INDIANA DEPARTMENT OF TRANSPORTATION

Driving Indiana's Economic Growth

Design Memorandum No. 21-16

June 17, 2021

TO: **All Design, Operations, and District Personnel, and Consultants**

FROM: ***/s/ Stephanie J. Wagner***
Stephanie J. Wagner
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Bridge Engineering Division

SUBJECT: **Prestressed-Concrete Structure**

REVISES: ***Indiana Design Manual* (IDM) Chapter 406, 406-4.02, 406-4.02(01), 406-5.02, 406-5.05, 406-6.0, 406-7.0, 406-7.01 through 406-7.04, 406-8.01, 406-8.02, 406-9.01 through 406-9.03, 406-10.0, 406-11.0, 406-12.01, 406-12.03(02), 406-12.03(03), 406-12.05, 406-12.06**

EFFECTIVE: **Immediately**

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IDM Chapter 406, Prestressed-Concrete Structure, has been updated to reference the *AASHTO LRFD Bridge Design Specifications*, 8th Edition with interim revisions through May 2018. Many of the previous code references were not consistent with the current specifications. Other minor changes have been made to clarify the Department's expectations related to the design of prestressed members. The changes that have been made in the IDM do not conflict with the *AASHTO LRFD Bridge Design Specifications* and should not necessitate changes to any projects currently in design.

IDM Revisions

406-4.02 Normal-Weight and Lightweight Concrete [Rev. Oct. 2012, Jun. 2021]

The minimum f'_c for prestressed or post-tensioned concrete components shall be shown on the plans. Such a strength outside the range shown in Section 406-1.0 is not permitted without written approval of the Director of Bridges. For lightweight concrete, the air dry unit weight shall be shown on the plans as 119 lb/ft^3. The modulus of elasticity will be calculated using the 119 lb/ft^3 value. The unit weight of the lightweight concrete will be taken as 124 lb/ft^3. The additional weight is to account for the mild reinforcing steel and the tensioning strands. See *LRFD* 5.4.2.2 for the coefficient of thermal expansion.

The following will apply to concrete.

1. The design compressive strength of normal-weight and lightweight concrete at 28 days, f'_c, shall be in the range as follows:

   a. prestressed box beam: 5 to 7 ksi
   b. prestressed I-beam: 5 to 7 ksi
   c. prestressed bulb-tee beam: 6 to 8 ksi

   An exception to the range shown above will be allowed for a higher strength if the higher strength can be documented to be of significant benefit to the project, it can be effectively produced, and approval is obtained from the Director of Bridges.

At release of the prestressing strands, f'_c shall not be less than 4 ksi, and shall be determined during the beam design. The specified concrete compressive strength at release shall be rounded to the next higher 0.1 ksi.

406-4.02(01) Shrinkage and Creep [Rev. Jun. 2021]

Losses due to creep and shrinkage, for other than than a segmentally-constructed bridge, that require a more-precise estimate including specific materials, structural dimensions, site conditions, construction methods, and age at various stages of erection, can be estimated by means of the methods specified in *LRFD* 5.4.2.3.2 and 5.4.2.3.3. Other acceptable methods are those described in the CEB-FIP code, or ACI, see LRFD 5.4.2.3.1. The annual average ambient relative humidity shall be taken as 70%.

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406-5.02 Service-Limit State [Rev. Jun. 2021]

See *LRFD* 5.6.7 or control of cracking, 5.6.3.5 for deformations, and 5.9.2 for stress limits for concrete.

406-5.05 Extreme-Event-Limit State [Rev. Jun. 2021]

See *LRFD* 5.5.5 and Table 3.4.1-1.

406-6.0 DESIGN CONSIDERATIONS, FLEXURE AND AXIAL FORCE EFFECTS [REV. APR. 2017, JUN. 2021]

See *LRFD* 5.8.2 for a strut-and-tie model overview that can be used in the design of an anchorage zone, deep beam, bracket, or corbel.

