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Curved, Precast, Pretensioned Concrete I-Girder Bridges

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Modern highway construction frequently requires bridges with horizontally curved alignments. Such bridges can be created by superimposing a curved deck slab onto straight girders or by splicing segmental straight girders on the chords of a curved roadway. Of these two methods, a curved superstructure usually results in simpler construction and better appearance.

Curved steel girders have received considerable attention during the past 15 years. As a result, the American Association of State Highway and Transportation Officials' (AASHTO) *LRFD Bridge Design Specifications*[1] was revised in 2004 and again in 2005 to combine the design of straight and curved steel girders. The concept of using curved, precast, prestressed concrete girders as an alternative to curved steel girders is gradually being recognized by bridge designers. Several projects in Florida, Pennsylvania,[2] Colorado,[3] and Nebraska[4] have demonstrated the cost effectiveness of such an alternative.

A few studies on curved, post-tensioned concrete girder bridges have been published.[2–4] However, curved, pretensioned concrete girder bridges have been common practice in only the Netherlands for over a decade (**Fig. 1**). Curved, pretensioned concrete girder bridges have not gained popularity in the United States.

The pretensioned concrete I-girder is the most economical shape for mass production. Thus, the use of curved, pretensioned concrete I-girders may be potentially more cost effective than the use of curved steel girders and curved, post-tensioned concrete girders. In this paper, the feasibility of long-bed fabrication of curved, precast, pretensioned concrete I-girders and the associated construction issues are discussed. A cost comparison of curved, pretensioned

Editor's quick points

- The use of curved, precast, pretensioned concrete girders has many advantages as an alternative to curved, post-tensioned concrete girders and curved steel girders.
- This paper summarizes the current practice of horizontally curved bridge construction.
- A curved, precast, pretensioned concrete I-girder has the potential to become the most cost-effective system for curved-bridge construction.

and curved, post-tensioned concrete girder bridges is also presented.

Analysis of curved beams

McManus et al.[5] presented analyses of horizontally curved steel girders in 1969. Their survey was limited to work involving curved bridges and monorails loaded normal to the plane of curvature. Zureick[6] presented methods for horizontally curved I-girder analysis in a 1999 paper. Those methods were focused on horizontally curved steel I-girder bridges.

The 2005 interim revisions of the AASHTO LRFD specifications divided the structural analysis methods into two categories: approximate and refined methods. The refined analysis methods, which are applicable to curved, pretensioned concrete I-girders, include the finite-element method and the grillage-analogy method.[7–12] Because these two methods have been widely available in computer programs for curved-bridge analyses, classical methods such as the finite-difference method,[13,14] folded-plate method,[15] and finite-strip method[16,17] have become less popular.

The V-Load[18] and M/R[19] methods are approximate analysis methods. The lateral deflection of bridges with long spans and sharp skew may be significantly underestimated by the V-Load method because the method does not account for the horizontal shear stiffness of the concrete deck or the girder twist. The M/R method is applicable for horizontally curved closed-frame (for example, box girder) bridges. These two approximate methods are best suited for preliminary design, and may be used for final design for bridges with radial or horizontal skew less than 10 degrees.

AASHTO specifications for horizontally curved steel girders

AASHTO Guide Specifications for Horizontally Curved Steel Girder Highway Bridges[20] provides the current practice for the design and analysis of curved-steel-girder bridges. It was first published in 1980, incorporating the allowable-stress-design (ASD) method. The AASHTO guide specifications were subsequently updated under the National Cooperative Highway Research Program (NCHRP) project 12-38 (report 424)[21] in the load-factor-design (LFD) format and published in 2003. During the transition from ASD to LFD, examples were developed in report 424 to illustrate how the new provisions are applied to the design of a curved I-girder and a curved box girder. An effort was initiated in 1999 as the NCHRP project 12-52 to convert the AASHTO guide specifications into the load-resistance-factor-design (LRFD) method (report 563).[22] The new provisions are applied to the design of a curved I-girder and a curved box girder.

Figure 1. A curved, pretensioned concrete box-girder bridge in Rotterdam, Netherlands, is a prime example of standard practice for bridges in the Netherlands for more than a decade. Courtesy of Spanbeton.

A major construction issue associated with the erection of curved steel I-girders is lateral stability. Due to their low torsional stiffnesses, lateral bracing must be provided for the first several curved I-girders erected. Lateral stability is no longer a concern once a number of curved girders have been erected over piers and abutments with lateral bracings in place between adjacent girders.

Curved, precast, prestressed concrete girders

Curved, precast, prestressed concrete girders have gradually received attention by bridge designers as an alternative to using curved steel girders. For instance, design specifications and commentary for horizontally curved concrete box-girder highway bridges have been developed under the NCHRP project 12-71. Design provisions are also provided in chapter 12, "Curved and Skewed Bridges," of PCI's *Precast Prestressed Concrete Bridge Design Manual*.[23] The simplest way to support a curved roadway is to use straight beams beneath a curved deck. For practical curve radii encountered in highway bridge construction, a curve approximated by 20-ft-long (6 m) chords will appear as a smooth curve. The appearance will be poor if the offset between the arc and the chord segment exceeds 1.5 ft (0.5 m), in which case the use of curved beams may be desirable.

To avoid problems associated with low torsional stiffness, many designers are inclined to use precast, post-tensioned concrete box sections or U-sections for full-length curved beams. The precast concrete box beams are closed at the top to achieve adequate torsional resistance. The maximum span of precast concrete box beams is often limited by the allowable shipping weight. Segmental construction—with drop-in segments between segments cantilevered over the piers—is the most common construction method used for long-span curved box-girder bridges. Diaphragms are often used at girder joints to achieve lateral stability before the concrete segments are post-tensioned in the field.

Figure 2. The Pennsylvania Department of Transportation used curved, precast, post-tensioned concrete box girders produced by Schuylkill Co. for the Philadelphia Airport renovation. Courtesy of Joseph Nagle, Schuylkill Co.

Figure 3. The curved, precast, post-tensioned concrete box girders used for the Philadelphia Airport renovation are in their final position. Courtesy of Joseph Nagle, Schuylkill Co.

Box girders

The curved precast concrete box girders in **Fig. 2** and **3** were used by the Pennsylvania Department of Transportation[2] for the Philadelphia International Airport renovation. Curved, precast, post-tensioned concrete box girders were erected over two and three continuous spans. The radius of curvature was 478 ft (146 m) for the two-span girders and 326 ft (99 m) for the three-span girders. The approximate lengths of the three spans were 92 ft (28 m), 135 ft (41 m), and 92 ft. The chord-segment length of the girders was 20 ft (6 m) and the girders were field spliced at the piers and jointed with cast-in-place concrete diaphragms.

The computer model developed by ABAM[24] was used for the design of the curved precast, post-tensioned concrete box girders. The girders, cross beams, and deck were modeled using one-dimensional grillage elements. The precast concrete girders were post-tensioned at the plant to carry their own weights. Diaphragms were provided for overturning stability. The ultimate strength of the bridge was investigated for two critical stress conditions: placing the cross beam and the deck and imposing the full superimposed dead load and live load on the deck.

The torsion and shear forces at each horizontal angle point between chord segments were analyzed. Twisting moments were produced by the girder self-weight on a simple span and by the deck weight on a continuous span. The twisting moments were resisted by the deck and the cross beams, while the shear forces were resisted by the diaphragm between the chord segments.

U-girders

Summit Engineering Group designed a U-shaped precast concrete girder for a bridge project that spans Interstate 25 just north of the U.S. Route 36 and Interstate 76 interchange in Denver, Colo.[3] The longest span of the bridge (**Fig. 4**) was 200 ft (61 m). Segments that were 100 ft (30 m) long were cantilevered from the piers and supported by temporary shoring (**Fig. 5**). A 100-ft-long drop-in segment was spliced between the cantilevered girders.

The entire precast concrete assembly was post-tensioned in the field. The effect of curvature on primary bending according to the AASHTO LRFD specifications was considered and analyzed by the M/R method[19] for preliminary design. Grid analysis and three-dimensional finite-element analysis were subsequently conducted for the final design.

The Arbor Road Bridge[4] in Lincoln, Neb., (**Fig. 6**) is an Interstate 80 overpass and consists of two spans about 142 ft (43.3 m) and 136 ft (41.5 m) long, respectively. The bridge is horizontally curved with a skew of 31 degrees and has a central angle of about 3 degrees. During the design phase, a curved, precast concrete girder was considered as an alternative to a curved steel girder.

The original design was a steel I-girder with a 7.5-in.-thick (190 mm), cast-in-place concrete deck slab. Grade 50 ksi (345 MPa) steel plate was to be used on parts of the I-girder to allow a girder depth of 43.5 in. (1100 mm), which increased to 67.5 in. (1710 mm) at the pier. The superstructure consisted of five girder lines spaced at 8 ft (2.4 m). Intermediate steel diaphragms were spaced at about 18.5 ft (5.6 m).

