



Use of 0.7-in.-diameter strands in pretensioned bridge girders

**George Morcoux,
Kromel Hanna,
and Maher K. Tadros**

In 1988, U.S. strand manufacturers proposed increasing the diameter of prestressing strands used in pretensioned concrete bridge girders from 0.5 in. (13 mm) to 0.6 in. (15 mm) while maintaining the minimum spacing between strands at 2 in. (50 mm). The objective of this proposal was to increase the total prestressing force transferred to the concrete by 42%, which significantly improves the structural capacity and durability of bridge girders.

At that time, the development-length equation, which was developed in the early 1960s based on research conducted by Hansen and Kaar,¹ stated that the minimum spacing between strands required to ensure adequate bond with the surrounding concrete must be equal to four times the strand diameter. This means that 0.6-in.-diameter (15 mm) strands cannot be used at a spacing of less than 2.4 in. (61 mm).

This large spacing negates the advantages of having larger-diameter strands because it results in a prestressing force per unit area of concrete less than that of 0.5-in.-diameter (13 mm) strands at 2 in. (50 mm) spacing. In addition, most manufacturers refused to accommodate the new spacing requirements because of the high costs associated with retooling their prestressing beds and equipment. Therefore, the Federal Highway Administration (FHWA) issued a memorandum that forbade the use of 0.6-in.-diameter (15 mm) strands at 2 in. spacing on public structures until further studies were conducted to ensure their safety.²

After several years of research conducted by Buckner³ and the introduction of the development-length magnification factor k , the FHWA announced in 1996 that the minimum spacing for 0.6-in.-diameter (15 mm) strands would be 2 in. (50 mm) and the minimum spacing for 0.5-in.-diameter (13 mm) strands would be 1.75 in. (45 mm). Shortly after that announcement, the American Association of State

- Full-scale specimens were tested to investigate production concerns and evaluate transfer length, development length, and end-zone cracking associated with 0.7-in.-diameter (18 mm) strands.
- A positive production experience and predictable test results indicated that 0.7-in.-diameter strands can be used with no major changes to current production practices or design criteria according to the current American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*.
- Using these large-diameter strands in pretensioned concrete girders at 2 in. (50 mm) spacing will result in an increase of approximately 35% in the prestressing force compared with the same number of 0.6-in.-diameter (15 mm) strands, thus allowing for longer spans, shallower depths, and wider girder spacing.