The assumptions for service and fatigue limit states are described in *LRFD* 5.6.1. Asumptions for strength and extreme-event-limit states are described in *LRFD* 5.6.2.

For stress calculations in prestressing steel at nominal flexure resistance, the equations for components with bonded and unbonded tendons provided in *LRFD* 5.6.3.1.1 and 5.6.3.1.2 are acceptable. For components with both bonded and unbonded tendons, the simplified analysis provided in *LRFD* 5.6.3.1b is acceptable.

The flexural resistance may be computed with the equations provided in *LRFD* 5.6.3.2, or a more-precise calculation can be used as described in *LRFD* 5.6.3.2.5.

The amount of prestressed tensile reinforcement is limited by the minimum reinforcement requirements provided in *LRFD* 5.6.3.3.
Instantaneous deflections, long-term deflections, and cambers shall be computed with the modulus of elasticity, moment of inertia, and cracking moment specified in *LRFD* 5.6.3.5.2. The methods provided therein to obtain long term deflections from instantaneous deflections are acceptable.

406-7.01 General [Rev. Jun. 2021]

LRFD 5.8.2 allows the strut-and-tie model and the sectional-design model for shear design of prestressed concrete,. In a region near a discontinuity, the strut-and-tie model shall be used. The sectional-design model is appropriate for the design of a girder, slab, or other region of components where the assumptions of traditional beam theory are valid. See *LRFD* 5.8.2 and *PCI Bridge Design Manual* Section 8.12 for more information regarding the strut-and-tie model.

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Torsional effects shall be investigated only if the condition in *LRFD* 5.7.2.1 for normal weight concrete, or slightly modified for lightweight concrete, is satisfied.

Transverse reinforcement, minimum and maximum requirements, types of transverse reinforcement, and shear stresses of concrete are provided in *LRFD* 5.7.2. They shall be satisfied in the design.

406-7.02 Sectional-Design Model [Rev. Jun. 2021]

LRFD 5.7.3 discusses the sectional-design model. The general formulas used to calculate the nominal shear resistance are shown in *LRFD* 5.7.3.3-1. The parameters used to evaluate these expressions depend on the adopted approach. For a prestressed-concrete structure, the use of either the General Procedure shown in *LRFD* 5.7.3.4.2 or the General Procedure for Shear Design with Tables in *LRFD* Appendix B5 is acceptable.

In order to account for the tension caused by shear, the longitudinal-reinforcement requirements shown in *LRFD* 5.7.3.5 and 5.7.3.6.3 shall be satisfied.

406-7.03 Interface Shear Transfer – Shear Friction [Rev. Jun. 2021]

A cast-in-place concrete deck designed to act compositely with precast-concrete beams shall be able to resist the horizontal shearing forces at the interface between the two elements. *LRFD* 5.7.4.1 discusses the requirements for shear transfer. The nominal shear resistance of the interface and the factored interface shear force are provided in *LRFD* 5.7.4.5. The most appropriate condition of the interaction between concrete-slab and concrete-girder surfaces shall be selected individually from the six situations of cohesion and friction factors provided in *LRFD* 5.7.4.4. The requirement for minimum area of interface shear reinforcement provided in *LRFD* 5.7.4.2 shall be satisfied.

406-7.04 Segmental Concrete Bridges [Rev. Jun. 2021]

Segmental concrete bridges should be designed in accordance with *LRFD* 5.12.5.

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406-8.01 General Considerations and Stress Limitations [Rev. Jun. 2021]

General requirements for design, concrete strength, buckling, section properties, crack control, location of tendon relative to the duct, and stresses due to imposed deformations are provided in *LRFD* 5.9.1. Contrary to the *LRFD* requirements, INDOT does not allow a transformed section for a pretensioned member.

The stress limitations for prestressing tendons, deformed high-strength bars, and concrete before and after losses have occurred, are provided in *LRFD* 5.9.2.2.

