_D^2}} \quad (6)$$

If D and R follow a log-normal distribution, the reliability index can be computed with the following equation:

$$\beta = \frac{\ln\left(\frac{\overline{R}}{\overline{D}}\right)}{\sqrt{V_R^2 + V_D^2}} \quad (7)$$

Where V_R and V_D are the coefficient of variation (COV) of $R$and D, respectively, equal to the standard deviation divided by the mean.

If D and R follow other statistical distribution, a random simulation algorithm, such as Monte Carlo simulation, has to be utilized to compute the reliability index.

Different from new design, load ratings must consider the real physical condition of a bridge at the time of rating. Deteriorations may change the load distribution in the structure, and/or reduce the resistance of structural components. Therefore, LRFR introduces a condition factor to account for the physical condition of a bridge/member in computing its load ratings.

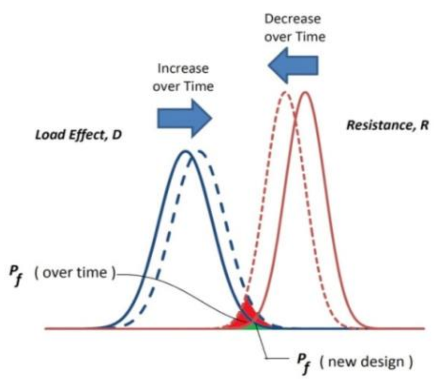


Figure 2. *Probability of failure over time*

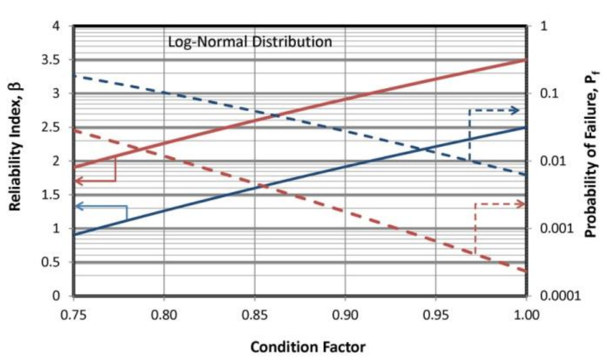


Figure 3. *Reliability index and probability of failure overtime*

Figure 2 demonstrates the impact of structural condition change on the probability of failure during the life of a bridge. Figure 3 shows the reliability index vs the condition factor (1.0 refers to no deterioration; 0.75 means 25% reduction in resistance).

The computation of the reliability index is dependent of the statistics of load and resistance data. In calibrating the LRFR, Moses [3] used normal distribution models for dead loads and resistance and a log-normal distribution model for live loads (Table 2).

Table 2. *Statistics for reliability index calibration*

Case	Bias	COV	Distribution
Dead Load	1.14	0.08	Normal
Live Load	1.00	0.18	Log-Normal
Resistance	1.12	0.1	Normal

Bias: the ratio of the mean value to nominal design value.

COV: the ratio of the standard deviation to mean value.

3. Fundamentals of Bridge Rating

In the each country, since highway bridges are designed for the design vehicles, most engineers tend to believe that the bridge will have adequate capacity to handle the actual present traffic. This belief is generally true if the bridge was constructed and maintained as shown in the design plan. However, changes in a few details during the construction phase, failure to attain the recommended concrete strength, unexpected settlements of the foundation after construction, and unforeseen damage to a member could influence the capacity of the bridge. In addition, old bridges might have been designed for a lighter vehicle than is used at present, or a different design code. Also, the live-load-carrying capacity of the bridge structure may have altered as a result of deterioration, damage to its members, aging, added dead loads, settlement of bents, or modification to the structural member.

Sometimes, an industry would like to transport their heavy machinery from one location to another location. These vehicles would weigh much more than the design vehicles and thus the bridge owner may need to determine the current live load carrying capacity of the bridge.

Rating Principles

In general, the resistance of a structural member (R) should be greater than the demand (Q) as follows:

$$R \geq Q_d + Q_l + \sum_i Q_i \quad (8)$$

Where Q_d is the effect of dead load, Q_l is the effect of live load, and Q_i is the effect of load i.

