4. STRUCTURAL ANALYSIS AND EVALUATION

The analysis of bridges and structures is a mixture of science and engineering judgment. In most cases, use simple models with conservative assumptions to arrive at the design forces for various elements. For example, for straight beam bridges with small skews, use beam line models with approximate distribution factors to arrive at the design moments, shears, and reactions. For more complex structures or for situations where refinement offers significant benefits, a more refined analysis (e.g., grillage or 3-D) might be justified. Situations where this might be appropriate include curved bridges, bridges with large skews, or when evaluating the critical element of a bridge with marginal live load capacity. If the designer believes the bridge analysis requires a grillage model or that a complex bridge component requires a 3D model, the designer shall, in conjunction with the State Bridge Design Engineer, determine the appropriate level of analysis and modelling.

In all but the most complex bridges, time-dependent behavior will not be modeled. The impacts of creep, shrinkage, and relaxation will be accounted for by using code prescribed equations for these effects. While time-dependent material effects are not modeled, designers and evaluators of continuous post-tensioned structures should include secondary moments due to post-tensioning in their analysis.

Satisfying force equilibrium and identifying a load path to adequately transfer the loads to the foundations is the primary analysis goal for designers.

The remainder of this section contains guidance on a variety of topics. Topics include quality control and quality assurance, load distribution, load rating, substructure fixity, and lastly, LRFD usage.

4.1 Design QC/QA Process

Engineering software and spreadsheets play an important role in the design of bridges. The Bridge Office evaluates and utilizes vendor software and develops spreadsheets to assist office personnel. This process does not remove the responsibility of the designer to verify (through hand calculations, other programs, past experience, etc.) that results are accurate, cost efficient, constructible, and reasonable. The Bridge Design Automation Committee evaluates programs that may be used by in-house designers and maintains a list of approved spreadsheets.

[4.4]

As part of the quality control process, all components of the design, whether designed by hand or using computer programs, must be checked by a second engineer. Any discrepancies between the results of the original design and the design check must be resolved as part of the quality control/quality assurance (QC/QA) process. Thorough checks for all designs are crucial. This goal is often more difficult to achieve when using vendor-supplied design products because of the user's inability to see the complete set of assumptions and computations within the software. Due to the varying intricacy of bridge elements, different levels of checking must be used.

Basic

Basic components are primarily designed by hand calculations, by a spreadsheet, or with a vendor-supplied design application. Examples of bridge elements that may be reviewed using a basic level check include, but are not limited to, abutments, splices, bearings, and most cases of prestressed concrete beams.

A basic level check may be done in one of three ways:

- an independent set of calculations
- a line-by-line check of calculations
- using software that has been validated for a similar situation.

An independent set of calculations may be done by hand, spreadsheet, or using design software. To be considered a fully independent set of calculations, the second set cannot use the same software package or spreadsheet as the first. A comparison of input, intermediate output and final output values from the design and independent check calculation packages is also required.

If the design is performed using design software, the checking engineer must perform a complete assessment of all input values and a review of the output to confirm a reasonable answer. For a line-by-line check, every line of calculations must be verified by the checking engineer.

If an independent set of calculations is not completed, the checking engineer must handwrite initials on each page of calculations, computer input, and computer output that has been reviewed to indicate that the check has been performed. Preprinted checker initials are not acceptable as part of the quality control process. This applies both to line-by-line checks and designs performed using validated software.

Validation of software used to perform basic level checks may be accomplished through hand calculations or by replication of the results of the design examples given in this manual, where such an example exists. Verification of each step in the design process must be done. Once validation of the software has been completed, the process specified under the basic check can be considered adequate. It is the designer's responsibility to verify that the validation that has been done remains current, i.e. that software changes are reviewed and current specification updates are included. The designer must include documentation in the calculation package stating that the software used has been validated.

