Shear Assessment of Complex Concrete Pier Caps

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The Lake Avenue Bridge over Interstate 35 (I-35) in Duluth, Minn., is a stylish, cast-in-place reinforced concrete box-girder bridge, which was constructed in 1982. Supporting a single-point urban interchange (SPUI), the bridge connects downtown Duluth to the tourist hotspot of Canal Park along Lake Superior and is one of the primary means of access to downtown and Canal Park from I-35. Every June, the structure is a focal point for the thousands of runners who pass under it just before making the final turn to the Canal Park finish line of Grandma's Marathon.

The Lake Avenue Bridge consists of multiple concrete box-girder units with complex geometry to fit the SPUI and the ramps to I-35. When the Minnesota Department of Transportation (MnDOT) required a load rating for this structure, it retained Michael Baker International (MBI) to prepare a load and resistance factor rating (LRFR). MBI developed a three-dimensional (3D) finite-element model of the structure (**Fig. 1**) using midas Civil software, following the grillage analysis methods specified for horizontally curved concrete box-girder bridges in *Design Specifications and Commentary for Horizontally Curved Concrete Box-Girder Highway Bridges,* published by the National Cooperative Highway Research Program.[1]

To perform a load rating of the box-girder web lines and tributary flange widths, the MBI evaluation team used output forces from this model in conjunction with spreadsheets that tracked the many reinforcement transitions along the length of the bridge units. Following the project scope of work, the team also used the demands output from the model to conduct load ratings using strut-and-tie modeling (STM) of the internal integral cap beams over the piers (**Fig. 2**) and of the bridge's corbel joints between superstructure units (**Fig. 3**).

The intent of the technical approach was to rigorously apply the American Association of State Highway and Transportation Officials (AASHTO) *Manual for Bridge Evaluation* (MBE);[2] however, the evaluation team understood and expected that various elements of the piers would not meet current AASHTO design and detailing requirements. In the eighth edition of the *AASHTO LRFD Bridge Design Specifications,*[3] Articles 5.1 and 5.5.1.2 establish a clear path that leads to the conclusion that STM is the only appropriate *design* approach for new structures with disturbed regions. But when faced with evaluating existing structures designed and detailed using a different standard, the solutions are not always as clear (see the FHWA article in the Fall 2019 issue of *ASPIRE*®).

The evaluation team load rated the bridge for the HL-93 loading at the inventory and operating levels, and the standard Minnesota legal and permit vehicle loadings. The nearly 40-year-old bridge is in good condition, and the superstructure and corbel joints had passing load ratings for all legal vehicles and nearly all permit vehicles. However, the integral cap beams did not have adequate shear capacity for some current legal loads when analyzed with STM or when using a sectional model approach, as would have been used during their initial design. The problematic cap beam regions were nearly all located within a distance extending horizontally outward from the face of the piers equal to the effective shear depth d_v. Within these regions, the existing vertical reinforcing steel area in the integral cap beams was not enough to provide the shear reinforcement contribution capacity V_s required to produce passing load ratings using sectional analysis, or the required reinforcing steel area to satisfy the vertical tie demands from STM for the same applied loads.

AASHTO LRFD specifications require that the shear capacity within a distance extending d_v from the face of the support be evaluated if concentrated loads are located within this distance. On the Lake Avenue Bridge, most of the integral cap beams support box-girder web lines within

Lake Avenue Bridge looking north on Interstate 35. Photo: Minnesota Department of Transportation.