The concrete alternative consisted of four girder lines spaced at 9.33 ft (2.8 m). The concrete alternative used a prismatic U-girder section, which is 45.8 in. (1160 mm) deep at its left web and 43.5 in. (1100 mm) deep at its right web to match the 5.5% cross slope super elevation. The bottom flange of the U-girder is 5 in. (127 mm) thick for most of the girder length and is thickened to about 12 in. (300 mm) at the pier end to accommodate the negative moment requirements in that area. The girder web thickness is 7.75 in. (197 mm) at the top and was increased to 8.25 in. (210 mm) at the bottom to facilitate removal of the steel forms inside the U shape.

Each precast concrete girder consists of four straight segments: three are the standard 40 ft (12.2 m) steel form length and the fourth, near the pier, varies in length for each of the girders. Internal concrete diaphragms, about 5.5 in. (140 mm) wide, were placed at the bend between the adjacent straight segments.

Although the construction took longer than expected, the precast, prestressed concrete option turned out to be more cost effective than the steel option. It is anticipated that minimizing the number of field construction steps and performing as much of the post-tensioning at the precasting facilities as possible would significantly expedite the construction.

I-girders

To the authors' knowledge, curved, precast concrete I-girders are not produced as a single piece. The spliced-girder technique has been used for curved bridges with radii as sharp as 500 ft (152 m), but only with concrete I-girders that are precast as straight pieces. Straight I-girders have been used as chords to create angle changes at splice locations at the site.

To accommodate post-tensioning ducts and reinforcement, the minimum web thickness of the bulb-tees and standard precast concrete I-girders should be 7 in. to 8 in. (180 mm to 200 mm). The splice area must be wide enough for the post-tensioning duct to curve at an acceptable radius in plan. Chapter 12 of the *Precast Prestressed Concrete Bridge Design Manual* provides guidelines for the analysis and design of curved, prestressed concrete bridges using the spliced-girder technique. The Annacis Channel Bridge[25] in British Columbia, Canada; the Moore Haven Bridge in Florida; and the Loysburg Bypass Bridge[26] in Pennsylvania are examples.

Figure 4. Summit Engineering Group designed a U-shaped, precast, post-tensioned concrete box-girder bridge for Interstate 270 that spans Interstate 25 just north of the U.S. Route 36 and Interstate 76 interchange in Denver, Colo. Courtesy of Gregg Reese, Summit Engineering.

Figure 5. The 100-ft-long segments were cantilevered from the piers and supported by temporary shoring for the Interstate 270 bridge in Denver, Colo. Note: 1 ft = 0.305 m. Courtesy of Gregg Reese, Summit Engineering.

Figure 6. The Arbor Road Bridge in Lincoln, Neb., is a two-span, horizontally curved, precast concrete–girder bridge with a skew of 31 degrees and a central angle of about 3 degrees.

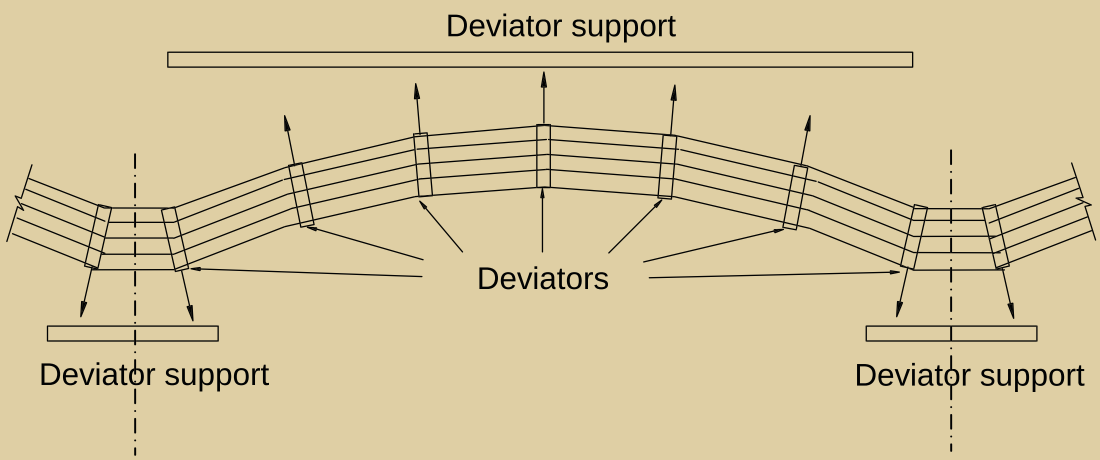

Figure 7. In the proposed horizontal-strand-deviation method, the deviators pull the tendons sideways at predetermined locations to create chord segments along the curve. The deviator supports must be designed to resist the pull forces from the deviators. Note: The drawing is not to scale, and the horizontal curvature is exaggerated.

Feasibility of curved, pretensioned I-girders

The construction of horizontally curved, precast, pretensioned concrete girders is similar to that of straight girders with harped tendons. However, in horizontally curved girders, the steel tendons are pulled horizontally from their straight direction (instead of vertically) using deviators. The steel tendons, which are segmented into chords within the required curvature, should run parallel to the length of each concrete chord. With properly designed deviators and supports, horizontally curved precast concrete girders can be pretensioned in a plant.

Figure 7 illustrates the concept of pretensioning horizontally curved girders. The deviators pull the tendons sideways at predetermined locations to create tendons that are segmented into chords along the curve. The deviator supports must be designed to resist the pull forces from the deviators. As illustrated in **Fig. 8**, the fabrication sequence is the same as that for straight girders.

1. Prestressing: The tendons are laid out in a prestressing bed. A deviator is positioned in the radial direction such that the pull force would bisect the angle at the bend of adjacent chord segments. The pull forces

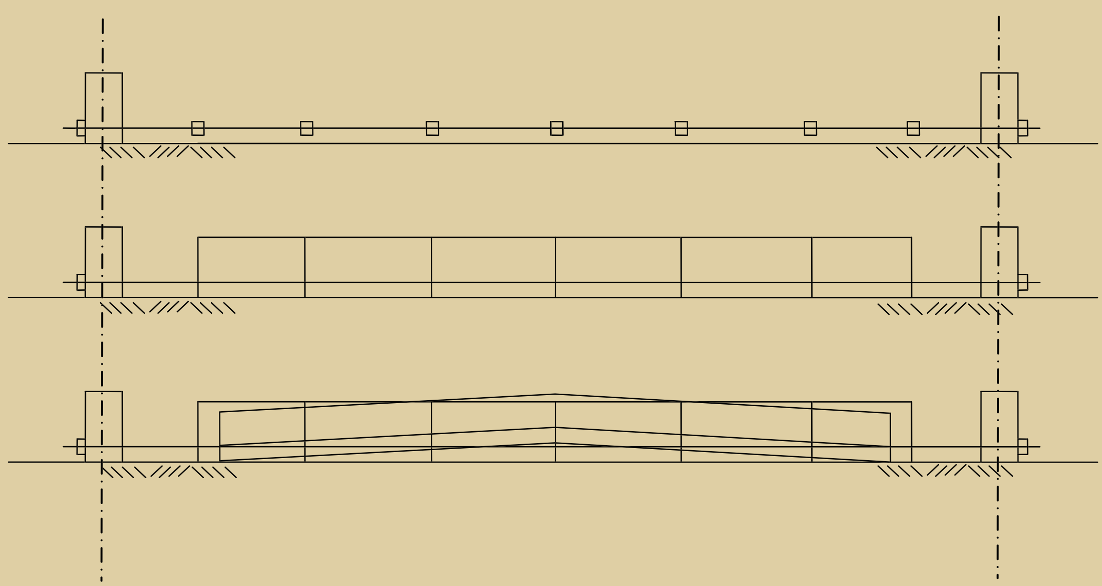

Figure 8. The fabrication sequence for pretensioning a curved precast concrete girder is the same as for straight girders. Note: The drawing is not to scale, and the camber is exaggerated.

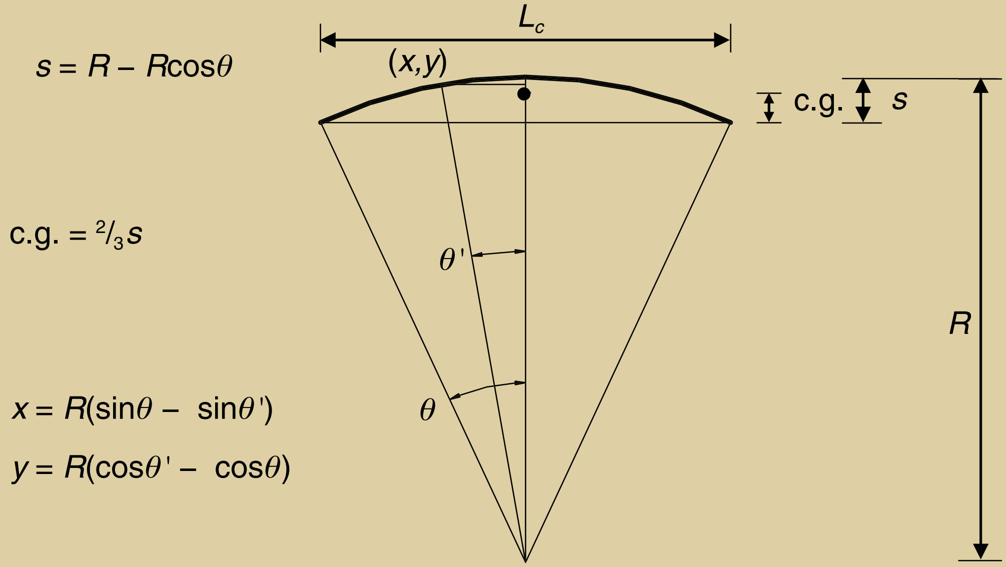

Figure 9. This drawing illustrates the plan view of a horizontally curved girder. c.g. = center of gravity.

are determined from the total prestressing force and the geometry of the layout (Fig. 7). Seating losses in the prestressing bed, relaxation losses, friction losses at the support, and losses due to direction change of prestressing force should be accounted for when determining the total prestressing force.