Intermediate

Intermediate components are those that are designed using a software design package, but whose outputs cannot easily be verified using hand computations and spreadsheets. Bridge elements requiring an intermediate level check include, but are not limited to, piers, straight steel girders, steel box girders, and prestressed beams that are flared or have variable width overhangs.

Unlike software packages that fall under the basic level check, validation of design software used for an intermediate level check is impossible because of the variety or complexity of the bridge component. Although running the design example from this manual, where one is available, provides some assurance in the software, there remain too many potential variables unchecked. Therefore, the software cannot be adequately validated, and an independent analysis is required for this type of analysis. A comparison of input, intermediate output and final output values from the design and independent check calculation packages is also required. The check may be performed by a second software package or via hand calculations or a spreadsheet. Depending on the complexity of the design, a hand check may use moderate simplifying assumptions. Sound engineering judgment must be used in making those assumptions. Input values that must be checked include geometry and live load distribution factors. At a minimum, output values must be compared for section properties, dead load moments and shears, live load moments and shears, and code checks. The checking engineer need not examine each load case generated by a program; however, load cases should be reviewed to validate loads were correctly combined and applied to find the maximum effects. Determination of critical live load cases for checking should be accomplished by load patterning.

Complex

Complex bridge components are those that cannot reasonably be designed by hand or spreadsheet, even if moderate simplifications are made. Bridge elements that require a complex level check include, but are not limited to, concrete box girders, curved steel girders, and structures requiring a soil-structure interaction model.

The intricacies of these bridge elements require using two independent analyses with input and output compared at each stage of the design process. Verification of the results can only be completed using a second piece of software and comparing the modeling method, initial assumptions, and output results. A comparison of output values at each stage must be done, including, but not limited to, geometry, live load distribution, section properties, dead and live load moments and shears, and code checks.

4.2 Load Distribution

The LRFD Specifications encourage the use of either refined or approximate methods of analysis for determination of load distribution. The default analysis method for determination of the lateral load distribution for typical deck on beam bridges and slab span bridges is the approximate method of analysis given in the LRFD Specifications. Lateral live load distribution factors determined using the LRFD Specifications are dependent on multiple characteristics of each bridge and there are specific ranges of applicability for their use. Extending the application of such approximate methods beyond the limits requires sound and reasonable judgement. Otherwise refined analytical methods should be used.

[4.6.2]

4.2.1 Dead Load Distribution

Deck, Wearing Course, Future Wearing Surface, Railing, Barriers, and Medians

For beam bridges, the dead load of the deck is distributed to the beams based on their respective tributary widths. Superimposed dead loads (wearing course, future wearing surface, railings, barriers, and medians), with the exception of sidewalk loads, are to be distributed equally to all beam lines.

For concrete slab bridges (reinforced or post-tensioned) the weight of the barrier loads should be distributed to the edge strip. For design of the interior strip, the weight of the barriers should be distributed across the entire width of the slab and combined with other superimposed dead loads.

Sidewalks

Distribute sidewalk loads to the beams by simple distribution except when checking load case 2 as specified in Article 4.2.3 of this manual.

Miscellaneous Loads – Conduits, Sign Structure, etc.

Conduit loads supported by hangers attached to the deck should be distributed equally to all beams. Sign structures, architectural treatment panels, and sound walls, whose load acts entirely outside the exterior beam, should be assumed to be carried by the exterior beam.

4.2.2 Live Load Distribution

Equations and tables for live load distribution factors are provided in the LRFD Specifications.

4.2.2.1 Steel and Prestressed Concrete Beams

[4.6.2.2]

For typical beam bridges, use the live load distribution factor (LLDF) formulas provided in the LRFD Specifications for interior beam flexure (single lane, multiple lanes, and fatigue), and interior beam shear (single lane, multiple lanes, and fatigue). For exterior beams, use the lever rule and LLDF formulas to determine the amount of live load carried by the exterior beam. In addition, use the rigid cross section equation (LRFD C4.6.2.2.2d-1) for steel beam bridges. The number of diaphragms/cross frames found in steel beam bridges makes rigid cross-section rotation and deflection a valid behavior to consider. Use of the rigid cross section equation is not required for design of precast prestressed concrete exterior beams.

