Design Considerations for Unbonded Post-Tensioning Tendons

by R. Kent Montgomery, FIGG

Post-tensioned concrete structures are economical and durable solutions for bridges and buildings. Although most designs use internal bonded post-tensioning tendons, unbonded external and internal tendons can also be utilized. However, structures with unbonded tendons exhibit fundamentally different behaviors that must be correctly addressed to produce reliable designs. This article discusses these differences while focusing on current bridge design provisions in the United States.

Types of Unbonded Tendons

For bridges, the most common type of unbonded tendon is external to the cross section, anchored at each end of a span, and deviated within the span to achieve the desired profile. In the United States, this type of tendon typically uses bare strands within ducts filled with grout to provide corrosion protection. However, in other countries, external tendons with ungrouted epoxy-coated strands and individually sheathed strands have been used. Ducts have also been filled with a flexible filler, such as wax or grease, to provide corrosion protection. Details at the deviators include rigid steel pipe ducts bonded to the diaphragm and diabolos, which are radiused openings that do not result in any bond at the deviators (see the Concrete Bridge Technology article in the Fall 2015 issue of *ASPIRE*®).

Tendons internal to the cross section are typically grouted and bonded, but they can also be unbonded. For decades, building elements have used unbonded sheathed strands and, more recently, the Florida Department of Transportation has used flexible filler for internal ducts rather than cementitious grout. The flexible filler does not bond the strands to the cross section but does provide corrosion resistance of the PT tendons (see the Concrete Bridge Technology article in the Winter 2017 issue of *ASPIRE*).

Flexural Design Considerations

At the service limit state, the designs for bonded and unbonded tendons are essentially the same. The tendons are tensioned, and forces are transferred to the cross section at the anchorages and tendon deviations. Whether the tendon is bonded or unbonded makes no appreciable difference for either the tendon forces or concrete stresses. Designing for the service limit state for both bonded and unbonded tendons involves selection of the tendon forces and tendon paths to achieve concrete stresses within the limits of the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*.[1]

However, at the strength limit state, there are fundamental differences between bonded and unbonded tendon designs. For internal tendons bonded to the cross section, strain compatibility is a reasonable assumption and the stress increase in the tendons after the section cracks can be calculated from strain compatibility and material properties. Article 5.6.3.1.1 of the AASHTO LRFD specifications presents simplified design equations that were developed using the previous considerations. These equations estimate the stress in bonded tendons at the strength limit state. Once the stress in the tendons is determined, the nominal flexural resistance is easily calculated from equations in Article 5.6.3.2 and compared to the strength limit state moment demands.

For unbonded tendons, strain compatibility is not valid and the stress in the tendons is primarily governed by global displacements of the cracked structure between bonded sections of the

External tendons in grouted ducts inside the U.S. Route 181 Harbor Bridge in Corpus Christi, Tex. Photo: FIGG.

Ungrouted epoxy-coated strands inside the Matoba Viaduct, which crosses the Matoba River in Japan. Photo: DYWIDAG-Systems International.

Tendon using flexible filler. Flexible filler can be used in both external and internal tendons. Photo: University of Florida.

tendons. Computation of tendon stresses from global displacements is sufficiently complex that Article 5.6.3.1.2 of the AASHTO LRFD specifications includes simplified equations for predicting the ultimate stress in unbonded tendons. Once the ultimate tendon stress is calculated, the nominal flexural resistance is computed using the same equations as for bonded tendons. The equations in Article 5.6.3.1.2 are based on research at the University of Texas that tested a scale model of a three-span segmental bridge with external unbonded tendons.[2] The test model used grouted external tendons running through rigid pipes in deviators to achieve the draped profile. It should be noted that, although the tendons were grouted within the pipes, some slip between the pipe and deviators was observed. Therefore, the equations are based on the tendon length between anchorages, with the effective tendon length being further dependent on the number of hinges expected to form within a given span. While the testing that was used to develop the current AASHTO LRFD specifications equations was specific to a typical span-by-span bridge of the time, it is this author's opinion that these equations provide a reasonable estimate for ultimate tendon stresses for most situations involving 100% unbonded tendons, including external tendons and internal tendons using flexible filler.

The AASHTO LRFD specifications do not provide detailed equations for cases in which both bonded and unbonded tendons exist at the same section. Rather, Article 5.6.3.1.3 provides two forms of guidance. The first is a description of a detailed analysis approach, which is conceptually correct but relatively complex. The second method conservatively uses the service level stress f_{pe} in unbonded tendons for the ultimate stress in the unbonded tendons, while using the bonded tendon equations in the AASHTO LRFD specifications to compute the ultimate stress in the bonded tendons. For this method, the size of the compression block is computed using both the bonded and unbonded tendons. It is this author's opinion that this is a reasonable method if the stress in the unbonded tendons at the strength limit state is limited to f_{pe}.