2. Placing concrete: Concrete is placed in the forms and cured until the required initial strength is reached.

3. Prestress release: The tendons are released from the abutment at the live end of the prestressing bed. The eccentricity of the tendons produces camber in the member. Prestress losses due to deformation of concrete, radial friction, and direction change of tendons may be determined using the conventional procedures.

Geometry of curved girders

Figure 9 shows the plan view of a horizontally curved girder. The degree of curvature θ can be computed from the span (or chord) length L_c and the radius of curvature R of the girder. If a curved bridge girder is made of a series of short straight segments, the location of each segment can be computed from the radius of curvature R and the central angle of the segment θ'. The center of gravity of the girder is located at $^2/_3$ of the maximum offset distance s between the arc and the chord, which can be approximated using Eq. (1).

$$s \cong \frac{L_c^2}{8R} \tag{1}$$

Experimental study

A prestressed concrete beam in the shape of a circular arc made of chord segments was fabricated in the structural research laboratory at the University of Nebraska to illustrate the feasibility of a curved, pretensioned concrete member. A rectangular section instead of an I-section was chosen for simplicity.

Description of the curved beam

Figure 10 shows the test beam, which had a 10 in. × 10 in. (254 mm × 254 mm) cross section and a total length of 12 ft (4 m). The test beam, with an R of 30 ft (9 m) and a θ equal to 22.9 degrees, was made of three straight-chord segments. Steel tendons were pulled from straight lines using deviators to create chord segments with θ' equal to 7.63 degrees. Two lifting points were located 3 ft (1 m) from either end of the beam.

Deviators and supports Each deviator was attached to a 1-in.-diameter (25 mm) threaded rod (**Fig. 11**). The supports, made of two 2 in. × 3$^1/_2$ in. × $^3/_{16}$ in. (50 mm × 89 mm × 5 mm) steel tubes, were bolted to the prestressing bed to anchor the threaded rods. **Figure 12** shows a close-up image of a deviator.

Prestressing strands The test beam was prestressed with four 0.5-in.-diameter (13 mm) prestressing strands of 270 ksi (1860 MPa) tensile strength. The distance from the centroid of the strands to the bottom of the beam was 2 in. (50 mm). The beam was reinforced with two no. 3 (10 M) reinforcing bars at 2 in. (50 mm) from the top of the beam and no. 3 stirrups at 8 in. (200 mm) spacing. Three extra

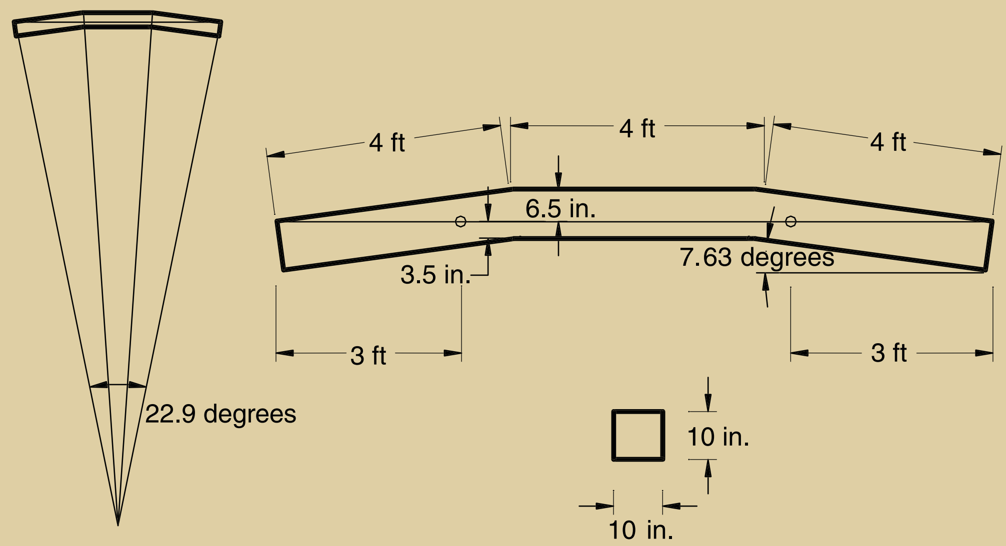

Figure 10. The test beam had an *R* of 30 ft, and steel tendons were pulled from straight lines using deviators to create chord segments with ***θ'*** equal to 7.63 degrees. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

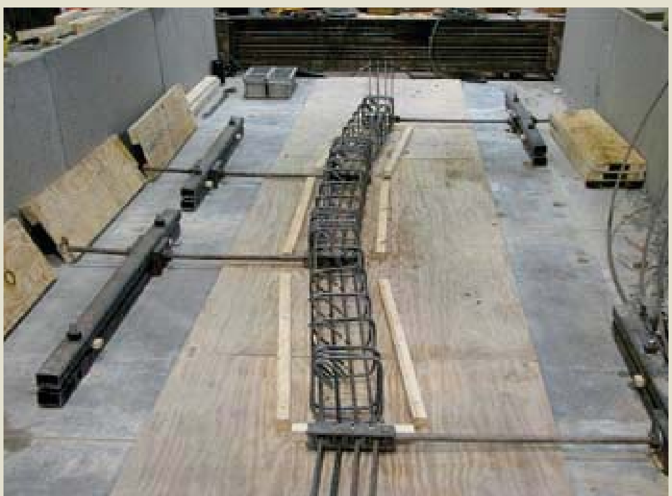

Figure 11. For the deviators and support layout, each deviator was attached to a 1-in.-diameter threaded rod. Note: 1 in. = 25.4 mm.

stirrups at 2 in. (50 mm) spacing were also used at the support locations (**Fig. 13**).

Prestressing and release

The strands were stretched using a hydraulic jack to an initial tensile stress f_{pi} of 202.5 ksi (1397 MPa). **Figure 14** shows the test beam shortly before release of the prestressing force. The strands were released after the beam was cast and cured for 26 hours. On the day of release, three cylinders were tested and the average compressive strength of the concrete f'_{ci} was 2500 psi (17,000 kPa). After the prestressing strands and the threaded rods were flame cut, the beam was subjected to the self-balanced forces shown in **Fig. 15**. The beam was statically determinate, and the stress resultants due to the eccentricity of prestressing strands were able to be calculated. Each of the three

Figure 12. Shown is one of the deviators used on the test beam.

Figure 13. Three extra stirrups at 2 in. spacing were used at the support locations. Note: 1 in. = 25.4 mm.

Figure 14. The test beam was cured for 26 hours before the prestressing strands were released.

segments was under a compressive axial force of 141 kip (627 kN) and an out-of-plane bending moment of 424 kip-in. (48 kN-m). No in-plane bending or torsional moments were induced. A concentrated torque of 56.4 kip-in. (6.4 kN-m), produced by the release of the 18.8 kip (84 kN) pull force, was necessary for moment equilibrium at the bend of adjacent segments. The camber at midspan was measured to be about 0.75 in. (19 mm).

Strain readings at release Four strain gauges, denoted as gauges 1, 2, 3, and 4, were installed on the beam as shown in **Fig. 16**. Gauge 1 was installed on the top face, and gauge 2 was installed on the side face at 2 in. (51 mm) from the bottom of the beam. Both gauges 1 and 2 were placed at 3 ft 8 in. (1.118 m) from the end. Gauges 3 and 4 were installed on the top and the side faces at the midspan, respectively. **Figure 17** presents the strain time histories during the prestressing-force release. The theoretical strains based on mechanics-of-materials equations would be 360×10^{-6} and -1031×10^{-6} at the locations of gauges 3 and 4, respectively. **Table 1** summarizes the maximum and minimum strain readings with their corresponding approximated stresses, which were calculated using the Popovics equations,[27] and predicted stresses, which were calculated using the AASHTO LRFD specifications' prestress loss analysis procedure.[1]

Lifting

Two lifting points were installed at 3 ft (0.9 m) from either end of the beam. The beam was lifted by a crane with an inclined chain. The angle between the beam and the chain was 75 degrees (**Fig. 18**). The specimen did not tilt or twist during the lifting. No cracks were observed after lifting.