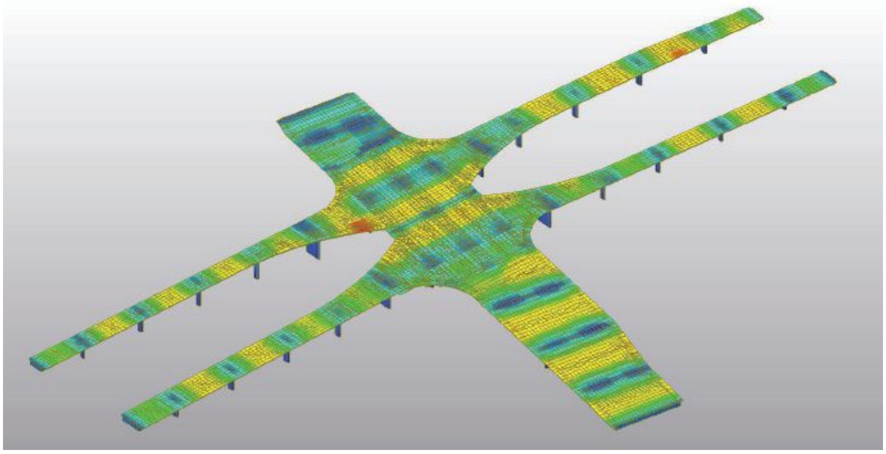


Figure 1. Rendering of the three-dimensional finite-element model of Lake Avenue Bridge. Figure: Michael Baker International.

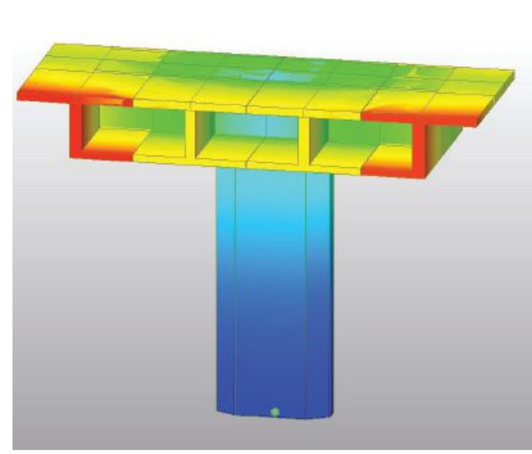


Figure 2. Cross section of the three-dimensional finite-element model showing the cast-in-place reinforced concrete box-girder unit, pier column, and integral pier cap beam for a Lake Avenue Bridge ramp structure. Figure: Michael Baker International.

this distance; the evaluation team initially treated these as concentrated loads, with the critical section being taken at the face of support. The team also considered taking the critical section at a distance of d_v from the face of the support if a detailed bridge inspection found no signs of shear cracking in the d_v region. They reasoned that if an inspection of these regions found no shear cracks after nearly 40 years of service, the performance of the bridge would be demonstrating that the loads from the webs and integral flanges were effectively acting more like distributed loads, for which AASHTO LRFD specifications permit the critical section for shear to be taken at d_v from the support face for a sectional analysis. MnDOT's District 1 bridge inspection staff performed a supplementary inspection of multiple cells of the bridge adjacent to the integral cap beams, which revealed narrow, diagonal cracking in the cap beams near the support faces, as shown in **Fig. 4**.