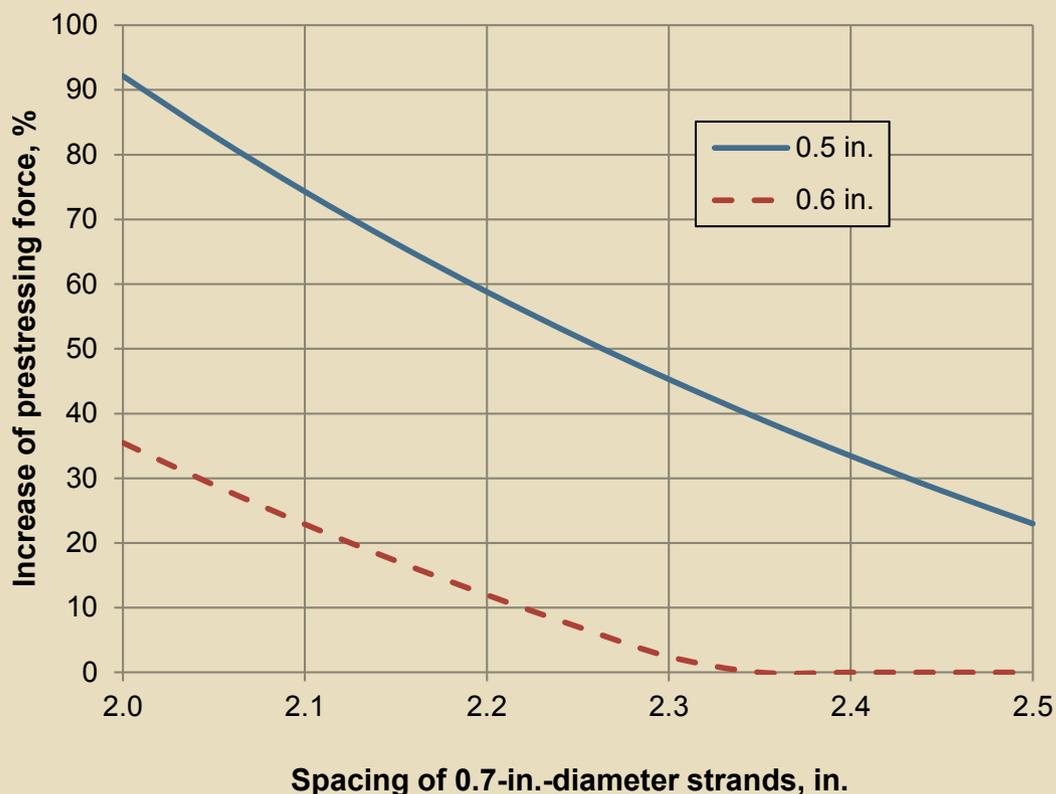


Figure 1. Increase of prestressing force due to using 0.7-in.-diameter strands at different spacings when compared with 0.5-in.- and 0.6-in.-diameter strands at 2 in. spacing. Note: 1 in. = 25.4 mm.

Highway and Transportation Officials (AASHTO) adopted the new FHWA spacing requirements in its bridge design specifications.

The 0.7-in.-diameter (18 mm) strands were first used in external prestressing cables of the Narrows Bridge over the Swan River in Perth, Australia, which was opened to traffic in November 1959.⁴ Since then, several bridges around the world were built using 0.7-in.-diameter (18 mm) strands for unbonded, external post-tensioning. In the United States, only two manufacturers currently produce 0.7-in.-diameter strands, which are primarily used for mining applications.

ASTM A416-06⁵ is the first standard that introduces 0.7-in.-diameter (18 mm), Grade 270 (1860 MPa), low-relaxation strand for prestressed concrete applications. The AASHTO M203-07⁶ specifications followed exactly the same requirements as ASTM A416 for 0.7-in.-diameter strands. These requirements are similar to those of smaller-diameter strands with regard to minimum breaking strength (270 ksi [1860 MPa]), yield strength (243 ksi [1680 MPa]), and elongation (3.5%).^{5,6}

The 0.7-in.-diameter (18 mm) strands have a cross-sectional

area of 0.294 in.² (190 mm²) and weigh 1 lb/ft (1.5 kg/m). Prestressing one 0.7-in.-diameter strand to 75% of its ultimate strength results in a prestressing force of 59.5 kip (265 kN), which is 35% higher than that of 0.6-in.-diameter (15 mm) strand and 92% higher than that of 0.5-in.-diameter (13 mm) strand.

Russell et al.⁷ conducted a detailed study on optimized sections for high-strength concrete bridge girders in 1996. This study evaluated the effect of strand size and spacing on the capacity and cost of different concrete bridge girders at various concrete strengths. Despite the unavailability of 0.7-in.-diameter (18 mm) strand in the U.S. market at the time, its cost-effectiveness was compared with that of other strand sizes.

This comparison indicated that using 0.7-in.-diameter (18 mm) strands at 2 in. (50 mm) in a 10,000 psi (69 MPa) bulb-tee girder (BT-72) results in the longest girder span and most cost-effective superstructure compared with 0.5-in.-diameter (13 mm) and 0.6-in.-diameter (15 mm) strands.⁸ Another analytical study conducted by Vadivelu and Ma⁹ has shown that the span capacity of BT-72 with 0.6-in.-diameter strands can be achieved by using BT-54 with 0.7-in.-diameter strands.