Discussion

The fabrication of the curved, precast, pretensioned concrete beam was successful. The specimen had minor cracks due to the stiff deviator supports (namely, the threaded rods). In practice, the deviators should be allowed to move from their supports to minimize potential cracking. The predicted concrete stresses at release using conventional analysis compared well with those computed from strain-gauge readings.

Experimental results implied that horizontally curved, pretensioned concrete girders can be fabricated using the existing construction techniques. No in-plane bending or torsional moments were induced by the pull forces at the bend of the prestressing strands. However, full-scale experimental investigations are warranted before guidelines for the analysis, design, and construction of horizontally curved, precast, pretensioned concrete girders can be developed.

Construction issues

Fabrication

The lengths of curved I-girders should be made as long as permissible for cost effectiveness. Constraints include the maximum offset and maximum transportable weight, length, and width; a curved, pretensioned concrete girder with two or three 40-ft-long (12 m) chord segments is generally feasible. During prestressing, sufficient anchoring capacities to carry the pull forces from deviators must be provided by the deviator supports along the prestressing bed. Restraining forces from stiff supports may cause cracking in the girder. Therefore, a flexible support, which could self-adjust for the deflection angle of the prestressing strands and allow the girder to move freely at prestressing-force release, should be used.

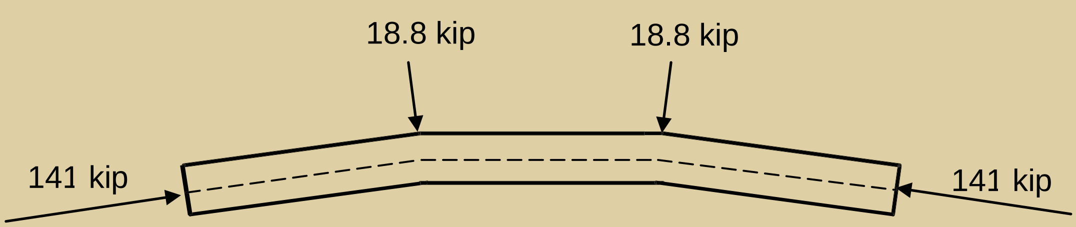

Figure 15. After the prestressing strands and the threaded rods were flame cut, the beam was subjected to the self-balanced forces. Note: 1 kip = 4.448 kN.

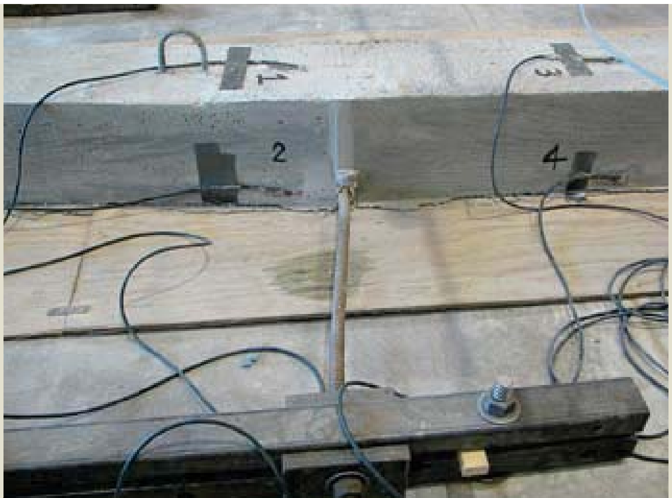

Figure 16. Four strain gauges, denoted as gauges 1, 2, 3, and 4, were installed on the beam.

Deviator design for the NU I-girder Figure 19 shows a full-scale deviator that was fabricated. The deviator consists of four components:

- five straps containing four layers of rollers,
- a solid round steel tie to hold the straps,
- a holding plate and an end plate to transfer pull force,
- high-strength steel threaded rod to transfer the pull force to the support.

The straps are to be embedded in the bottom flange of the girder and are disposable. All of the other components are reusable. This deviator was designed for a Nebraska Uni-

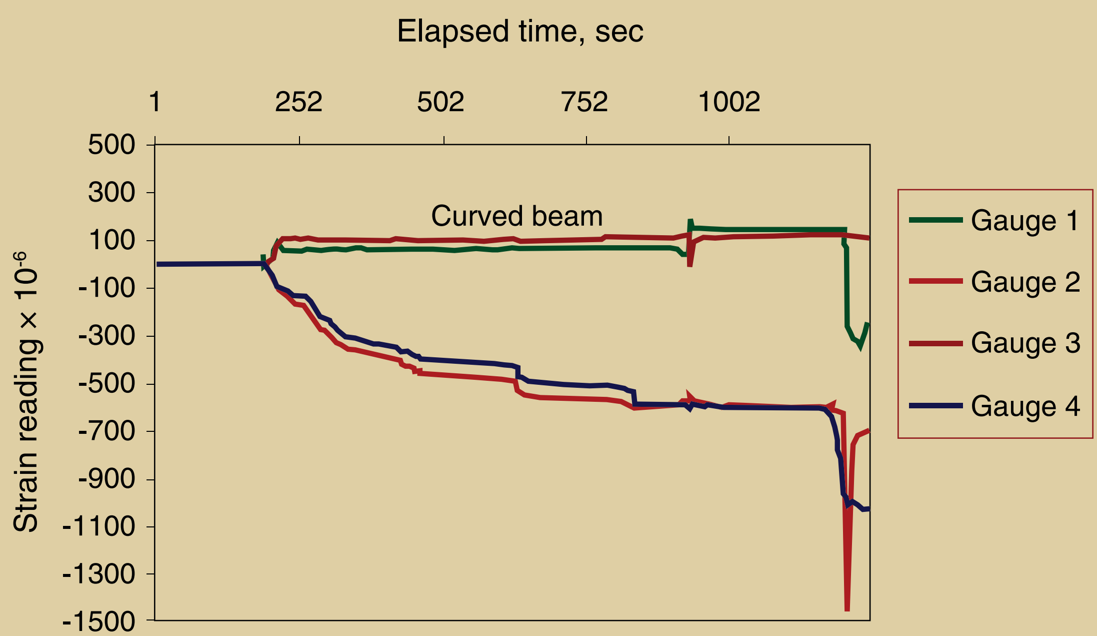

Figure 17. This graph presents the strain readings at prestress release.

Table 1. Concrete strains at prestress transfer

Gauge	Location	Strain readings × 10^{-6}		Approximated stress, ksi	Predicted stress, ksi
		Maximum	Minimum		
1	Top	183	-353	0.94	0.51
2	Bottom	6	-1463	-2.4	-2.5
3	Top	121	-30	0.34	0.48
4	Bottom	6	-1047	-2.1	-2.3

Note: The negative sign denotes compressive, and the positive sign denotes tensile. Approximated stress was calculated using the Popovics equation from "A State-of-the-Art Report: A Review of Stress-Strain Relationships for Concrete" in the *ACI Journal*. Predicted stress was calculated using the American Association of State Highway and Transportation Officials' *LRFD Bridge Design Specifications: 2004 and 2005 Interim Revisions* prestress loss analysis procedure. 1 ksi = 6.895 MPa.

Figure 18. Two-point lifting points were installed at 3 ft from either end of the beam and lifted by a crane with a chain, which formed an angle of 75 degrees with the beam and the chain. The beam was lifted by a crane with an inclined chain. Note: 1 ft = 0.305 m.

Figure 19. The prototype deviator for a curved NU I-girder consisted of four components: five straps with four layers of rollers, a solid round steel tie to hold the straps, a holding plate and end plate to transfer pull force, and a high-strength steel threaded rod to transfer the pull force to the support. Note: NU = Nebraska University.

versity (NU) I-girder. It can be used to pull up to fifty-four 0.6-in.-diameter (15 mm) prestressing strands.

As shown in **Fig. 20**, an NU I-girder had a chord length of 40 ft (12 m) along a specified radius of curvature of 700 ft (213 m). The central angle of each chord segment was 3.28 degrees. The computed component force on the device from each chord segment was 2.51 kip (11.2 kN). The maximum force from 54 strands was 136 kip (605 kN), which is transferred from the deviator to the support. As shown in **Fig. 21**, a deviator was assumed to be supported by two steel piles cantilevered 1 ft (0.3 m) above the ground. Two 4-ft-long (1.2 m), 1-in.-thick (25 mm), 12-in.-wide (300 mm) steel bearing plates were used to carry the 136 kip (605 kN) force.

Prestressing bed design The pallet must be designed for at least 96 in. (2440 mm) width of falsework, as shown in **Fig. 22**. The horizontal deviator may be installed between two 40-ft-long (12 m) standard forms. If an inside gap of 8 in. (203 mm) is assumed, then an outside gap from 8 in. to 22.62 in. (200 mm to 575 mm) would be required for 0 degrees to 7 degrees of curvature, respectively (**Fig. 23**). The prestressing bed design for two 140-ft-long (43 m) curved girders (Fig. 20) would require a 400-ft-long (122 m) and 15-ft-wide (4.6 m) pallet (**Fig. 24**).

Lifting

Stability while lifting a curved girder is a major construction issue. Precast, prestressed concrete girders are usually erected by one crane using two lifting points or by two cranes using one lifting point each. The locations of the two lifting points can be found at the intersections of centroidal lines of the section with a horizontal line through the center of gravity (in plan) of the curved girder.