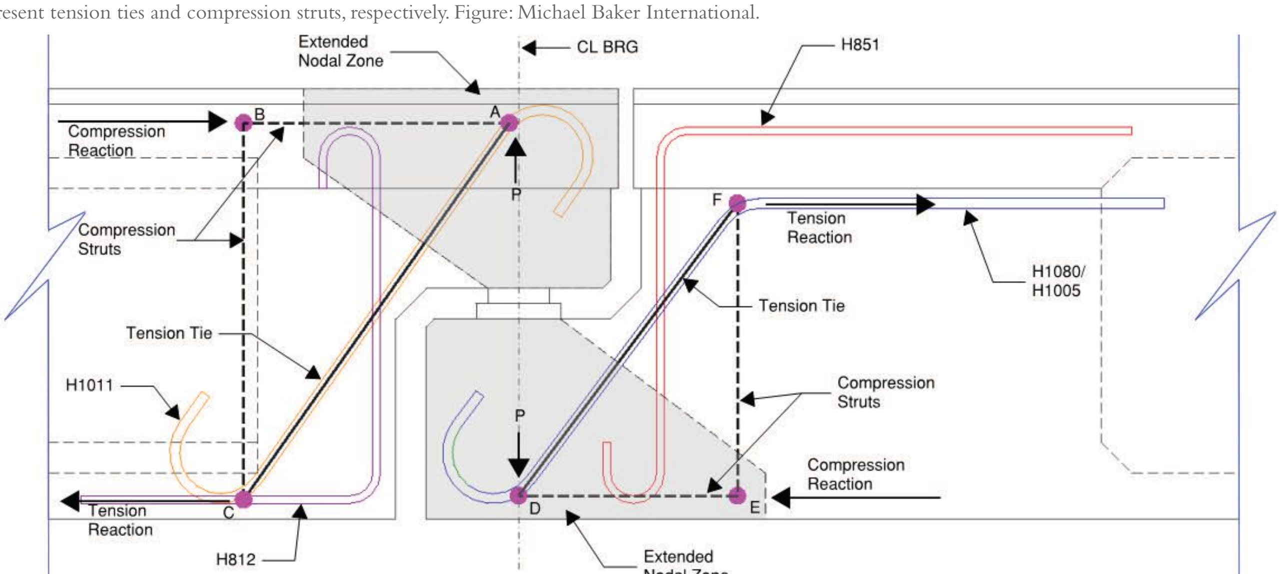
Given the multiple, fine shear cracks in the integral cap beams within the d_v distance and poor rating results using an all-sectional or all-STM approach, the observed fair performance of the integral cap beams needed to be reconciled with the poor results of multiple calculation models that indicated more extensive shear cracking with wider crack widths should be present. The evaluation team had to either resolve these discrepancies or use the results of the models to load post the bridge, which would potentially be followed by costly retrofit repairs.

The analysis team obtained higher load-rating results that better reflected the good condition of the cap beams by using a hybrid analysis method incorporating both sectional analysis and STM. They used STM to evaluate the integral cap beams within d_v from the face of the column, and applied the sectional method in the span beyond d_v from the column face because that method discretely considers the concrete and shear reinforcement contributions to shear, V_c and V_s, both of which appear to be intact. At the interface between the B- and D-regions (as described in AASHTO LRFD specifications), the hybrid analysis ensures there is a load path to couple the B- and D-regions together and carry the demand to the columns.

In the STM for the example cap beam shown in **Fig. 5**, forces V_A and V_B each equal one-half of the total shear demand V_u at a distance d_v from the left face of the column. This analysis causes vertical tie *AB* in the model to only carry half of the total shear demand V_u. The other half of the total shear demand V_u is applied to top node *A* and transferred by the diagonal strut *AD* and other struts and ties into model supports *D* and *F* (which represent the pier), without creating demand in tie *AB*.

If the entire cap beam had been modeled using STM, vertical tie *AB* would be required to carry the entire shear demand at distance d_v from the face of the

Figure 3. Lake Avenue Bridge corbel joint showing the primary reinforcement and strut-and-tie models used for evaluation. Note: Solid and dashed lines represent tension ties and compression struts, respectively. Figure: Michael Baker International.