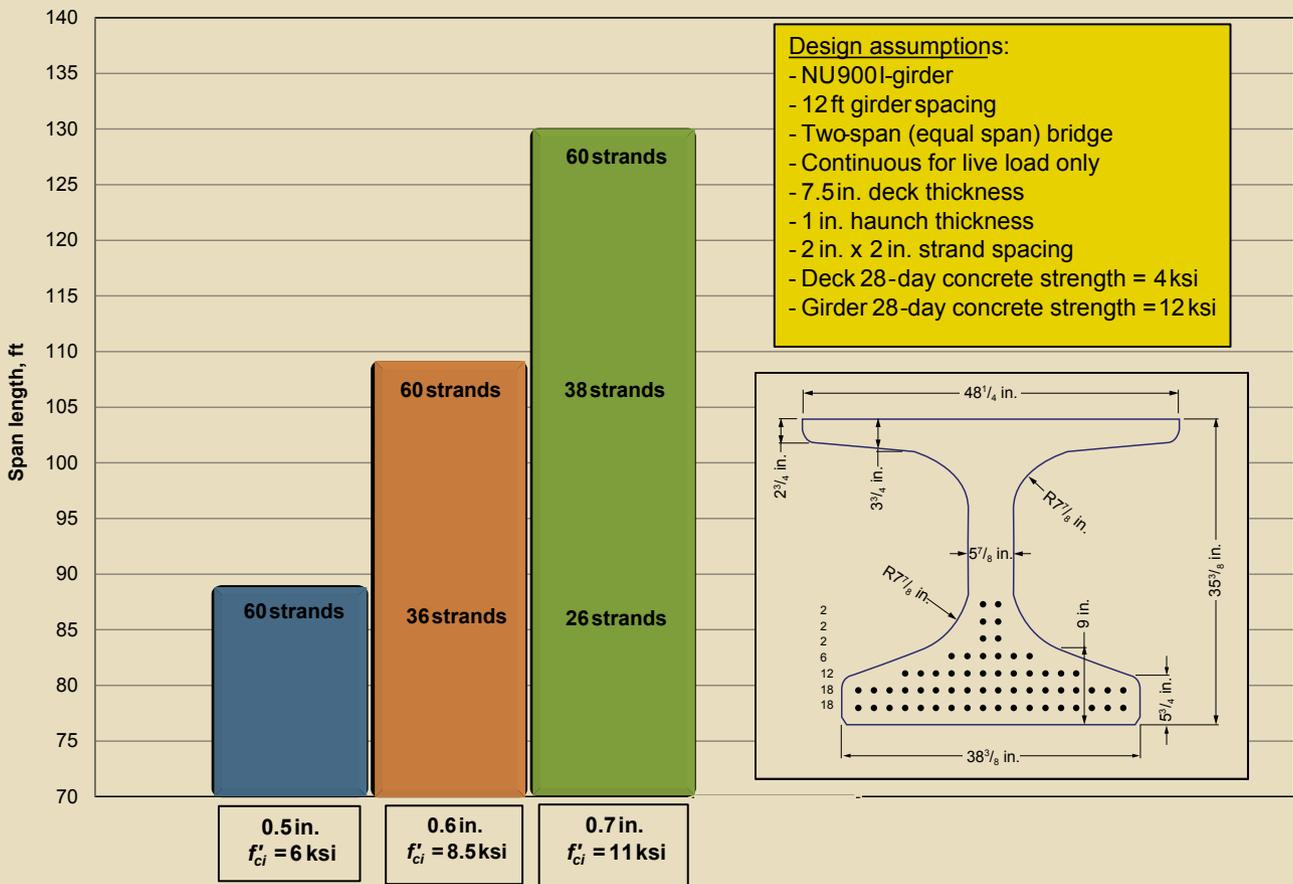


Figure 2. Span capacity of NU900 I-girder when different strand diameters are used. Note: f'_{ci} = girder concrete strength at release. 1 in. = 25.4 mm; 1 ft = 0.305 m; 1 ksi = 6.895 MPa.

Figure 1 shows the increase in prestressing force when 0.7-in.-diameter (18 mm) strands are used in pretensioned concrete girders at different horizontal and vertical spacing compared with that of 0.6-in.-diameter (15 mm) and 0.5-in.-diameter (13 mm) strands at 2 in. (50 mm) spacing. This figure demonstrates the significant increase in prestressing force that can be applied to the bottom flange of a concrete girder when 0.7-in.-diameter strands are used at smaller spacing.