Eq. (8) applies to design as well as evaluation. In the bridge evaluation process, maximum allowable live load needs to be determined. After rearranging the above equation, the maximum allowable live load will become:

$$Q_l \leq R - \left(Q_d + \sum_i Q_i\right) \quad (9)$$

Maintenance engineers always question whether a fully loaded vehicle (rating vehicle) can be allowed on the bridge and, if not, what portion of the rating vehicle could be allowed on a bridge. The portion of the rating vehicle will be given by the ratio between the available capacity for live load effect and the effect of the rating vehicle. This ratio is called the rating factor (RF).

$$RF = \frac{\text{Available capacity for the live load effect}}{\text{Rating vehicle loaddemand}} = \frac{R - \left(Q_d + \sum_i Q_i\right)}{Q_l}$$

When the rating factor equals or exceeds unity, the bridge is capable of carrying the rating vehicle. On the other hand, when the rating factor is less than unity the bridge may be overstressed while carrying the rating vehicle.

The capacity of a member is usually independent of the live load demand. Thus, Eq. (10) is generally a linear expression. However, there are cases where the capacity of a member dependent on the live load forces. For example, available moment capacity depends on the total axial load in biaxial bending members. In a biaxially loaded member, the Eq. (10) will be a second-order expression.

Thermal, wind, and hydraulic loads may be neglected in the evaluation process because the likelihood of occurrence of extreme values during the relatively short live-load loading is small. Thus, the effects of the dead and live loads are the only two loads considered in the evaluation process.

Rating Philosophies

During the structural evaluation process, the location and type of critical failure modes are first identified; Eq. (10) is then solved for each of these potential failures. Although the concept of evaluation is the same, the mathematical relationship of this basic equation for allowable stress design (ASD), load factor design (LFD), and Load and resistance factor design (LRFD) differs. Since the resistance and load effect can never be established with certainty, engineers use safety factors to give adequate assurance against failure. ASD includes safety factors in the form of allowable stresses of the material. LFD considers the safety factors in the form of load factors to account for the uncertainty of the loadings and resistance factors to account for the uncertainty of structural response. LRFD treats safety factors in the form of load and resistance factors that are based on the probability of the loadings and resistances.

The LRFR method was first introduced in the AASHTO Guide Manual for Condition Evaluation and Load and Resistance Factor Rating (LRFR) of Highway Bridges in 2003. The Guide Manual further evolved into the AASHTO Manual for Bridge Evaluation (MBE), 1st Edition, 2008 and the 2nd Edition of the MBE published in 2011[4]. Even though the MBE includes all three analytical load rating methods (ASR, LFR and LRFR), the LRFR method is considered the most advanced. It is a reliability based method for bridge live load capacity evaluation.

For ASD, the rating factor expression Eq. (10) can be written as:

$$RF = \frac{R - \left(\sum D + \sum_i L_i(1+\mathrm{I})\right)}{L(1+\mathrm{IM})} \tag{11}$$

For LFD, the rating factor expression Eq. (10) can be written as:

$$RF = \frac{\phi R_n - \sum \gamma_D D - \sum_{i=1}^{n} \gamma_{Li}\,\mathrm{L_i}(1+\mathrm{I})}{\gamma_L\,\mathrm{L}(1+\mathrm{IM})} \tag{12}$$

For LFRD, the rating factor expression Eq. (10) can be written as:

$$RF = \frac{\phi R_n - \sum \gamma_D D - \sum_{i=1}^{n} \gamma_{Li}\,\mathrm{L_i}(1+\mathrm{I})}{\gamma_L\,\mathrm{L}(1+\mathrm{IM})} \tag{13}$$

where R is the allowable stress of the member; ϕR_n is nominal resistance; D is the effect of dead loads; L_i is the live load effect for load i other than the rating vehicle; L the nominal live load effect of the rating vehicle; I is the impact factor for the live load effect; γ_D, γ_{Li}, and γ_L are dead and live load factors, respectively. [6]