Unlike the Standard Specifications, the LRFD live load distribution factors (LLDF) for beam bridges are dependent on the stiffness of the components that make up the cross section [LRFD Equation 4.6.2.2.1-1]. Theoretically, the distribution factor changes for each change in cross section (at flange plate changes in plate girders, for example). However, this is more refinement than is necessary. For simple span structures a single LLDF (computed at midspan) may be used. For continuous structures, a single LLDF may be used for each positive moment region and for each negative moment region, with the moment regions defined by the dead load contraflexure points. For bridges with consistent geometry (same number of beam lines in each span, etc.) the largest positive moment LLDF may be used for all positive moment locations. Similarly, the largest negative moment LLDF may be used for all negative moment regions. Also note that for continuous structures, use the span length “L” as defined by LRFD Table 4.6.2.2.1-2 for LLDF calculations.

For skewed superstructures:

[4.6.2.2.2e]

- Apply the live load distribution reduction factor for moment per LRFD Article 4.6.2.2.2e.

[4.6.2.2.3c]

- Apply the live load distribution correction factor for shear to all beams and throughout the entire beam length.

4.2.2.2 Slab Spans and Timber Decks [4.6.2.3]

Design concrete slabs and timber decks using a one foot wide longitudinal strip. The LRFD Specifications provide equations for live load distribution factors (LLDF) that result in equivalent strip widths, E, that are assumed to carry one lane of traffic. Convert the equivalent strip width to a live load distribution factor for the unit strip by taking the reciprocal of the width.

$$LLDF = \frac{1}{E}$$

4.2.3 Sidewalk Pedestrian Live Load [3.6.1.6]

Unlike the Standard Specifications, no reduction in sidewalk pedestrian live load intensity based on span length and sidewalk width is provided in the LRFD Specifications.

1) Consider two loading cases when designing a beam bridge with a sidewalk: Use a pedestrian live load on the sidewalk equal to 0.075 ksf, and apply it in conjunction with a vehicular live load in the traffic lanes adjacent to the sidewalk. Use the lever rule to determine distribution of sidewalk dead load, pedestrian live load, and vehicular live load to outer beams.

2) Place vehicular live load on the sidewalk and in adjacent traffic lanes with no pedestrian live load on the sidewalk. For this load case, assume dead load, including sidewalk, is carried equally by all beams.

4.3 Load Rating

The bridge load rating determines the safe load carrying capacity. Ratings are calculated for a new bridge and are recalculated throughout the bridge's life as changes occur.

Unlike design, where only one benchmark or level of safety is used, two different levels have historically been used for load rating. These rating levels are referred to as the “inventory rating” and “operating rating”. The inventory rating corresponds to the factors of safety or levels of reliability associated with new bridge designs. The operating rating corresponds to slightly relaxed safety factors or reliability indices and is used for infrequent, regulated loads. Calculations for overload permit evaluations and for bridge weight postings are made at the operating level.

The Design Data block on the front sheet of a set of bridge plans should contain the LRFR HL-93 operating rating factor for the bridge.

When the bridge plan is to the point where all the essential information for the superstructure is shown, the plan should be sent to the Bridge Rating Unit. They will calculate the operating rating for the bridge.

Bridges designed for the local road system are generally prepared by the local agency and/or their consultants. It is the responsibility of the local agency to assure that ratings are calculated and reported to the Bridge Asset Data Management Unit.

Detailed information on load rating of bridges in Minnesota can be found in the *MnDOT Bridge Load Rating and Evaluation Manual*, found here: http://www.dot.state.mn.us/bridge/datamanagement.html

4.4 Substructure Fixity

The overall fixity of the bridge should be examined in detail for bridges on steep grades, moderate to severe curvature, or when the columns are tall or slender. The following guidelines for providing fixity at bearings should be followed.