For example, NU900 I-girder, the smallest girder of the NU series,¹⁰ can span up to 89 ft (27 m) using sixty 0.5-in.-diameter (13 mm) strands and up to 109 ft (33.2 m) using sixty 0.6-in.-diameter (15 mm) strands. Sixty is the maximum number of strands in NU girders at 2 in. (50 mm) spacing. However, the same girder can span up to 130 ft (39.6 m) when sixty 0.7-in.-diameter (18 mm) strands are used.

This example was calculated using the *AASHTO LRFD Bridge Design Specifications*¹¹ service III limit state for a two-span bridge continuous for live load assuming 12 ft (3.6 m) spacing between girder lines; 12 ksi (83 MPa) final concrete strength; 4 ksi (28 MPa), 7.5-in.-thick (191 mm), cast-in-place concrete deck; and 1 in. (25 mm) haunch.

Figure 2 shows the cross-section dimensions of NU900 I-girder, design assumptions, and the span comparison when the three different strand diameters are used. The minimum required girder concrete strength at release increases as the prestressing force increases, which indicates the need for higher-strength concrete when 0.7-in.-diameter (18 mm) strands are used.

Another advantage of 0.7-in.-diameter (18 mm) strands is that fewer strands and chucks provide the same amount of prestressing force of 0.6-in.-diameter (15 mm) strands. This results in a significant labor savings during the jacking and release operations in addition to higher flexural capacity due to lowering the center of gravity of the strands. Figure 2 also shows that the NU900 I-girder can span 109 ft (33.2 m) using only thirty-eight 0.7-in.-diameter strands compared with sixty 0.6-in.-diameter strands, which is 22 (37%) fewer strands to jack and release per girder. The same girder can span 89 ft (27 m) using only twenty-six 0.7-in.-diameter strands compared with sixty 0.5-in.-diameter (13 mm) strands, which is 34 (57%) fewer strands to jack and release per girder.

Figure 3 shows the number of prestressing strands required for a NU900 I-girder at various span lengths and