Load rating methodology

Bridge design and rating are similar in the overall approach, but differ in several aspects. LRFD design method was calibrated for a reliability index of 3.5 for strength limit states and requires checking strength and service limit states to ensure serviceability and durability for a service life of 75 years with limited maintenance. Bridge ratings generally require the Engineer to consider a wider range of variables than bridge design. [5, 8]

The added cost of overly conservative evaluation standards would be prohibitive, since load restrictions, rehabilitation and replacement would increase. Therefore, the LRFR method adopted two levels of reliability for different rating vehicles with different length of exposure duration (design life for design load rating and inspection interval for legal load rating). Design load rating (HL-93 live loading) includes inventory level rating with the same target reliability index of 3.5 as used in design. It is primarily used to compare an existing bridge to a new design. Operating level rating of the design load is based on a reduced reliability index of 2.5, mainly served as a screening tool for legal load rating.

The load factor rating design loads do not adequately represent current loads on the highways and do not provide a uniform safety level for various bridge types and span lengths. Therefore, legal load calculations are commonly used to ensure the structural integrity of public bridges. Three AASHTO legal loads produce controlling moment and shear reactions for the short, medium, and long spans respectively. AASHTO MBE includes some common vehicle types such as the Routine Commercial Vehicles Type 3, 3S2 and 3-3, and Specialized Hauling Vehicles SU4, SU5, SU6 and SU7. AASHTO legal loads are used in load rating calculations.

Legal load rating recognizes a shorter duration of exposure corresponding to the routine inspection cycle. For a balance between reliability and economy, a lower target reliability of 2.5 has been chosen for legal load rating at the strength limit state. Application of serviceability limit states is done on a more selective basis than prescribed for design. The main purpose of legal load ratings is to determine load posting needs.

Permit load rating is to ensure the safe operation of highway bridges by evaluating the bridge capacities under over-weight vehicles requiring a permit. For annual routine permits and escorted single trip permits, are liability index of 2.5 was used. For single trip and multiple trip special permits allowing the permit vehicles to mix with traffic, a reliability index of 3.5 was selected:

$$RF = \frac{C - \gamma_{DC}.DC - \gamma_{DW}.DW \pm \gamma_P.P}{\gamma_L.LL(1+IM)} \quad (14)$$

For the Strength Limit States:

- $C = \varphi_C \varphi_S \varphi R_n$
- $\varphi_C \varphi_S \geq 0.85$

For the Service Limit States: $C = f_R$.

RF denotes the Rating Factor. C is the capacity, equal to the allowable stress f_R or the factored member resistance. R_n represents the nominal member resistance in the LRFD code and computed from the as inspected condition. DC, DW, PL, LL and IM denote the load effects due to weight of structural components and attachments, weight of wearing surface and utilities, other permanent loads, live load, and dynamic allowance, respectively γ_{DC}, γ_{DW}, γ_{PL} and γ_{LL} are the corresponding load factors, φ_c, φ_s and φ are the condition factor, system factor and resistance factor, respectively.

Condition factor

The condition factor, φ_c is to account for the increase dun certainty in the capacity of deteriorated members and the likely increased future deterioration of these members between inspection cycles. φ_c varies from 0.85 to 1.0 depending on the structural condition.

Table 3. *Condition factor*

Structural Condition of Member	Super structure Condition Rating (SI & A Item 59)	Condition Factor, φ_c
Good or Satisfactory	6 or Higher	1.00
Fair	5	0.95
Poor	4 or Lower	0.85

System factor

The system factor, φ_s is to account for the level of redundancy of the complete superstructure system. φ_s corresponds to the load factor modifier for redundancy in the LRFD Specifications.