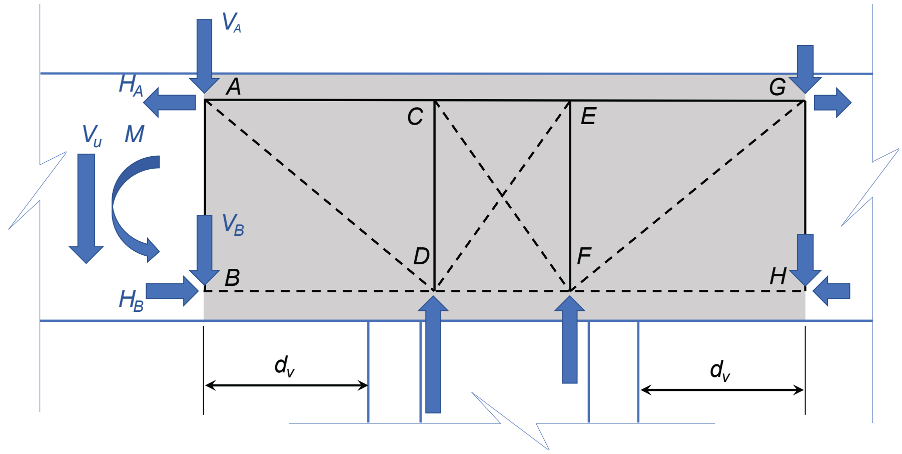


Figure 5. Strut-and-tie model of the hybrid analysis of the integral cap beam. V_A and V_B each equal one-half of the total shear demand V_u. Note: Solid and dashed lines represent tension ties and compression struts, respectively. Strut-and-tie modeling was used in the D-region of the cap beam (shaded gray). The sectional model was used in the B-region of cap beam (not shaded). Figure: Michael Baker International.

column, assuming no concentrated loads are applied at nodes *A* or *B*. Flexural demands were similarly addressed but are not shown for clarity.

Horizontal forces H_A and H_B are obtained from the moment *M* at the interface between the sectional and strut-and-tie models. These forces are equal and opposite, and are equal to the moment *M* divided by the vertical distance between nodes *A* and *B*. The forces are applied in the direction needed to induce tensile and compressive axial forces in the horizontal chords of the strut-and-tie model that are of the same sense as the top and bottom flexural stresses induced by the moment *M* at the interface. For the Lake Avenue Bridge integral pier caps, this procedure resulted in the top chords of the strut-and-tie models being in tension over the piers, and the bottom chords in compression.

This hybrid analysis approach recognizes the contribution of concrete to shear strength by not requiring that vertical tie *AB* transfer the entire shear demand V_u up to node *A*, as would be needed for the STM of the entire cap. The existing vertical reinforcing steel area in the cap beams was sufficient to satisfy the vertical tension demand in tie *AB* obtained using the hybrid approach. The overlapping diagonals *CF* and *DE* in the example model of Fig. 5 were analyzed as compression-only truss elements, which effectively removes one of the two diagonals for different unbalanced live-loading patterns. This technique ensures that all ties are horizontal or vertical and align with the existing reinforcement layout.

All portions of the integral cap beams that did not have passing legal load ratings using the original sectional method checks were evaluated using the hybrid approach. The evaluation team's 3D finite-element model was used to generate concurrent live-load forces for use in the hybrid method to evaluate capacity.

Using this hybrid analysis method produced passing ratings for Minnesota legal loads and permit loads for all the Lake Avenue Bridge integral pier cap beams. These results conform with the condition observed in these regions of the bridge and avoid the need for load posting or structure retrofits. The Lake Avenue Bridge should provide many more decades of service to Duluth's citizens and visitors, and will continue to serve as a landmark for weary marathon runners nearing the finish line.

Figure 4. Diagonal cracking (dashed lines) noted during inspection of an integral cap beam of the Lake Avenue Bridge. Cap beam is on the left, and girder web is on the right. Photo: Minnesota Department of Transportation.

References

1. National Cooperative Highway Research Program (NCHRP). 2008. *Design Specifications and Commentary for Horizontally Curved Concrete Box-Girder Bridges: Final Report*. NHCRP Project 12-71. Washington, DC: Transportation Research Board. *http://onlinepubs.trb.org/onlinepubs/archive/notesdocs/nchrp12-71_fr.pdf*
2. American Association of State Highway and Transportation Officials (AASHTO). 2018. *Manual for Bridge Evaluation*, 3rd ed. Washington, DC: AASHTO.
3. AASHTO. 2017. *AASHTO LRFD Bridge Design Specifications*, 8th ed. Washington, DC: AASHTO.

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EDITOR'S NOTE

This is the first part of a two-part Concrete Bridge Technology article series on strut-and-tie modeling (STM) by these authors. The second article will discuss how to use STM for portions of new design that are more challenging than what is typically shown in example problems, as well as some of the techniques Michael Baker International uses for complex designs.