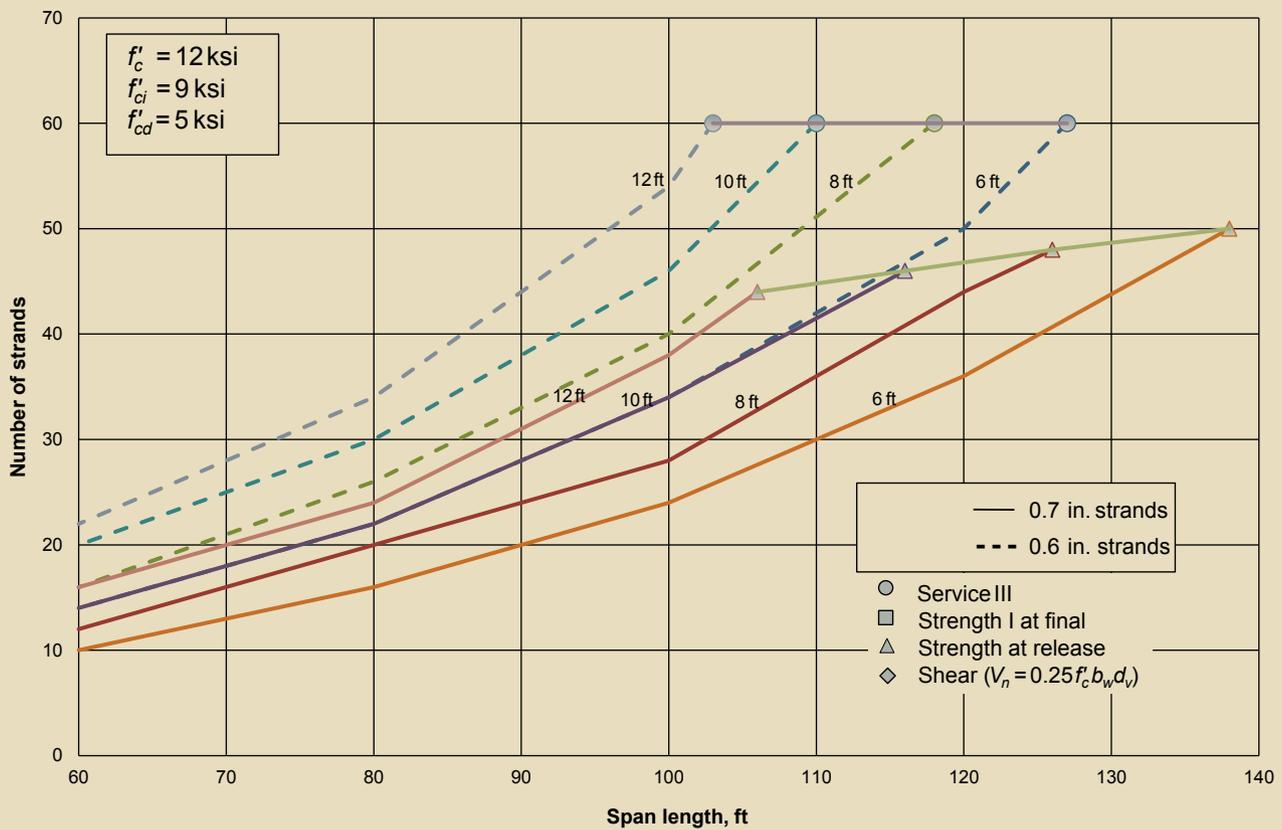


Figure 3. Design chart for NU900 using 0.6-in.- and 0.7-in.-diameter strands. Note: b_w = width of girder web; d_v = shear depth; f'_c = girder 28-day concrete strength; f'_{cd} = deck 28-day concrete strength; f'_{ci} = girder concrete strength at release; V_n = nominal shear capacity. 1 in. = 25.4 mm; 1 ft = 0.305 m; 1 ksi = 6.895 MPa.

girder spacing when 0.6-in.-diameter (15 mm) and 0.7-in.-diameter (18 mm) strands are used. This design chart demonstrates the effect of using larger-diameter strands on increasing girder span and reducing girder spacing, which could result in significant savings in the total bridge construction cost.

In the past few years, the use of high-strength concrete (greater than or equal to 10 ksi [69 MPa]) in precast, prestressed concrete bridge girders has become a common industry practice. For this development to be beneficial in making high-strength girders, a parallel development in prestressing strands is needed to enhance the flexural capacity of the girder. Combining the use of 0.7-in.-diameter (18 mm) strands with high-strength concrete will significantly improve the flexural capacity of bridge girders, allowing for longer spans, shallower depths, and wider girder spacing.

Figure 4 shows the steady increase in the positive moment capacity of NU900 with concrete strength when using 0.7-in.-diameter (18 mm) strands, which is not the case with 0.5-in.-diameter (13 mm) and 0.6-in.-diameter (15 mm) strands. This is because the higher tensile force of the larger strand diameter results in a deeper compression block that benefits from higher concrete strength in

the top flange. Alternatively, Fig. 4 also demonstrates that higher compressive strength of the concrete is essential for the strand to be fully used, which means that the strand's ultimate stress is higher than its yield strength of 243 ksi (1680 MPa). This confirms the conclusions made by Russell et al.⁸ regarding optimized girder design that combines 0.7-in.-diameter strands and 10 ksi (69 MPa) concrete.

Despite the advantages of using 0.7-in.-diameter (18 mm) strands in pretensioned concrete bridge girders, extensive investigation was needed to evaluate the effect of larger strand diameter on girder design as well as the production challenges associated with handling heavier and stiffer strands. Current AASHTO LRFD specifications provide requirements for the transfer length, development length, end-zone reinforcement, and minimum spacing of prestressing strands for diameters 0.5 in. (13 mm) and 0.6 in. (15 mm), but not 0.7 in. (18 mm). The applicability of these requirements to 0.7-in.-diameter strands needed to be experimentally evaluated.

This paper presents the results of conducted to develop quality control and design criteria required to introduce 0.7-in.-diameter (18 mm) strands at 2 in. (50 mm) spacing in pretensioned concrete I-girders for bridge construction. The focus of this paper is to investigate the challenges as-

sociated with the design and production of I-girders using 0.7-in.-diameter strands. Two full-scale NU900 I-girders (A and B) were fabricated and tested to experimentally investigate these changes.

