LRFD Method of Bridge Design

A general statement for assuring safety in engineering design is that the resistance of the components provided exceed the demands put on them by applied loads, that is:

$$Resistance\ (R) \geq Applied\ Loads\ (Q)$$

To account for the variability of both sides of the equation, the resistance side is multiplying by a statistically based resistance factor (ϕ), whose value is usually less than one, and the applied load side is multiplying by a statistically based load factor (γ), whose value is usually greater than one. Because the load effect at a particular limit state involves a combination of different load types (Q_i) that have different degrees of predictability, the load effect is represented by a summation of $(\gamma_i Q_i)$ values. If nominal resistance is given by (R_n), the safety criterion is:

$$\phi R_n \geq \sum \gamma_i Q_i$$

Since the above equation involves both load factors and resistance factors. The design method is called Load Resistance Factor Design (LRFD).

The resistance factor (ϕ) for a particular limit state must account for the uncertainties in:

- Material properties
- Strength predicting equations
- Workmanship
- Quality control
- Failure consequence.

Also, the load factor (γ_i), for a particular load type must consider the uncertainties in:

- Loads magnitude
- Loads arrangement (positions)
- Possible loads combinations.

In selecting resistance factors and load factors for bridges, probability theory has been applied to data on strength of materials and statistics on weights of materials and vehicular loads.

Advantages of LRFD Method

- Account for variability in both resistance and load.
- Achieves fairly uniform levels of safety for different limit states and bridge types without involving a probability or statistical analysis.
- Provides a rational and consistent method of design.
- Provides consistency with other design specifications (ACI, AISC, …) that are familiar to engineers and new graduates.

Disadvantages of LRFD Method

- Requires a change in design philosophy (from previous AASHTO methods).
- Requires an understanding of the basic concepts of probability and statistics.
- Requires availability of sufficient statistical data and probabilistic design algorithms to make adjustments in resistance factors.

Limit States

A limit state is a condition beyond which a bridge system or bridge component cases to fulfill the function for which it is designed. In LRFD, there are four main cases of limit states to complete the overall calculation to design and check the bridge adequacy and functionality. These cases are:

- ***Strength Limit States***
  - Strength I: basic load combination relating to the normal vehicular use of the bridge without wind.
  - Strength II: load combination relating to the use of the bridge by owner-specified special design vehicles, evaluation permit vehicles, or both without wind.
  - Strength III: load combination relating to the bridge exposed to wind velocity exceeding 90 km/hr.
  - Strength IV: load combination relating to very high dead load to live load force effect ratios.
  - Strength V: load combination relating to normal vehicular use of the bridge with wind velocity of 90 km/hr.

- ***Extreme Event Limit States***
  - Extreme Event I: load combination including earthquake.
  - Extreme Event II: load combination relating to ice load, collision by vessels and vehicles.

- ***Service Limit States***
  - Service I: load combination relating to the normal operational use of the bridge with a 90 km/hr. wind and all loads taken at their nominal values. Also, used for live load deflection control, crack width and investigation of slope stability.
  - Service II: load combination intended to control yielding of steel structures and slip of slip-critical connections due to vehicular live load.
  - Service III: for longitudinal analysis of tension in prestressed concrete superstructures with the objective of crack control and to principal tension in the webs of segmental concrete girders.
  - Service IV: load combination relating only to tension in prestressed concrete columns with the objective of crack control.

- ***Fatigue and Fracture Limit States***
  - Fatigue I: load combination relating to infinite load-induced fatigue life.
  - Fatigue II: load combination relating to finite load-induced fatigue life.

The basic LRFD design expression in AASHTO Bridge specifications that must be satisfied for all limit states, both global and local, shall be taken as:

$R_r \geq Q_u$

$\phi R_n \geq \sum \eta_i \gamma_i Q_i$

The additional parameter (η_i) is known as load modifier which is incorporated to consider ductility (η_D), redundancy (η_R) and operational importance (η_I) of the bridge. It is given for loads for which maximum and minimum values of (γ_i) are approximated by:

$\eta_i = \eta_D \eta_R \eta_I \geq 0.95$ [for maximum value of load]

$\eta_i = 1/\eta_D \eta_R \eta_I \leq 1.05$ [for minimum value of load]

For ductility, the bridge structural system shall be proportioned and detailed to ensure the development of significant and visible inelastic deformations at the strength and extreme event limit states before failure. The value of (η_D) for various limit states is specified as:

- For the strength limit state:
  - $\eta_D \geq 1.05$ [nonductile components and connections]
    $= 1.00$ [conventional designs and details complying with these specifications]
    ≥ 0.95 [additional ductility-enhancing components and connections]
- For all other limit states:
  - $\eta_D = 1.00$

For redundancy, the main elements and components whose failure is expected to cause bridge collapse shall be designated as failure-critical and the associated structural system as nonredundant. Whereas, those elements and components whose failure is not expected to cause bridge collapse shall be designated as nonfailure-critical and the associated structural system as redundant. The value of (η_R) for various limit states is specified as:

- For the strength limit state:
  - $\eta_R \geq 1.05$ [nonredundant members]
    $= 1.00$ [conventional levels of redundancy]
    ≥ 0.95 [exceptional levels of redundancy]
- For all other limit states:
  - $\eta_R = 1.00$

The operational importance is applied to the strength and extreme event limit states only. The owner may declare a bridge or any structural component and connection thereof to be of operational importance. The value of (η_I) for various limit states is specified as:

- For the strength limit state:
  - $\eta_I \geq 1.05$ [important bridges]
    $= 1.00$ [typical bridges]
    ≥ 0.95 [relatively less important bridges]
- For all other limit states:
  - $\eta_I = 1.00$