Table 4. *System factor for flexural and axial effects*

Super structure Type	System Factor, φ_S
Welded members in two-girder/truss/arch bridges	0.85
Riveted members in two-girder/truss/arch bridges	0.90
Multiple eye bar members in truss bridges	0.90
Three-girder bridges with girder spacing 6 ft (1.83m)	0.85
Four-girder bridges with girder spacing ≤ 4 ft (1.22m)	0.95
All other girder bridges and slab bridges	1
Floor beams with spacing >12 ft (3.66m) and non-continuous stringers	0.85
Redundant stringer subsystems between floor beams	1

Loads

All permanent loads shall be considered in the load ratings. In addition to dead loads, pre-stressing/post-tensioningandanylockedinforcesduringconstructionshould be included in the calculation. If the secondary load effects from creep and shrinkage will reduce the load ratings, such effects should also be considered for some types of bridges such as segmental concrete bridges.

For design load rating, the design live load model of HL-93 specified in the LRFD Specifications shall be used. For legal load rating, load ratings should be conducted for AASHTO legal loads. For permit load rating, the actual permit truck shall be used in the load rating analysis.

For different load ratings, different dynamic allowance may be used per the MBE, considering the riding surface roughness and vehicle travelling speed. However, a dynamic allowance of 0.3 shall not be reduced for design load rating. The load factors to be used in the load rating are specified in MBE 2nd Edition.

Table 5. *Live load factors*

Traffic Volume (One direction)	Load Factor for Type 3, Type 3 S2, Type 3-3 and Lane Loads
Unknown	1.8
ADTT ≥ 5000	1.8
ADTT =1000	1.65
ADTT ≤ 100	1.4

Linear interpolation is permitted for other *ADTT*.

Rating procedure

In load rating a bridge, the structural condition and extent of deterioration of structural members should be considered in the computation of the load effects and the capacities. Whenever a change in structural condition or loadings occurs and the change reduces the live load carrying capacity of the bridge, a re-rating should be performed.

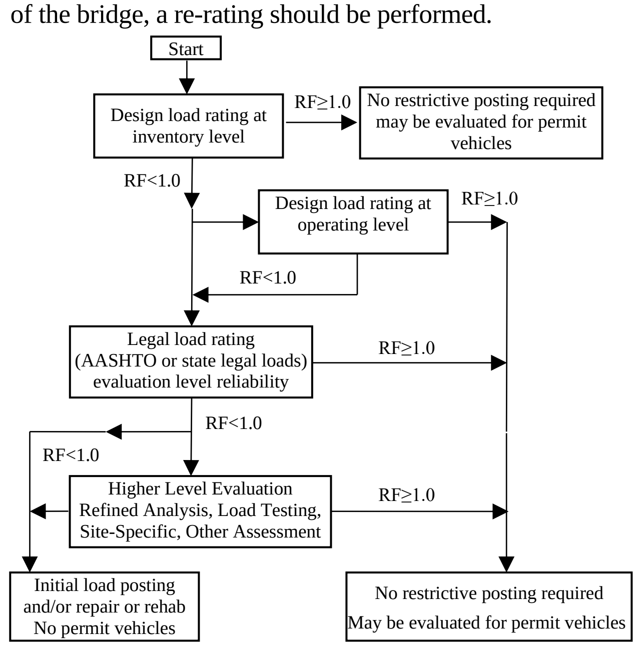


Figure 4. *Load and resistance factor rating flow char*

In the LRFR, the load rating procedures are structured to be performed in a sequential manner, starting with design load rating. In addition to fulfilling the NBI reporting required by the NBIS, it also serves as a screening. Load rating for AASHTO legal loads is required only when the load rating factor of the design load rating is lower than 1.0. Furthermore, only bridges that pass the load rating for AASHTO legal loads should be evaluated for overweight permits. Otherwise, the bridge should be posted or closed.

Example

This example is to demonstrate the LRFR through rating a simple span precast prestressed concrete bridge. The bridge was built in 1981. Figure 5 shows typical section of this bridge. The rating below calculation is for an interior girder.

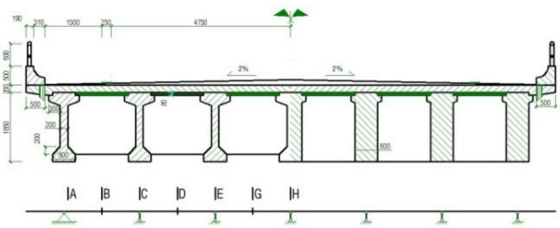


Figure 5. *Framing and typical section*

Span length: (37 m).