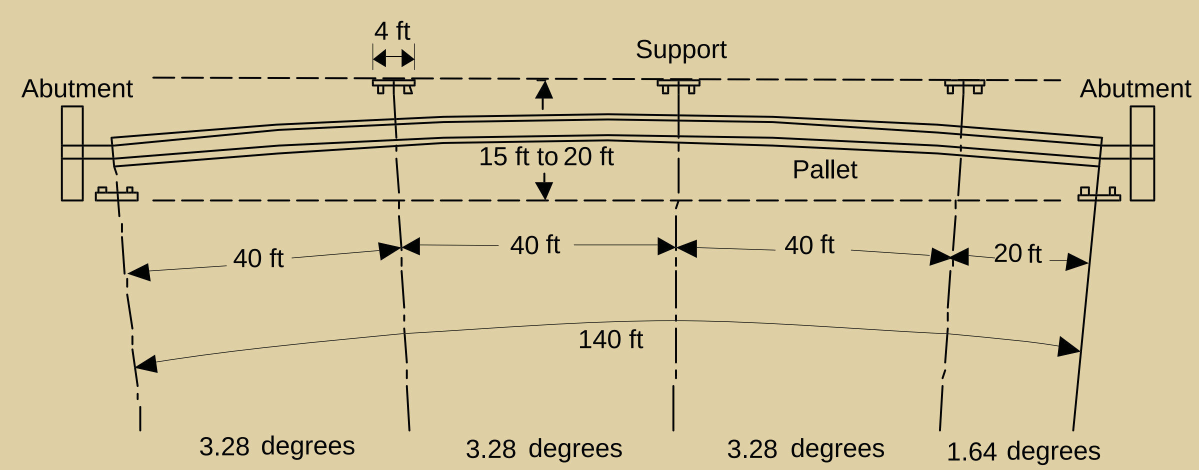

Figure 20. This diagram depicts the prestressing bed layout for an NU I-girder with 40-ft-long chords along a specified radius of curvature of 700 ft. Note: NU = Nebraska University. 1 ft = 0.305 m.

Figure 25 illustrates two lifting schemes by using one crane with two lifting points: the girder lifted vertically by straight cables and a spreader beam and the girder lifted vertically by inclined cables.

Inclined cables are not recommended for lifting a long beam because the inclined forces in the cables will cause in-plane moment and axial force. During erection, the weight of a horizontally curved girder will produce torsion as the center of gravity of the beam is offset from the centroidal axis of the beam. Therefore, stresses due to a combination of bending and torsion may be excessive and should be checked.

Figure 26 shows the moment, shear, and torsion that would be produced by the two-point lifting schemes, where the lifting points are assumed to be at the quarter points of the beam length. The torsional moment at either end of the beam is produced by one quarter of the beam weight, while that at midspan is produced by half of the

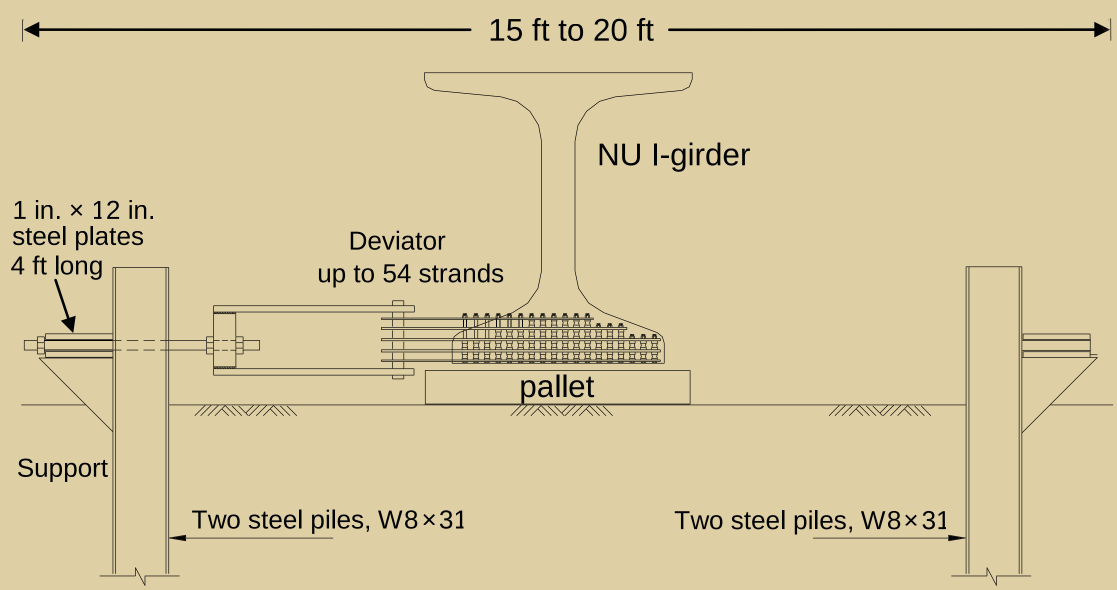

Figure 21. A deviator was assumed to be supported by two steel piles, cantilevered 1 ft above the ground. Note: NU = Nebraska University. W8 × 31 = 8 in. × 31 lb/ft. 1 in. = 25.4 mm; 1 ft = 0.305 m; 1 lb = 4.448 N.

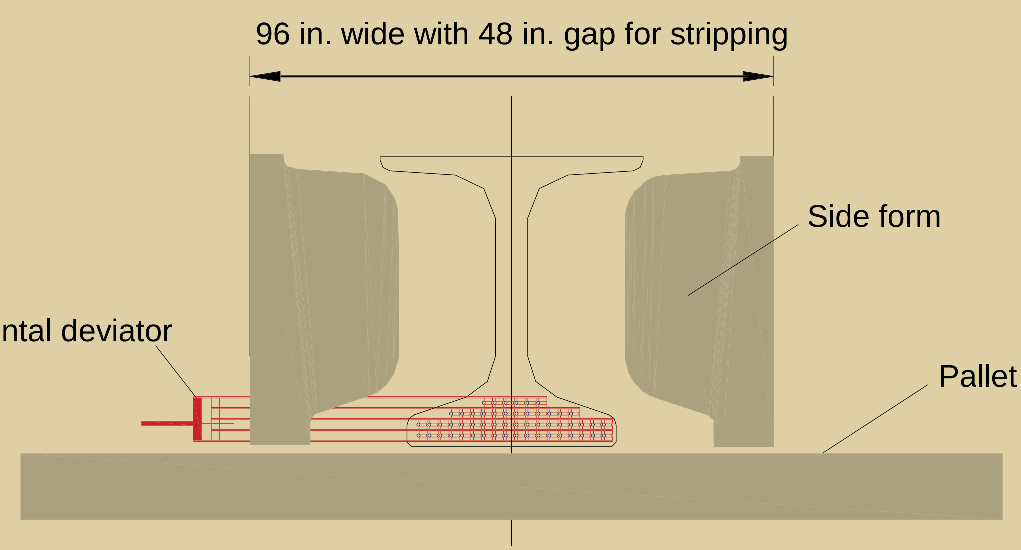

Figure 22. The cross section with movable side forms had a design requirement of at least a 96 in. width in order to remove the falsework. Note: 1 in. = 25.4 mm.

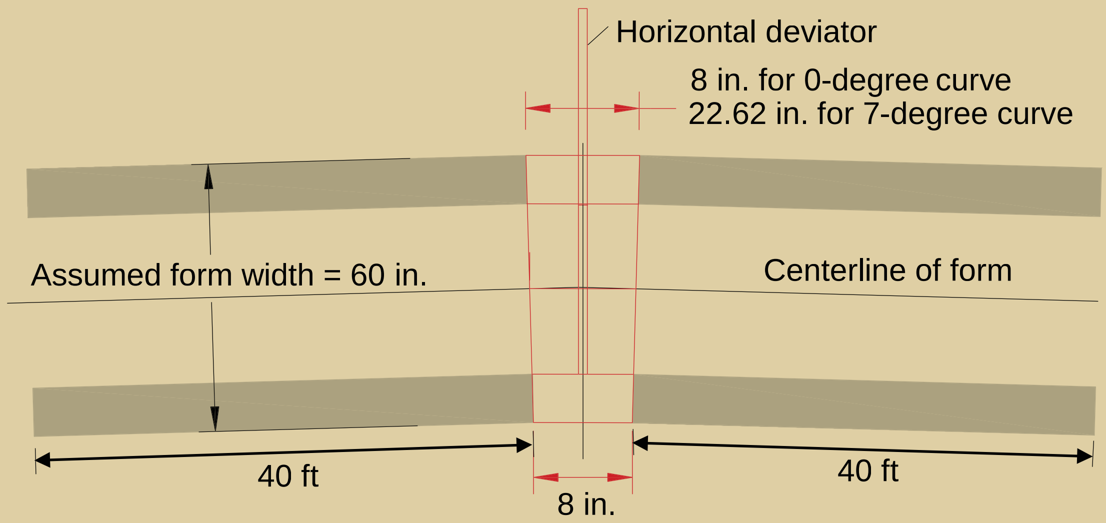

Figure 23. This plan view shows the joint form and deviator, which can be installed between two 40-ft-long standard forms. If an inside gap of 8 in. is assumed, then an outside gap from 8 in. to 22.62 in. would be required for 0 degrees to 7 degrees of curvature, respectively. Note: The drawing is not to scale. 1 in. = 25.4 mm; 1 ft = 0.305 m.

beam weight. Therefore, the torsional moments T may be calculated as Eq. (2).

$$T = \left(\frac{w_g L}{4}\right)\left(\frac{s}{3}\right) \tag{2}$$

where

w_g = beam self-weight per unit length

L = length of beam

An allowable tensile stress of $5\sqrt{f'_{ci}}$ may be used for concrete at lifting.