Load Designation

There is a wide range of loads and forces act on bridges. Depending on the bridge type, location and function, the designation loads can be determined. Generally, the design loads are classified into two main groups they are permanent and transient loads:

- ***Permanent Loads***
  - CR: force effects due to creep
  - DD: Downdrag force
  - DC: dead load of structural components and nonstructural attachments
  - DW: dead load of wearing surfaces and utilities
  - EH: horizontal earth pressure load
  - EL: miscellaneous locked-in force effects resulting from the construction process including jacking apart of cantilevers in segmental construction
  - ES: earth surcharge load
  - EV: vertical pressure from dead load of earth fill
  - PS: secondary forces from post-tensioning
  - SH: force effects due to shrinkage

- ***Transient Loads***
  - BL: blast loading
  - BR: vehicular braking force
  - CE: vehicular centrifugal force
  - CT: vehicular collision force
  - CV: vessel collision force
  - EQ: earthquake load
  - FR: friction load
  - IC: ice load
  - IM: vehicular dynamic load allowance
  - LL: vehicular live load
  - LS: live load Surcharge
  - PL: pedestrian Live load
  - SE: force effects due to settlement
  - TG: force effects due to temperature gradient
  - TU: force effects due to uniform temperature
  - WA: water load and stream pressure
  - WL: wind on live load
  - WS: wind load on structure

Load Combinations and Load Factors

The total factored load (Q) effect shall be taken as:

$$Q_u = \sum \eta_i \gamma_i Q_i$$

where:

η_i: load modifier

γ_i: load factors

Q_i: force effects

The values of (γ_i) depend on the case of design or analysis. ASSHTO specifications adopted these values as tabulated herein.

Table 3.4.1-1: Load Combinations and Load Factors

Load Combination Limit State	*DC DD DW EH EV ES EL PS CR SH*	*LL IM CE BR PL LS*	*WA*	*WS*	*WL*	*FR*	*TU*	*TG*	*SE*	Use One of These at a Time				
										EQ	*BL*	*IC*	*CT*	*CV*
Strength I (unless noted)	γ_p	1.75	1.00	–	–	1.00	0.50/1.20	γ_{TG}	γ_{SE}	–	–	–	–	–
Strength II	γ_p	1.35	1.00	–	–	1.00	0.50/1.20	γ_{TG}	γ_{SE}	–	–	–	–	–
Strength III	γ_p	–	1.00	1.00	–	1.00	0.50/1.20	γ_{TG}	γ_{SE}	–	–	–	–	–
Strength IV	γ_p	–	1.00	–	–	1.00	0.50/1.20	–	–	–	–	–	–	–
Strength V	γ_p	1.35	1.00	1.00	1.00	1.00	0.50/1.20	γ_{TG}	γ_{SE}	–	–	–	–	–
Extreme Event I	1.00	γ_{EQ}	1.00	–	–	1.00	–	–	–	1.00	–	–	–	–
Extreme Event II	1.00	0.50	1.00	–	–	1.00	–	–	–	–	1.00	1.00	1.00	1.00
Service I	1.00	1.00	1.00	1.00	1.00	1.00	1.00/1.20	γ_{TG}	γ_{SE}	–	–	–	–	–
Service II	1.00	1.30	1.00	–	–	1.00	1.00/1.20	–	–	–	–	–	–	–
Service III	1.00	γ_{LL}	1.00	–	–	1.00	1.00/1.20	γ_{TG}	γ_{SE}	–	–	–	–	–
Service IV	1.00	–	1.00	1.00	–	1.00	1.00/1.20	–	1.00	–	–	–	–	–
Fatigue I LL, IM & CE only	–	1.75	–	–	–	–	–	–	–	–	–	–	–	–
Fatigue II LL, IM & CE only	–	0.80	–	–	–	–	–	–	–	–	–	–	–	–

AASHTO Specifications

Table 3.4.1-2: Load Factors for Permanent Loads

Type of Load, Foundation Type and Method Used to Calculate Downdrag			Load Factor (γ_P)	
			Maximum	**Minimum**
DC	Strength IV only		1.50	0.90
	Other Cases		1.25	0.90
DD	Piles, α Tomlinson Method		1.40	0.25
	Piles, λ Method		1.05	0.30
	Drilled shafts, O'Neill and Reese (2010) Method		1.25	0.35
DW			1.50	0.65
EH	Active		1.50	0.90
	At-Rest		1.35	0.90
	AEP for anchored walls		1.35	N/A
EL			1.00	1.00
EV	Overall Stability		1.00	N/A
	Retaining Walls and Abutments		1.35	1.00
	Rigid Buried Structure		1.30	0.90
	Rigid Frames		1.35	0.90
	Flexible Buried Structures	Metal Box and Structural Plate Culverts with Deep Corrugations	1.50	0.90
		Thermoplastic Culverts	1.30	0.90
		All Others	1.95	0.90
ES			1.50	0.75

Table 3.4.1-3: Load Factors for Permanent Loads Due to Superimposed Deformation

Bridge Component		Load Factor (γ_P)	
		PS	CR, SH
Segmental Superstructures Supported by Concrete Substructures		1.00	γ_P for DC
Non-Segmental Concrete Superstructures		1.00	1.00
Substructures Supporting Non-Segmental Superstructures	Using I_g	0.50	0.50
	Using I_e	1.00	1.00
Steel Substructures		1.00	1.00

Table 3.4.1-4: Load Factors for Service III Load Combination

Bridge Component	Load Factor (γ_{LL})
Prestressed Concrete Components Designed Using the Refined Estimates of Time-Dependent Losses in Conjunction with Taking Advantage of the Elastic gain	1.00
All Other Prestressed Concrete Components	0.80