406-8.02 Loss of Prestress [Rev. Jun. 2021]

Total prestress losses in a member constructed and prestressed in a single stage are provided in *LRFD* 5.9.3. The losses are defined as instantaneous losses such as anchorage set, friction, elastic shortening, and time-dependent losses. The acceptable methods provided for determining the time-dependent losses are an approximate and a refined method. The refined method can be used for the final design of a nonsegmental prestressed concrete member. For a post-tensioned concrete member with multistage construction or prestressing, the prestress losses shall be computed by means of a time-dependent-analysis method such as that described in CEB-FIP (1978 / 1990). The approximate lump-sum estimate method shall be used for preliminary design only.

The values of the wobble and curvature friction coefficients, and the anchor-set loss assumed for the design shall be shown on the plans.

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406-9.01 Spacing of Prestressing Tendons and Ducts [Rev. Jun. 2021]

The minimum and maximum spacing of pretensioned strands are provided in *LRFD* 5.9.4. The minimum and maximum spacing of post-tensioning ducts are provided in *LRFD* 5.9.5. However, bundling of ducts will not be permitted. *LRFD* 5.9.5.3 provides requirements for longitudinal post-tensioning couplers.

406-9.02 Tendon Confinement and Effects of Curved Tendons [Rev. Jun. 2021]

LRFD 5.9.5.4 provides general requirements for tendon confinement, and in-plane and out-of-plane force effects. Shear resistance of the concrete cover against pullout shall be satisfied, or fully-anchored tiebacks shall be provided. Local confining reinforcement shall be provided if out-of-plane forces exceed the factored shear resistance of concrete cover. *LRFD* 5.9.5.5 provides the maximum unsupported length of external tendons.

406-9.03 Post-Tensioned and Pretensioned Anchorage Zone [Rev. Jun. 2021]

LRFD 5.9.5.6 provides general requirements for the anchorage zones at the end and intermediate anchorages. Requirements for design of general zones are provided in *LRFD* 5.9.5.6.5. The strut-and-tie, elastic stress analysis, and approximate method are acceptable. The design requirements for a local zone including special anchorage devices are provided in *LRFD* 5.8.4.4, 5.9.5.6.3, and 5.9.5.6.6. For a pretensioned anchorage zone, *LRFD* 5.9.4.4 shall be followed.

406-10.0 DEVELOPMENT OF PRESTRESSING STRANDS AND DEBONDING [REV. JUN. 2021]

The transfer length of pretensioned components is shown in *LRFD* 5.9.4.3. The specific requirements for development length and variation of pretensioned stress in strands for bonded or debonded strands are provided in *LRFD* 5.9.4.3.2 and 5.9.4.3.3. Where debonded, or shielded, strands are used, the following apply.

1. In a bulb-tee beam, not more than 25% of the total number of strands and not more than 40% in each horizontal row shall be debonded. The allowable percentage of debonded strands for an AASHTO I-beam or a box beam shall be not more than 50% of the total number of strands and of the strands in each horizontal row. Strands placed in the top flange of the beam shall not be included in the percentages shown above.

2. Exterior strands in each horizontal row shall not be debonded.

3. Bonded and debonded strands shall preferably alternate both vertically and horizontally.

4. Debonding termination points shall be staggered at intervals of not less than 3 ft.

5. Not more than four strands, or 40% of the total debonded strands, whichever is greater, shall be terminated at one point.

   See *LRFD* 5.9.4.3.3 for additional guidelines.

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6. Two strands shall be considered in the top of a box beam, 2 or 4 strands in the top flange of an I-beam, or up to 6 strands in a bulb-tee beam. This can significantly reduce the need for debonded strands in the bottom of the beam, and it facilitates the placement of the top mild reinforcement. Where strands are placed in the top flange, a note shall be shown on the plans indicating that these strands are to be cut at the center of the beam after the bottom strands are released and the pocket is then to be filled with grout. The top strands may not need to be cut if ultimate moment controls the number of strands in the bottom flange.