Handling and transportation

It is generally more economical to ship full-span beams to the site instead of assembling segments on-site. The maximum span length may be governed by the maximum permissible transportable weight, length, or width. Generally, the only unusual difficulty encountered during handling and transportation of curved I-girders is the support location. It is important to locate the lifting inserts and the support dunnage in a straight-line alignment with the center of gravity of the girder.

Erection

The weight of a horizontally curved girder would generally cause torsional moments at the supports and along the span. Temporary bracing is often required during erection for lateral stability until the end and intermediate diaphragms are cast. The crane can be released after the girder has gained sufficient lateral stability. The crossbeam spacing recommended in the AASHTO LRFD specifications may also be used for lateral bracing. The sequence of placement of the girders, diaphragms, and crossbeams must be specified on the construction drawings. **Figure 27**

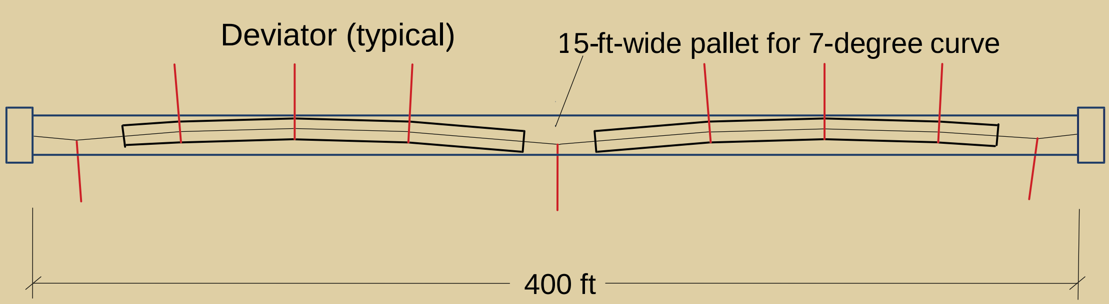

Figure 24. A 400-ft-long prestressing bed and a 15-ft-wide pallet are required to accommodate two 140-ft-long girders with curvatures up to 7 degrees or 700 ft radius. Note: 1 ft = 0.305 m.

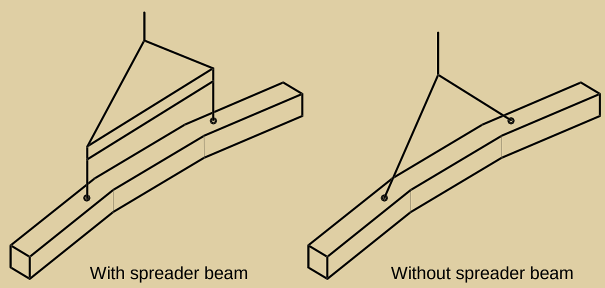

Figure 25. Two lifting schemes are illustrated for lifting curved girders.

shows the erection sequence proposed for a horizontally curved concrete girder bridge at the Interstate 480 overpass in Omaha, Neb., with a radius of curvature R of 533 ft (162 m). The girders would be launched from interior piers and completed with drop-ins.

Cost comparisons

During the design phase of the Arbor Road Bridge in Lincoln, value engineering[4] showed that the original steel-plate-girder option cost about 40% more than the projected cost of the curved, precast, prestressed concrete girder option. For the precast concrete girder option, 30% of the cost was for post-tensioning. The cast-in-place bridge deck in the original steel design cost about the same as the precast concrete deck panels and concrete overlay. In terms of overall cost, the concrete alternative was about 25% less than the original steel design.

Based on Fig. 21 and 23, **Table 2** presents the itemized costs for the deviators and supports for the proposed 400-ft-long (122 m) prestressing bed. This represents an initial cost of about \$20,000 for using the pretensioning scheme, even though the prestressing bed may be used for multiple projects. A hypothetical 280-ft-long (85 m) curved overpass supported by five girder lines is used herein for cost comparison between pretensioning and post-tensioning schemes.

Curved concrete NU I-girders, prestressed with fifty-four 0.6-in.-diameter (15 mm) prestressing strands, were assumed for the discussions. The costs of post-tensioning and pretensioning a 140-ft-long (43 m) curved concrete I-girder were first estimated.

A 0.6-in.-diameter (15 mm) prestressing strand weighs 0.74 lb/ft (1.1 kg/m), and the total weight of 54 strands in a 140-ft-long (43 m) curved concrete I-girder is 5594 lb (2530 kg). The unit cost of post-tensioning, including metal sheath, grouting, anchorage, and labor, is about \$2.50/lb (\$1.13/kg) of strand.

Curved, pretensioned concrete NU I-girders are assumed to be segmented into chord lengths along the specified curvature using the deviators, supports, and prestressing bed proposed in this paper. The unit cost of pretensioning, including anchorage and labor, is about \$0.75/lb (\$0.34/kg) of strand. Thus, the total cost of the post-tensioning option for the overpass would be $2.50 \times 5594 \times 10 = \$140,000$, while that of the pretensioning option would be $0.75 \times 5594 \times 10 + 20,000 = \$62,000$. This analysis shows that curved, precast, pretensioned concrete I-girders are 50% more economical than the post-tensioned concrete system.

Design example

Without delving into the details, an example is presented to illustrate the steps involved in the preliminary design of curved, precast, pretensioned concrete NU1800 I-girders

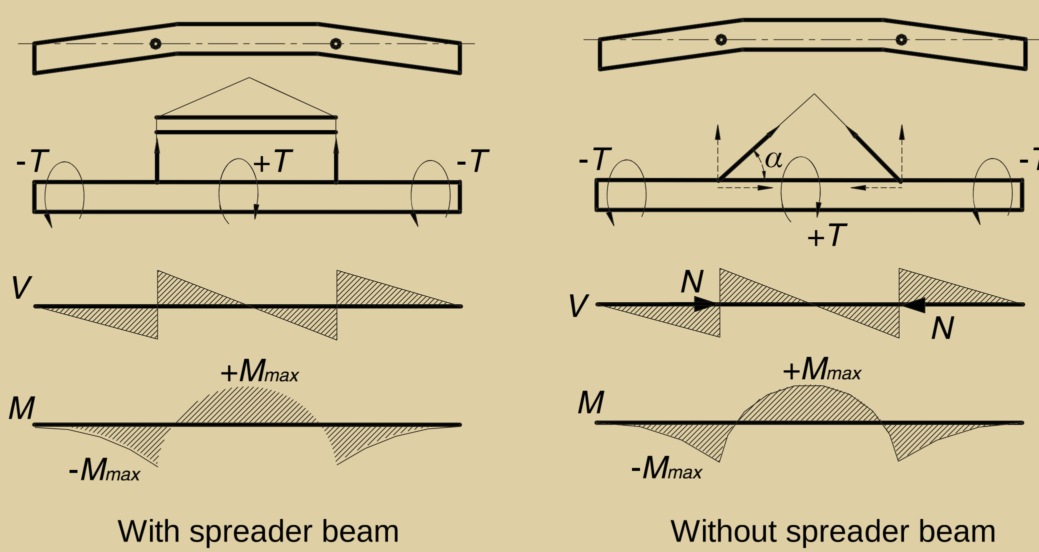

Figure 26. The bending-, shear-, and torsional-moment diagrams compare the two lifting schemes illustrated in Fig. 25.

for a two-span bridge. The following parameters are assumed for the bridge:

- The bridge has two 160-ft-long (49 m) spans.
- The radius of curvature is 700 ft (213 m).
- Each 160 ft beam is subdivided into four 40-ft-long (12 m) chord lengths.
- The curved deck is supported by four I-girder lines spaced at 10 ft (3 m).
- There are two design lanes, and the exterior-to-exterior deck width is 40 ft.
- The girders are 160 ft long, simply supported, and pretensioned for self-weight.
- Two girders are spliced on-site by post-tensioning for each girder line.
- The deck thickness is 8 in. (200 mm), and the wearing surface thickness is 0.5 in. (13 mm).

