NATIONAL TRANSPORTATION SAFETY BOARD

Bridge Factors Factual Report Attachment 54 – AASHTO Load and Resistance Factor Design (LRFD) Bridge Design Specifications, 7th Edition, 2014, with 2015 Interims, Guidance on Redundancy

Miami, FL

HWY18MH009

(7 pages)

where:

γ_i = load factor: a statistically based multiplier applied to force effects

ϕ = resistance factor: a statistically based multiplier applied to nominal resistance, as specified in Sections 5, 6, 7, 8, 10, 11, and 12

η_i = load modifier: a factor relating to ductility, redundancy, and operational classification

η_D = a factor relating to ductility, as specified in Article 1.3.3

η_R = a factor relating to redundancy as specified in Article 1.3.4

η_I = a factor relating to operational classification as specified in Article 1.3.5

Q_i = force effect

R_n = nominal resistance

R_r = factored resistance: ϕR_n

The influence of η on the girder reliability index, β, can be estimated by observing its effect on the minimum values of β calculated in a database of girder-type bridges. Cellular structures and foundations were not a part of the database; only individual member reliability was considered. For discussion purposes, the girder bridge data used in the calibration of these Specifications was modified by multiplying the total factored loads by η = 0.95, 1.0, 1.05, and 1.10. The resulting minimum values of β for 95 combinations of span, spacing, and type of construction were determined to be approximately 3.0, 3.5, 3.8, and 4.0, respectively. In other words, using $\eta > 1.0$ relates to a β higher than 3.5.

A further approximate representation of the effect of η values can be obtained by considering the percent of random normal data less than or equal to the mean value plus $\lambda\ \sigma$, where λ is a multiplier, and σ is the standard deviation of the data. If λ is taken as 3.0, 3.5, 3.8, and 4.0, the percent of values less than or equal to the mean value plus $\lambda\ \sigma$ would be about 99.865 percent, 99.977 percent, 99.993 percent, and 99.997 percent, respectively.

The Strength I Limit State in the *AASHTO LRFD Design Specifications* has been calibrated for a target reliability index of 3.5 with a corresponding probability of exceedance of 2.0E-04 during the 75-yr design life of the bridge. This 75-yr reliability is equivalent to an annual probability of exceedance of 2.7E-06 with a corresponding annual target reliability index of 4.6. Similar calibration efforts for the Service Limit States are underway. Return periods for extreme events are often based on annual probability of exceedance and caution must be used when comparing reliability indices of various limit states.

1.3.2.2—Service Limit State

The service limit state shall be taken as restrictions on stress, deformation, and crack width under regular service conditions.

C1.3.2.2

The service limit state provides certain experience-related provisions that cannot always be derived solely from strength or statistical considerations.

1.3.2.3—Fatigue and Fracture Limit State

The fatigue limit state shall be taken as restrictions on stress range as a result of a single design truck occurring at the number of expected stress range cycles.

The fracture limit state shall be taken as a set of material toughness requirements of the AASHTO Materials Specifications.

C1.3.2.3

The fatigue limit state is intended to limit crack growth under repetitive loads to prevent fracture during the design life of the bridge.

1.3.2.4—Strength Limit State

Strength limit state shall be taken to ensure that strength and stability, both local and global, are provided to resist the specified statistically significant load combinations that a bridge is expected to experience in its design life.

C1.3.2.4

The strength limit state considers stability or yielding of each structural element. If the resistance of any element, including splices and connections, is exceeded, it is assumed that the bridge resistance has been exceeded. In fact, in multigirder cross-sections there is significant elastic reserve capacity in almost all such bridges beyond such a load level. The live load cannot be positioned to maximize

1.3.2.5—Extreme Event Limit States

The extreme event limit state shall be taken to ensure the structural survival of a bridge during a major earthquake or flood, or when collided by a vessel, vehicle, or ice flow, possibly under scoured conditions.

1.3.3—Ductility

The structural system of a bridge 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.

Energy-dissipating devices may be substituted for conventional ductile earthquake resisting systems and the associated methodology addressed in these Specifications or in the *AASHTO Guide Specifications for Seismic Design of Bridges.*

For the strength limit state:

$\eta_D \geq$ 1.05 for nonductile components and connections

$=$ 1.00 for conventional designs and details complying with these Specifications

$\geq$ 0.95 for components and connections for which additional ductility-enhancing measures have been specified beyond those required by these Specifications

For all other limit states:

$\eta_D = 1.00$

the force effects on all parts of the cross-section simultaneously. Thus, the flexural resistance of the bridge cross-section typically exceeds the resistance required for the total live load that can be applied in the number of lanes available. Extensive distress and structural damage may occur under strength limit state, but overall structural integrity is expected to be maintained.

C1.3.2.5

Extreme event limit states are considered to be unique occurrences whose return period may be significantly greater than the design life of the bridge.