7. Top strands in a concrete box beam shall be placed near the sides of the box.

Minimum concrete cover for prestressing strands and metal ducts, and the general protection requirements for prestressing tendons are described in *LRFD* 5.14.

406-11.0 DIAPHRAGMS [REV. JUN. 2021]

Design considerations for diaphragms are provided in *LRFD* 5.12.4.

406-12.01 General [Rev. Jun. 2021]

Design requirements are provided for precast slab superstructures, beams, girders, diaphragms, segmental construction, arches, and prestressed piles *LRFD* 5.12.

406-12.03(02) Prestressing-Strands Configuration [Rev. Jun. 2021]

See Sections 406-13.0, 406-14.0, and 406-15.0 for typical strand patterns for standard prestressed beam sections. Other strand patterns may be used if there is reason for deviation from the standard pattern, and the *LRFD* criteria for spacing and concrete cover are followed. If 11 strands are placed in a horizontal row in the bottom of a bulb-tee beam, the bending diagram for the vertical stirrup must be modified. The strand pattern shown may be used for nominal ½-in. or 0.6-in. diameter strands. Section 406-4.03 provides criteria for the strand diameters used.

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The strand-pattern configurations shown in Sections 406-13.0, 406-14.0, and 406-15.0 were developed in accordance with the following.

1. Minimum center-to-center spacing of prestressing strands equal to 2 in.

2. Minimum concrete cover for prestressing strands shall be 1½ in., which includes the modification factor of 0.8 for a water/cement ratio equal to or less than 0.40 as described in *LRFD* 5.10.1.

3. Minimum concrete cover to stirrups and confinement reinforcement shall be 1 in.

The strand pattern has been configured so as to maximize the number of vertical rows of strands that can be draped. Due to the relatively thin top flange of a bulb-tee beam, strands placed in the top of the beam shall be at least 6 in. from the outside edge of the flange.

406-12.03(03) Mild-Steel Reinforcement [Rev. Jun. 2021]

See Sections 406-13.0, 406-14.0, and 406-15.0 for typical mild-steel reinforcement configurations for the standard prestressed beam sections. The vertical shear reinforcement shall be #4 stirrup bars where possible. To fully develop the bar for shear, the ends of the stirrup bar shall include a standard 90-deg stirrup hook. The maximum spacing of the vertical stirrups shall be in accordance with *LRFD* 5.7.2.6. The maximum longitudinal spacing of reinforcement for interface shear transfer shall be in accordance with *LRFD* 5.7.4.5.

A minimum of three horizontal U-shaped #4 bars shall be placed in the web of each bulb-tee at the ends of the beam. See Section 406-14.0 for location and spacing of these bars. This reinforcement will help reduce the number and size of cracks, which can appear in the ends of the beams due to the prestress force. *LRFD* 5.9.4.4.1 requires that vertical mild reinforcement shall be placed in the beam ends within a distance of one fourth of the member depth. This is to provide bursting resistance of the pretensioned anchorage zone. Enough mild reinforcing steel shall be provided to resist not less than 4% of the prestress force at transfer. The end vertical bars shall be as close to the ends of the beam as possible. The stress in the reinforcing steel shall not exceed 20 ksi.

Confinement reinforcement in accordance with *LRFD* 5.9.4.4.2 shall be placed in the bottom flange of each I-beam or bulb-tee as shown in Section 406-13.0 or 406-14.0, respectively. The reinforcement shall be #3 bars spaced at 6 in. for a minimum distance of 1.5 times the depth of the member from the end of the beam or to the end of the strand debonding, whichever is greater.