For short bridges on steep grades, the downhill abutment should be fixed. For longer bridges the flexibility of each pier and its bearings need to be considered to determine the appropriate substructure units to fix.

If pier flexibility and geometry permit, a minimum of two fixed piers per expansion unit should be used. For very flexible piers, such as pile bents or slender columns, the expansion bearings may be redundant (the pier may move before the bearings begin to slide).

For typical prestressed I-beam bridges with two sets of bearings on each pier (per beam line), sufficient anchorage to the pier is provided by using one line of bearings with anchor rods at a fixed pier. For river piers and for spans over 145 feet, designers should fix both sets of bearings.

See Section 14 of this manual for additional guidance.

4.5 Structural Models

For redundant structures, the distribution of internal forces is dependent on member stiffnesses. Engineering judgement needs to be exercised when assigning member properties and boundary conditions to determine the internal forces of members.

Often a simplified method can be used to arrive at a solution. For example, instead of setting up a continuous beam model, design moments in pile bent pier caps can be determined in the following manner: Positive moment requirements can be determined by assuming simple spans between the supporting piles. The required negative moment capacity can be computed assuming a propped cantilever for the outside spans and fixed/fixed boundary conditions for the interior spans.

4.6 Design Methodology & Governing Specifications

The *AASHTO LRFD Bridge Design Specifications* are extensive, but do not cover all bridge types. In addition, they were not written for bridge rehabilitation projects. MnDOT policy regarding these topics is given below.

4.6.1 Pedestrian Bridges

Design pedestrian bridges in accordance with the *LRFD Guide Specifications for Design of Pedestrian Bridges*. The pedestrian live load specified in the *AASHTO LRFD Bridge Design Specifications* is only for vehicular bridges that carry pedestrian traffic. The pedestrian bridge guide specifications address the design of pedestrian bridges.

4.6.2 Repair Projects

When repairing existing bridges, it is often not economically feasible to design the repaired structure to meet all current design code requirements, including live load capacity. To help establish uniform procedures for use on bridge repair projects, MnDOT developed the *Bridge Preservation and Improvement Guidelines* (BPIG). These guidelines are updated at regular intervals and provide a systematic approach to planning and performing bridge preservation and rehabilitation projects. The BPIG also includes condition and cost criteria for bridge replacement projects, as well as policies for upgrading substandard features like barriers and end posts. Appropriate bridge design standards have been established based on investment level, along with expected outcomes in terms of slowed deterioration, improved condition, or service life extension.

Bridge repair projects include all major bridge preservation and rehabilitation projects, which are defined as:

- Major bridge preservation: These projects involve extensive bridge repairs intended to extend the service life of structures while maintaining their existing design features. Some examples include joint replacements, deck patching and overlays, barrier replacements, and bridge painting projects.

- Bridge rehabilitation: These projects involve repairing deficiencies in structures and improving their geometrics and/or load-carrying capacity. Some examples include bridge widenings, deck replacements, and superstructure replacements.

The bridge designer will receive a copy of the *Bridge Repair Recommendations*, approved by the District, for each bridge in a proposed repair project. The MnDOT Regional Bridge Construction Engineer prepares the recommendations in accordance with the BPIG and specifies the scope of the bridge repair project.

Most repair projects were originally designed in accordance with the *AASHTO Standard Specifications for Highway Bridges*. Therefore, it may seem logical to design the repair using the same governing specifications. However, the *AASHTO Standard Specifications for Highway Bridges* is no longer being maintained, has not been updated since 2002, and has several documented deficiencies. Thus, it is appropriate for repair projects to be evaluated and designed using the current edition of the *AASHTO LRFD Bridge Design Specifications (LRFD)* along with the latest load and resistance factor rating (LRFR) requirements from the *Manual for Bridge Evaluation (MBE)*. The LRFD specifications are based on the latest research, incorporating the variability in material properties and loading, as well as being statistically calibrated to provide uniform reliability.