C1.3.3

The response of structural components or connections beyond the elastic limit can be characterized by either brittle or ductile behavior. Brittle behavior is undesirable because it implies the sudden loss of load-carrying capacity immediately when the elastic limit is exceeded. Ductile behavior is characterized by significant inelastic deformations before any loss of load-carrying capacity occurs. Ductile behavior provides warning of structural failure by large inelastic deformations. Under repeated seismic loading, large reversed cycles of inelastic deformation dissipate energy and have a beneficial effect on structural survival.

If, by means of confinement or other measures, a structural component or connection made of brittle materials can sustain inelastic deformations without significant loss of load-carrying capacity, this component can be considered ductile. Such ductile performance shall be verified by testing.

In order to achieve adequate inelastic behavior the system should have a sufficient number of ductile members and either:

- Joints and connections that are also ductile and can provide energy dissipation without loss of capacity; or
- Joints and connections that have sufficient excess strength so as to assure that the inelastic response occurs at the locations designed to provide ductile, energy absorbing response.

1.3.4—Redundancy

Multiple-load-path and continuous structures should be used unless there are compelling reasons not to use them.

For the strength limit state:

$\eta_R \geq$ 1.05 for nonredundant members

$=$ 1.00 for conventional levels of redundancy, foundation elements where ϕ already accounts for redundancy as specified in Article 10.5

$\geq$ 0.95 for exceptional levels of redundancy beyond girder continuity and a torsionally-closed cross-section

Statically ductile, but dynamically nonductile response characteristics should be avoided. Examples of this behavior are shear and bond failures in concrete members and loss of composite action in flexural components.

Past experience indicates that typical components designed in accordance with these provisions generally exhibit adequate ductility. Connection and joints require special attention to detailing and the provision of load paths.

The Owner may specify a minimum ductility factor as an assurance that ductile failure modes will be obtained. The factor may be defined as:

$$\mu = \frac{\Delta_u}{\Delta_y} \qquad \text{(C1.3.3-1)}$$

where:

Δ_u = deformation at ultimate

Δ_y = deformation at the elastic limit

The ductility capacity of structural components or connections may either be established by full- or large-scale testing or with analytical models based on documented material behavior. The ductility capacity for a structural system may be determined by integrating local deformations over the entire structural system.

The special requirements for energy dissipating devices are imposed because of the rigorous demands placed on these components.

C1.3.4

For each load combination and limit state under consideration, member redundancy classification (redundant or nonredundant) should be based upon the member contribution to the bridge safety. Several redundancy measures have been proposed (Frangopol and Nakib, 1991).

Single-cell boxes and single-column bents may be considered nonredundant at the Owner's discretion. For prestressed concrete boxes, the number of tendons in each web should be taken into consideration. For steel cross-sections and fracture-critical considerations, see Section 6.

The Manual for Bridge Evaluation (2008) defines bridge redundancy as "the capability of a bridge structural system to carry loads after damage to or the failure of one or more of its members." System factors are provided for post-tensioned segmental concrete box girder bridges in Appendix E of the Guide Manual.

System reliability encompasses redundancy by considering the system of interconnected components and members. Rupture or yielding of an individual component may or may not mean collapse or failure of the whole structure or system (Nowak, 2000). Reliability indices for

For all other limit states:

η_R = 1.00

1.3.5—Operational Importance

This Article shall apply 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 priority.

For the strength limit state:

$\eta_I \geq$ 1.05 for critical or essential bridges

$=$ 1.00 for typical bridges

$\geq$ 0.95 for relatively less important bridges.

For all other limit states:

η_I = 1.00

entire systems are a subject of ongoing research and are anticipated to encompass ductility, redundancy, and member correlation.

C1.3.5

Such classification should be done by personnel responsible for the affected transportation network and knowledgeable of its operational needs. The definition of operational priority may differ from Owner to Owner and network to network. Guidelines for classifying critical or essential bridges are as follows:

- Bridges that are required to be open to all traffic once inspected after the design event and are usable by emergency vehicles and for security, defense, economic, or secondary life safety purposes immediately after the design event.
- Bridges that should, as a minimum, be open to emergency vehicles and for security, defense, or economic purposes after the design event, and open to all traffic within days after that event.

Owner-classified bridges may use a value for $\eta < 1.0$ based on ADTT, span length, available detour length, or other rationale to use less stringent criteria.

1.4—REFERENCES

AASHTO. 2010. *AASHTO LRFD Bridge Construction Specifications*, Third Edition with Interims, LRFDCONS-3-M. American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO. 2011. *AASHTO Guide Specifications for LRFD Seismic Bridge Design*, Second Edition, LRFDSEIS-2. American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO. 2011. *The Manual for Bridge Evaluation*, Second Edition with Interim, MBE-2-M. American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO. 2013. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, 33rd Edition, HM-33. American Association of State Highway and Transportation Officials, Washington, DC.

Frangopol, D. M., and R. Nakib. 1991. "Redundancy in Highway Bridges." *Engineering Journal*, American Institute of Steel Construction, Chicago, IL, Vol. 28, No. 1, pp. 45–50.