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406-12.05 Continuity for Superimposed Loads [Rev. Jun. 2021]

A multi-span bridge using composite beams shall be made continuous for live load if possible. The design of the beams for a continuous structure is approximately the same as that for simple spans except that, in the area of negative moments, the member is treated as an ordinary reinforced-concrete section. The members shall be assumed to be fully continuous with a constant moment of inertia in determining both the positive and negative moments due to superimposed loads.

The traditional method of making simply-supported beams continuous is to construct a closure joint between the adjacent beam ends over the pier, conveniently as part of the diaphragm, and to place extra longitudinal steel in the deck over the pier support to resist the negative moment. Spans made continuous for live load are assumed to be treated as prestressed members in the positive-moment zone between supports, and as conventionally-reinforced members in the negative-moment zone over the support. The reinforcing steel in the deck shall carry all of the tension in the composite section due to the negative moment. The longitudinal reinforcing steel in the deck that makes the girder continuous over an internal support shall be designed in accordance with *LRFD* 5.12.3.3.8.

Continuity diaphragms shall be designed in accordance with *LRFD* 5.12.3.3.10 based on the compressive strength of the precast girder regardless of the strength of the cast-in-place concrete.

No allowable tension limit is imposed on the top-fiber stresses of the beam in the negative-moment region. However, crack width, fatigue, and ultimate strength shall be checked. If partial-depth precast, prestressed concrete stay-in-place forms are to be used, such as for an AASHTO I-beam superstructure, only the top mat of longitudinal steel reinforcement shall be used to satisfy the negative-moment requirements.

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406-12.06 Effect of Imposed Deformations [Rev. Jun. 2021]

Potential positive moments at the piers shall also be considered in the design of a precast, prestressed-concrete beam structure made continuous for live load. Creep of the beams under the net effects of prestressing, self-weight, deck weight, and superimposed dead loads will tend to produce additional upward camber with time. Shrinkage of the deck concrete will tend to produce downward camber of the composite system with time. Loss of prestress due to creep, shrinkage, or relaxation will result in downward camber. Depending on the properties of the concrete materials and the age at which the beams are erected and subsequently made continuous, either positive or negative moments can occur over the continuous supports.

Where beams are made continuous at the relatively young age of less than 120 days from time of manufacture, it is more likely that positive moments will develop with time at the supports. These positive restraint moments are the result of the tendency of the beams to continue to camber upward as a result of ongoing creep strains associated with the transfer of prestress. Shrinkage of the concrete deck, loss of prestress, or creep strains due to self-weight, deck weight, or superimposed dead loads all have a tendency to reduce this positive moment.

For a span of over 150 ft or for concrete whose creep behavior is known to be poor, a time-dependent analysis shall be made to predict positive restraint moments at the piers. The *PCI Bridge Design Manual*, Section 8.13.4.3, describes two methods to evaluate restraint moments at the piers. Positive-moment connections at the piers that have proven successful in the past shall be used based on experience with similar spans and concrete-creep properties.

Unless positive-moment-connecting steel calculations are made, the minimum number of strands to be used for the positive-moment connection over the pier shall be one-half the number of strands in the bottom row of the bottom flange of a bulb-tee or an I-beam. The minimum is 5 strands for a bulb-tee or I-beam type IV, 4 strands for an I-beam type II or III, or 3 strands for an I-beam type I.

The strands shall be extended and bent up without the use of heat to make the positive moment connection. For a box beam, the minimum number of strands to be extended into the positive-moment connection and bent up shall be 6 strands for a beam deeper than 27 in., or 4 strands for a beam depth equal to or less than 27 in.

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The strands extended into the positive-moment connection between beams shall not be debonded. The strands that are not used for the positive-moment connection shall be trimmed back to the beam end to permit ease of beam and concrete placement.

The prestressing-strand and concrete strengths shall be as shown in Section 406-4.0. The tensile and compressive stress limits shall be as shown in *LRFD* 5.9.2.3. *LRFD* requires that only 80% of the live-load moment is to be applied in checking the tensile stress at service condition.

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