Prestressed concrete I girders spaced at (6 x S=12 m). 200 mm concrete deck.

Prestressing steel: Low-relaxation 12.7 mm; Grade 270.

Yield strength: f_{py}=1674 MPa.

Tensile strength: f_{pu}=1860 MPa.

Concrete–f'$_{c}$=40 MPa.

Concrete–Deck: f'$_{c}$=40 MPa.

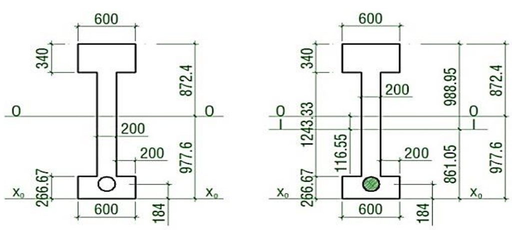
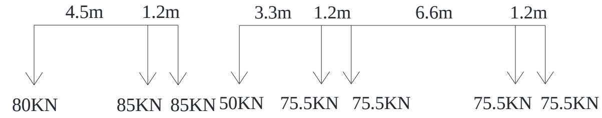


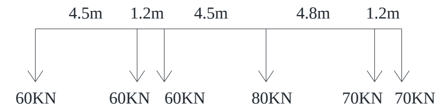
Figure 5. *Cross beam*

Design load: HL-93,

Legal loads: AASHTO Type 3, 3S2 and 3-3.



Load type 3 Load type 3S2



Load type 3-3

Figure 6. *Legal loads [8]*

As an illustrative example, only flexural capacity for Strength I and flexural stress for Service III limit states are included. The live load factors are as follows,

γ_{LL}=1.75 for Inventory level of design load rating.

γ_{LL}=1.35 for Operating level of design load rating.

γ_{LL}=1.8 for unknown ADTT and AASHTO Type 3, 3S2 and 3-3.

The results are shown in Table 6 below. Note that the shaded boxes are optional. Based on the results, there is no need to post this bridge for strength. However, State may post it in accordance with the serviceability (Service III).

The recommended posting procedure outlined in the LRFR calls for bridges to be rated at the legal load level under the legal load truck in question. If the rating factor from the analysis is greater than one, the bridge does not need to be posted for the given truck. If the rating factor is between 0.3 and 1.0, the AASHTO LRFR recommends the following safe posting load based on the rating factor:

$$\text{Safe posting load} = \frac{w}{0.7}(RF - 0.3) \tag{15}$$

If the rating factor from the legal load analysis is below 0.3, the AASHTO LRFR recommends that the legal truck used in the analysis not be allowed to cross the bridge. When the rating factors for all three of the AASHTO standard legal loads is below 0.3, the bridge should be considered for closure. [2]

Table 6. *Load rating results*

Load Rating Type	Load Type		Live Load Effects		Flexure RF		Controlling Rating	
			$M_{LL(KN.m)}$	f_{LL}(Mpa)	Strength I	Service III	RF	RT (tons)
Design Load Rating	HL-93	Inventory	4326.25	-7.25	0.82	0.74	0.74	-
		Operating	4326.25	-7.25	1.11		1.11	-
Legal Load Rating	Routine Commercial Vehicles	Type 3	2415.62	-4.02	1.45	1.20	1.2	30
		Type 3S2	3210.50	-5.17	1.35	1.13	1.13	40.68
		Type 3-3	3102.42	- 4.98	1.38	1.02	1.02	40.8

4. Conclusion

The following conclusions and comments can be drawn from this study:

LRFR is a reliability-based method for evaluating the bridge live load capacity. The LRFR method offers greater consistency and uniformity in reliability.

This paper provides an overview of the requirements of load rating bridges; the basic concept of structural reliability used in calibration of the Load and Resistance Factor Design (LRFD) and Rating (LRFR) method.

Evaluation and determine of allowable loads on a bridge.

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