Therefore, the following applies to all bridge repair projects, regardless of original design code:

- Load rating evaluations for repair projects shall be done using LRFR procedures. These evaluations should be performed during the scoping phase of the project. For typical projects, the Bridge Ratings Engineer will develop the evaluation. For special structures, the Bridge Ratings Engineer and State Bridge Design Engineer will determine if assistance is required to complete the evaluation and who will perform it.

- For bridge rehabilitation projects, such as deck replacements, widenings, and superstructure replacements, design and analysis shall be done using LRFD procedures. Because these types of projects are a major investment and significantly extend service life, it is important to evaluate the bridges using current standards.

- For major bridge preservation projects that significantly increase dead load, like those with bridge rail modifications or those that increase the deck thickness, design and analysis shall be done using LRFD procedures.

- Major bridge preservation projects such as deck repairs, painting, mill and overlays, and joint replacements typically do not require any analysis as part of the final plan development. However, these projects should include an up-to-date LRFR evaluation during the scoping phase of the project to assess potential areas of concern that may need to be addressed in the repair plan.

Minimum LRFR requirements for superstructures of bridge repair projects:

- As previously allowed in the BPIG, which required a minimum load factor rating of HS18 (0.9 x HS20 design vehicle), an LRFR inventory rating factor of 0.9 is the minimum acceptable level for the superstructure. This reduced inventory rating factor is considered acceptable recognizing that some of the service life of the bridge has transpired.

- For bridges with sidewalks, consider both of the load cases given in Article 4.2.3 of this manual. Consideration may be given to waiving Load Case 2 (vehicular load applied to the sidewalk) when the anticipated remaining life of the bridge is less than 10 years.

Minimum LRFR requirements for substructures (Note that this does not apply to foundations):

- Substructures are typically load rated only when significant additional loads will be applied. Evaluations may also be required if safety inspections note substantial deterioration or there is damage that indicates an inadequate design. Members that require evaluation will be noted in the repair recommendations.

- Traditional beam theory or strut-and-tie are both acceptable analysis methods for pier caps, provided the boundary conditions in AASHTO are met for the chosen analysis method.

- For bridge rehabilitation projects, the minimum acceptable LRFR inventory rating factor is 1.0 for substructures. (Because of rating software limitations regarding substructures, the minimum load rating requirement was set higher than for superstructures.)

- For major bridge preservation projects:
    - When the bridge currently has permit restrictions, the substructure inventory rating must be greater than or equal to the superstructure inventory rating.
    - When the bridge does not have current permit restrictions, the substructure inventory rating must be greater than or equal to 1.0, but need not exceed the superstructure inventory rating.
- The skin reinforcement requirements of AASHTO LRFD Article 5.7.3.4 need not be met for pier caps.

- For bridges with sidewalks, consider both of the load cases given in Article 4.2.3 of this manual. Consideration may be given to waiving Load Case 2 (vehicular load applied to the sidewalk) when the anticipated remaining life of the bridge is less than 10 years.

For cases where the required minimum inventory rating factor cannot be achieved, other options within the LRFR provisions of the MBE specifications and MnDOT policy can be considered. These options would need to be discussed on a case-by-case basis with the Bridge Ratings Engineer, Final Design Unit Leader, Bridge Construction Regional Engineer, State Bridge Design Engineer, State Bridge Construction and Maintenance Engineer, and the appropriate District personnel. In addition, a design exception can be recommended to the District based on investment level, cost, expected bridge service life, and service interruption risk.

4.6.3 Railroad Bridges and Bridges or Structures near Railroads

Railroad bridges are to be designed in accordance with the most current *AREMA Manual for Railway Engineering*.

Designers should be aware that oftentimes railroads have specific criteria for structural design of items carrying their tracks or in the vicinity of their tracks. The criteria vary from railroad to railroad. For example, the Duluth Mesabe & Iron Range Railway has a special live load. Other railroads have specific loading criteria and geometric limits for excavations near their tracks.

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