Plan geometry

The bridge is assumed to be on a 700 ft (210 m) radius curve, and the superstructure consists of four NU1800 I-girder lines spaced at 10 ft (3 m). The crossbeams (or internal diaphragms) are placed along radial lines between the girders. The arc-to-chord offset s is determined by Eq. (1):

$$s \cong \frac{L_c^2}{8R} = \frac{160^2}{8(700)} = 4.6 \text{ ft (1.4 m)}$$

This exceeds the recommended 1.5 ft (0.46 m). If the beam is subdivided into four chords (**Fig. 28**), the offset will be reduced to 3.5 in. (88 mm). The exterior-to-exterior deck width is 40 ft (12 m), with a 5 ft (1.5 m) overhang at the middle of each girder chord segment, as shown in **Fig. 29**.

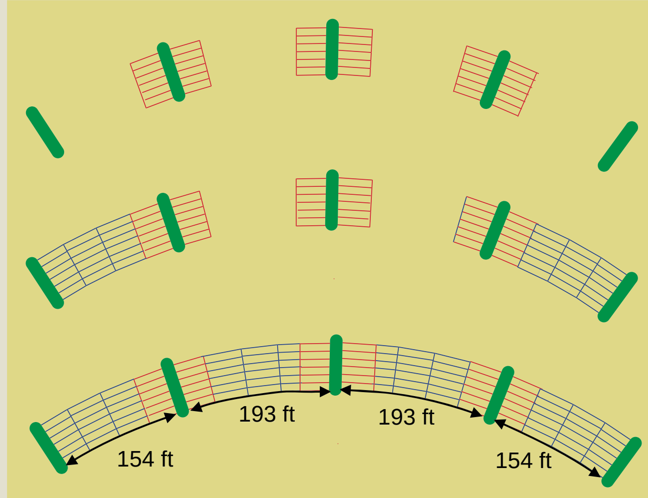

Figure 27. This erection sequence was proposed for a horizontally curved, precast, prestressed concrete girder bridge at the Interstate 480 overpass in Omaha, Neb. Note: 1 ft = 0.305 m.

Materials

The material properties required for many of the design calculations are listed for each component:

- Cast-in-place concrete slab structural thickness = 7.5 in. (190 mm) and 28-day design compressive strength $f_c' = 4.0$ ksi (28 MPa).
- Precast concrete beams' design span = 160 ft (49 m), release concrete strength $f_{ci}' = 5.8$ ksi (40 MPa), service concrete strength $f_c' = 6.5$ ksi (45 MPa), and concrete unit weight $w_c = 0.15$ kip/ft^3 (2400 kg/m^3).
- Prestressing strands are 0.6-in.-diameter (15 mm), seven-wire, low-relaxation strands with an area = 0.217 in.^{2} (140 mm^2), an ultimate strength $f_{pu}' = 270$ ksi (1860 MPa), an initial prestress $f_{pi} = 202.5$ ksi (1397 MPa), and a modulus of elasticity $E_p = 28{,}500$ ksi (197 GPa).
- Reinforcing bars are no. 3 (10M) mild steel with a yield strength $f_y = 60$ ksi (414 MPa), a stress at service $f_s = 24$ ksi (166 MPa), and a modulus of elasticity E_s = 29,000 ksi (200 GPa).

Table 2. Cost of deviators and supports for a typical 400-ft-long prestressing bed

Items	Unit	Cost per unit, $	Quantity	Total cost, $
Straps and rollers	1 set	408	9	3672
Holding plate	1 set	246	9	2214
Steel pile	1 each	400	18	7200
Support plate	1 set	680	9	6120
Sum				19,206
Note: 1 ft = 0.305 m.				

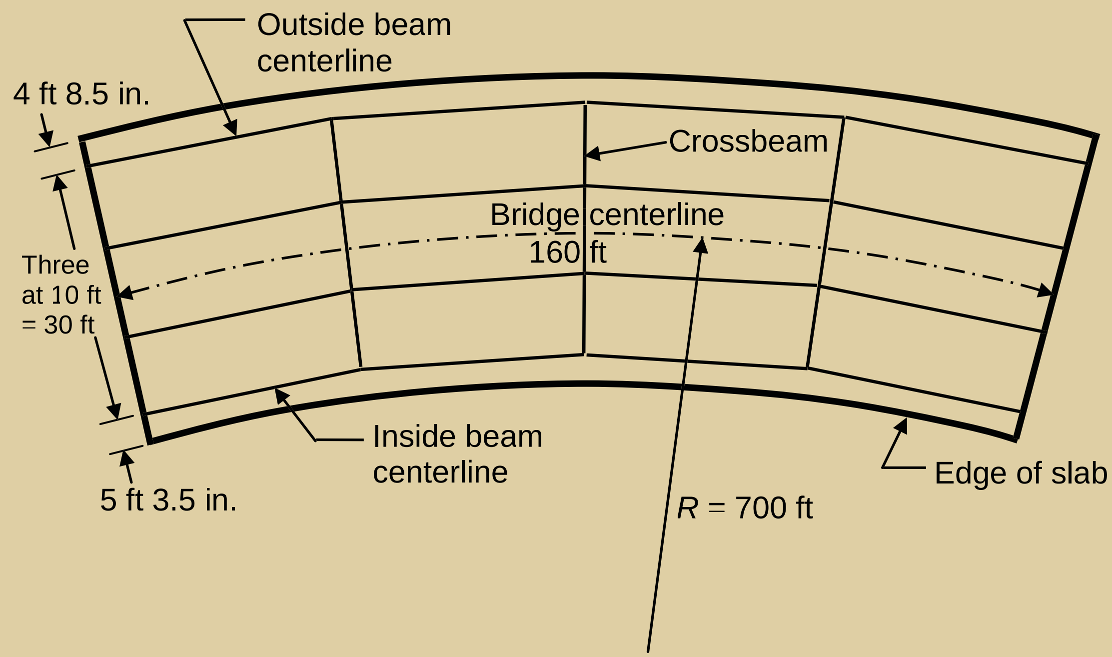

Figure 28. Shown is the plan geometry of the design example. Note: The drawing is not to scale. 1 in. = 25.4 mm; 1 ft = 0.305 m.

Fabrication

NU1800 I-girders are designed according to AASHTO LRFD specifications to act compositely with an 8 in. (200 mm) cast-in-place concrete deck to resist the superimposed dead loads and live loads. In general, the shear force acting on the girder is increased about 25% and moment is increased about 10% compared with those acting on a straight girder design. The superimposed dead loads consist of the railing and a 0.5-in.-thick (13 mm) wearing surface. The cast-in-place concrete haunch over the girder top flange is assumed to be 0.5 in. (13 mm) thick and 48.2 in. (1220 mm) wide. Pretensioning of the NU I-girders can be achieved by using the deviators and the prestressing bed already described in this paper. The total prestressing force is 2110 kip (9390 kN), and each deviator and support must carry a tensile force of 121 kip (539 kN). The stress limits in the concrete may be satisfied by debonding 14 strands at the girder ends, as shown in **Fig. 30**.

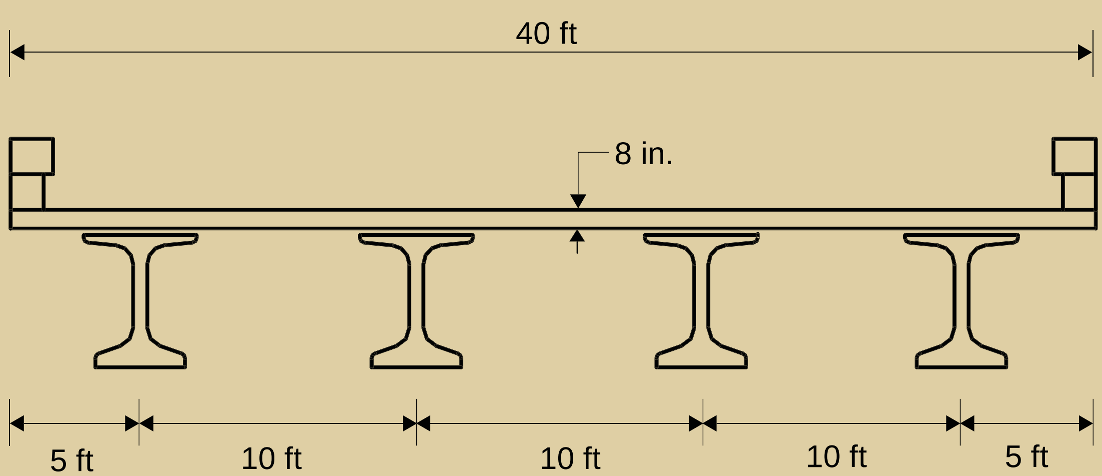

Figure 29. This drawing illustrates the bridge cross section at center span of a chord segment for the design example. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