It should be noted that when both bonded and unbonded tendons are present at the same section, calculating stress increases in the unbonded tendons above the service level needs to be approached with caution. This is because the magnitude of displacements, especially the local rotations at hinge locations, required to increase the stress in unbonded tendons could possibly result in the rupture of the bonded internal tendons prior to the stress in unbonded tendons reaching the level predicted by the equations in the AASHTO LRFD specifications. This phenomenon has been noted by Brenkus and colleagues and Megally and associates and appears to be dependent on the ratio of bonded to unbonded tendons.[3,4]

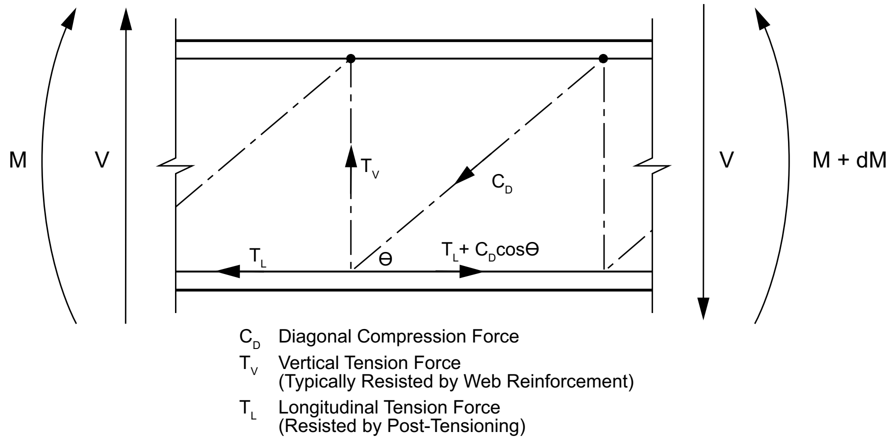
Shear Design

Two methods for shear design are included in the AASHTO LRFD specifications. Neither has a requirement for the tendons to be bonded. The primary method, which is presented in Article 5.7, uses a variable angle for the inclined compressive stresses. The second method, which is found in Article 5.12.5.3.8, is based on a method discussed by Ramirez and is an alternative procedure for segmental bridges.[5] It uses a simplifying approach of a 45-degree truss diagonal and does not require a check of the longitudinal tension reinforcement for shear design.

For post-tensioned structures, either method assumes that the forces in the inclined compressive struts are equilibrated by differential forces in the longitudinal tendons. However, if the tendons are not bonded, the force in the tendons essentially remains constant between bonded sections of the tendons, which is contrary to the conceptual models used for shear design. By using a 45-degree inclination of the compressive struts, the alternative method puts less demand on the longitudinal force transfer. The research by MacGregor and colleagues at the University of Texas[2] did not directly address this anomaly, but the investigators did not note any shear capacity deficiencies in the model structure. For the primary AASHTO LRFD method, the angle of the compressive struts in the conceptual truss is typically much less than 45 degrees for prestressed concrete members and a greater demand is placed on the longitudinal force in the tendons for equilibrium. The increased demand raises questions, at least conceptually, regarding the use of these provisions in conjunction with unbonded tendons. Some research into this conceptual discrepancy has been undertaken by Vecchio and coauthors, who concluded that the primary AASHTO LRFD specifications shear design procedure is conservative.[6] Further research regarding the shear behavior of members with unbonded tendons is underway at the University of Florida and will also be studied as a part of the National Cooperative Highway Research Program Project NCHRP 12-118.

Conclusions and Recommendations

The behavior of bridges using unbonded post-tensioning tendons is fundamentally different than that of bridges with bonded tendons. Designers must take



Forces in conceptual truss model illustrating differential tendon forces to equilibrate diagonal strut forces. Figure: R. Kent Montgomery.

these fundamental differences into account to correctly design structures with unbonded tendons.

While the AASHTO LRFD specifications provide a method for predicting the flexural strength of bridges with 100% bonded or 100% unbonded tendons, several issues have not been fully addressed, including the following:

- More detailed provisions in the AASHTO LRFD specifications regarding the flexural resistance of sections containing both bonded and unbonded tendons. It is this author's opinion that, although the simplified procedure wherein the stress in unbonded tendons at the strength limit state is taken as f_{pe} is conservative, refining this assumption would lead to more efficient designs.
- Research to confirm the validity of the shear design methods in the AASHTO LRFD specifications for bridges with unbonded tendons, both external and internal, including any required modifications to the current provisions.

References

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