Open Section—A flexural member having a cross-section which has no enclosed cell. An open-section member resists torsion primarily by nonuniform torsion, which causes normal stresses at the flange tips.

Orthotropic Deck—A deck made of a steel plate stiffened with open or closed steel ribs welded to the underside of a steel plate.

Permanent Deflection—A type of inelastic action in which a deflection remains in a component or system after the load is removed.

Pier—A column or connected group of columns or other configuration designed to be an interior support for a bridge superstructure.

Pitch—The distance between the centers of adjacent bolt holes or shear connectors along the line of force.

Plastic Analysis—Determination of load effects on members and connections based on the assumption of rigid-plastic behavior; i.e., that equilibrium is satisfied throughout the structure and yield is not exceeded anywhere. Second-order effects may need to be considered.

Plastic Hinge—A yielded zone which forms in a structural member when the plastic moment is attained. The beam is assumed to rotate as if hinged, except that the plastic moment capacity is maintained within the hinge.

Plastic Moment—The resisting moment of a fully-yielded cross-section.

Plastic Strain—The difference between total strain and elastic strain.

Plastification—The process of successive yielding of fibers in the cross-section of a member as bending moment is increased.

Plate—A flat rolled product whose thickness exceeds 0.25 in.

Portal Frames—End transverse truss bracing or Vierendeel bracing to provide for stability and to resist wind or seismic loads.

Post-Buckling Resistance—The load that can be carried by a member or component after buckling.

Primary Member—A member designed to carry the internal forces determined from an analysis.

Prying Action—Lever action that exists in connections in which the line of application of the applied load is eccentric to the axis of the bolt, causing deformation of the fitting and an amplification of the axial force in the bolt.

Redistribution Moment—An internal moment caused by yielding in a continuous span bending component and held in equilibrium by external reactions.

Redistribution of Moments—A process that results from formation of inelastic deformations in continuous structures.

Redistribution Stress—The bending stress resulting from the redistribution moment.

Redundancy—The quality of a bridge that enables it to perform its design function in a damaged state.

Redundant Member—A member whose failure does not cause failure of the bridge.

Required Fatigue Life—A product of the single-lane average daily truck traffic, the number of cycles per truck passage, and the design life in days.

Residual Stress—The stresses that remain in an unloaded member or component after it has been formed into a finished product by cold bending, and/or cooling after rolling or welding.

Reverse Curvature Bending—A bending condition in which end moments on a member cause the member to assume an S shape.

Rigid Frame—A structure in which connections maintain the angular relationship between beam and column members under load.

St. Venant Torsion—That portion of the internal resisting torsion in a member producing only pure shear stresses on a cross-section, also referred to as pure torsion or uniform torsion.

Second-Order Analysis—Analysis in which equilibrium conditions are formulated on the deformed structure; that is, in which the deflected position of the structure is used in writing the equations of equilibrium.

Secondary Member—A member in which stress is not normally evaluated in the analysis.

Service Loads—Loads expected to be supported by the structure under normal usage.

Shape Factor—The ratio of the plastic moment to the yield moment, or the ratio of the plastic section modulus to the elastic section modulus.

Shear-Buckling Resistance—The maximum load that can be supported by a web plate without experiencing theoretical buckling due to shear.

Shear Connector—A mechanical device that prevents relative movements both normal and parallel to an interface.

Shear Flow—Shear force per unit width acting parallel to the edge of a plate element.

Shear Lag—Nonlinear distribution of normal stress across a component due to shear distortions.

Sheet—A flat rolled product whose thickness is between 0.006 and 0.25 in.

Single Curvature Bending—A deformed shape of a member in which the center of curvature is on the same side of the member throughout the unbraced length.

Skew Angle—The angle between the axis of support relative to a line normal to the longitudinal axis of the bridge, i.e. a zero-degree skew denotes a rectangular bridge.

Slab—A deck composed of concrete and reinforcement.

Slender Element Section—Cross-section of a compression member composed of plate components of sufficient slenderness such that local buckling in the elastic range will occur.

Slender Flange—For a composite section in negative flexure or a noncomposite section, a discretely braced compression flange with a slenderness at or above which the nominal flexural resistance is governed by elastic flange local buckling, provided that sufficient lateral bracing requirements are satisfied.

Slender Unbraced Length—For a composite section in negative flexure or a noncomposite section, the limiting unbraced length of a discretely braced compression flange at or above which the nominal flexural resistance is governed by elastic lateral torsional buckling.

Slender Web—For a composite section in negative flexure or a noncomposite section, a web with a slenderness at or above which the theoretical elastic bend-buckling stress in flexure is reached in the web prior to reaching the yield strength of the compression flange.

Slenderness Ratio—The ratio of the effective length of a member to the radius of gyration of the member cross-section, both with respect to the same axis of bending, or the full or partial width or depth of a component divided by its thickness.

Splice—A group of bolted connections, or a welded connection, sufficient to transfer the moment, shear, axial force, or torque between two structural elements joined at their ends to form a single, longer element.