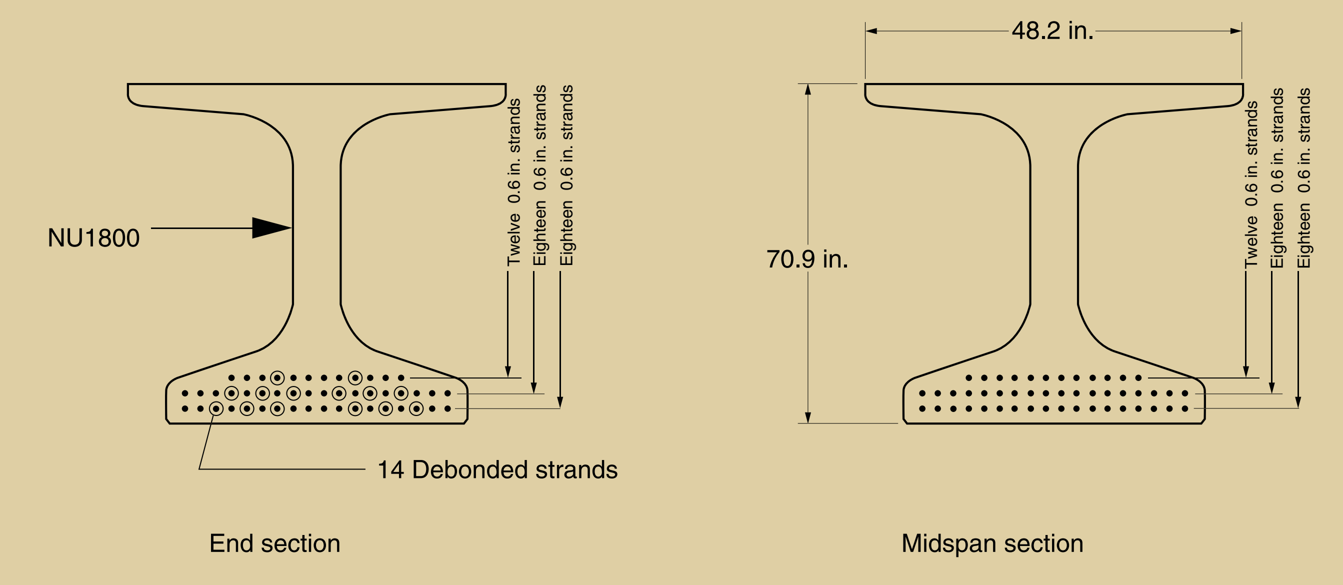

Figure 30. The design example NU1800 I-girder cross section has the illustrated strand pattern. Note: NU = Nebraska University. 1 in. = 25.4 mm.

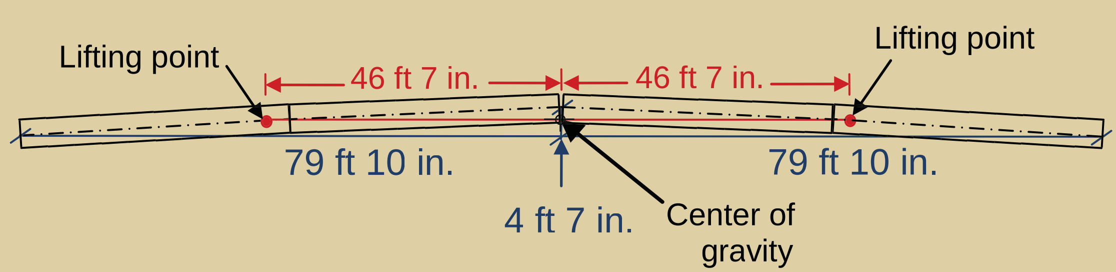

Figure 31. The lifting point locations for the design example were 46 ft 7 in. from the center of gravity. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

Handling, transportation, and erection

On the plan, the pickup and support points must be located on a line through the center of gravity of a curved beam. Based on the geometry, the center of gravity of the 160-ft-long (49 m) girder is located at 20.56 in. (522 mm) from the centerline of the girder. As shown in **Fig. 31**, the center of gravity B is within half of the top flange width of NU1800 at 48.2 in. (1220 mm). It is desirable to install the lifting inserts along the girder centerline, and the locations are simply the intersections of the girder centerline with the line passing through the center of gravity of the girder. The lifting points are on either side of the line of symmetry at a distance of 46 ft 7 in. (14.2 m). The width of the curved girder w to be accommodated on a transporter can be expressed as Eq. (3).

$$w = \left(R + \frac{B}{2}\right) - \left(R - \frac{B}{2}\right)\cos\theta \qquad (3)$$

where

R = 700 ft (213 m)

B = 48.2 in. (1224 mm)

θ = 6.55 degrees

yielding

w = 8.6 ft (2.6 m)

This is less than the maximum allowable width for oversized shipment of 14.5 ft (4.5 m). The total weight of the girder is

$$893 \text{ lb/ft} \times 160 \text{ ft} = 142{,}880 \text{ lb} = 143 \text{ kip (636 kN)}$$

Special 13-axle transporters with a cab for a steerable rear dolly will be required to allow a maximum shipping weight[24] of 314 kip (1397 kN). Other considerations, including turning radius, maximum posted weights along the route, and maximum grade crossings, must be planned.

Temporary bracings are required during the erection of a single curved girder to resist the torsional moment M_t at the ends of a simple-span curved beam due to its self-weight,[23] which can be calculated from Eq. (4).

$$M_t = \frac{WL^2}{24R} = \frac{142.88\left(160^2\right)}{24\left(700\right)} = 218 \text{ kip-ft (296 kN-m)} \quad (4)$$

The torsional moment can be easily resisted by anchoring the girder bottom flanges at abutments and piers. In curved bridges, crossbeams or diaphragms should be designed for the shears and moments resulting from the direction change of the primary moments in the girder at the crossbeams. The longitudinal forces in the bottom flange of a girder line have a transverse component at the location of a crossbeam, similar to the deviator force. The crossbeam must be deep enough to brace the bottom flange to resist this component. Once the girders are braced together and ready to receive the deck, one can proceed as if erecting a curved steel-plate girder bridge.

Conclusion

Can precast concrete girders be used on a curved alignment? How much would it cost relative to a steel-girder design? Which prestressing scheme, pretensioned or post-tensioned concrete systems or a combination of both, is more cost effective? These are the questions often posed by bridge designers. The objectives of this study are to summarize current practice and to assess the feasibility of using curved, precast, pretensioned concrete I-girders for bridge construction. The significant findings from this investigation are summarized as follows:

- Straight precast, prestressed concrete girders and curved deck edges are routinely constructed as chords for horizontally curved alignments in the United States. Post-tensioning may be required if it is desired to have the spans continuous for deck weight.

- Curved, precast, post-tensioned concrete bridges have recently been used successfully. Splicing partial-span segments helped to make a girder look curved. For curvatures less than 3 degrees, a curved bridge with 20-ft-long (6 m) straight-chord girders would appear as a smooth curve. For sharper curvatures, most designers exclusively use curved steel girders.

- Curved, precast, pretensioned concrete bridges have been in common practice in the Netherlands for more than a decade. Box and bathtub girders are preferred for their better torsional rigidity than that of I-girders. Curved, precast, pretensioned concrete bridges are nonexistent in the United States.

- Experimental results showed that a precast, pretensioned concrete beam that is segmented into chord lengths along a curvature can be easily prefabricated. It is feasible to use existing facilities at precast concrete plants to produce full-span, curved, pretensioned concrete I-girders using the deviators and supports proposed in this study. The span range of curved girders can be readily extended using the existing splicing and post-tensioning techniques.

- Preliminary cost analysis has indicated that using curved, precast, pretensioned concrete I-girders has the potential to become the most cost-effective curved-bridge design alternative.

- The design example illustrates that using long-bed, precast, pretensioned concrete I-girder production for curved bridge construction is highly feasible.

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Notation

B = half of the top flange width of the girder

E_p = modulus of elasticity of prestressing steel

E_s = modulus of elasticity of mild-steel reinforcement

f_{pi} = initial tensile stress of prestressing steel

f_s = stress at service of mild-steel reinforcement

f_y = yield strength of mild-steel reinforcement

f_c' = concrete compressive strength

f_{ci}' = average compressive strength of the concrete at release

f_{pu}' = ultimate strength of prestressing steel

L = girder span length

L_c = chord segment length

M_t = torsional moment

R = radius of curvature of the girder

s = maximum offset between the arc and the chord

w = width of curved girder to be accommodated on a transporter

w_c = unit weight of concrete

w_g = girder weight per unit length

W = girder weight

θ = degree of curvature

θ' = central angle of the segment

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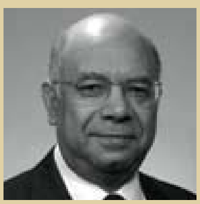

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Synopsis

The use of curved, precast, pretensioned concrete girders as an alternative to curved post-tensioned concrete girders and curved steel girders may have many advantages. A feasibility study has shown that the pretensioned concrete system is more cost effective than the other two. Many bridge designers have gradually recognized this trend.

This paper summarizes a review of the current practice of horizontally curved bridge construction. A $^1/_{10}$-scale, curved, precast, pretensioned concrete beam was fabricated in the laboratory to illustrate the feasibility of fabrication in a precast concrete plant. A cost analysis was conducted to compare the estimated cost of a curved, precast, pretensioned concrete I-girder with that of a curved, precast, post-tensioned concrete I-girder. The results showed that the pretensioned concrete system has the potential to become the most cost-effective system for curved bridge construction.

Keywords

Bridge, cost analysis, curved, girder, pretensioning.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process.

Reader comments

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