AASHTO LRFD specifications affected by strand diameter

According to the 2007 AASHTO LRFD specifications with 2008 interim revisions,¹¹ the transfer length and development length for fully bonded prestressing strands are calculated as follows:

$$l_t = 60d_b \quad (\text{Section 5.11.4.1})$$

l_t = transfer length

d_b = nominal strand diameter

$$l_d \geq k \left(f_{ps} - \frac{2}{3} f_{pe} \right) d_b \quad \text{Eq. (5.11.4.2-1)}$$

l_d = development length

k = development-length magnification factor

= 1.0 for pretensioned panels, piling, and other pretensioned members with a depth of less than or equal to 24.0 in. (610 mm)

= 1.6 otherwise

f_{ps} = average stress in prestressing steel

f_{pe} = effective stress in prestressing steel

For partially bonded prestressing strands, the development length should be determined using Eq. (5.11.4.2-1) with k equal to 2.0.

Transfer length is the length of the strand, measured from the end of the prestressed concrete member, over which the effective prestress is transferred to the concrete. The transferred force along the transfer length is assumed to increase linearly from zero at the end of the member to the effective prestress at the end of the transfer length. Transfer length is important for shear design and concrete stresses at release at girder ends. An overestimated transfer length might result in inefficient shear design and higher-than-predicted stresses at release, while an underestimated transfer length might result in inadequate shear design and lower-than-predicted stresses at release.

The development length of prestressing strands is defined as the minimum strand embedment in concrete required to reach the ultimate capacity of the section without strand

slippage. Thus, at the end of the development length, the ultimate stress in the strand could be reached without strand-concrete bond failure. The development length is necessary for identifying the critical sections in flexure and calculating their ultimate capacities. An underestimated development length might result in a lower girder capacity at sections within the development length, while an overestimated development length might result in uneconomical design that is overreinforced.

The AASHTO LRFD specifications' equations for transfer and development length of prestressing strands are applicable for bridge girders with a minimum concrete strength of 4.0 ksi (27.6 MPa) (section 5.4.2.1) and a bottom flange reinforcement as specified in section 5.10.10.2). These equations were developed based on the results of experimental investigations conducted on prestressing strands with diameters up to 0.5 in. (13 mm).

The k factor accommodates, in part, the use of 0.6-in.-diameter (15 mm) strands as well as the new spacing requirements (section 5.11.3.3.1). These requirements stipulate that the distance between pretensioning strands at member ends within the transfer length shall not be less than a clear distance taken as 1.33 times the maximum size of the aggregate nor less than the center-to-center distances specified as 2 in. (50 mm) for 0.6-in.-diameter strands and 1.75 in. (45 mm) for 0.5-in.-diameter (13 mm) strands. The requirements also allow bundling up to four strands at locations other than member ends so that the minimum clear distance between groups of bundled strands is not less than 1.33 times the maximum size of the aggregate or 1.0 in. (25 mm). By considering the 0.7-in.-diameter (18 mm) strand as a bundle of two 0.5-in.-diameter strands, the 2 in. center-to-center spacing can be considered acceptable by the current specifications except at the member ends, which is experimentally investigated in this study.

Also, according to the 2007 AASHTO LRFD specifications section 5.10.10.1, the total area of reinforcement located within the distance $h/4$, where h is the overall height of the girder, from the end of the girder should not be less than 4% of the total prestressing force at transfer divided by 20 ksi (138 MPa). This reinforcement is required for crack control and resisting the bursting force at the girder ends due to prestressing. Using larger strand diameter results in a higher concentration of prestressing force per unit area of concrete and might, consequently, necessitate a different amount or distribution of end-zone reinforcement.

Design and fabrication of girder A

Girder A was an NU900 girder that had a total length of 40 ft (12.1 m) and a simple span of 39 ft (11.8 m). **Figure 5** shows the cross section and reinforcing details of girder A. This section had adequate flexural and shear capacities for

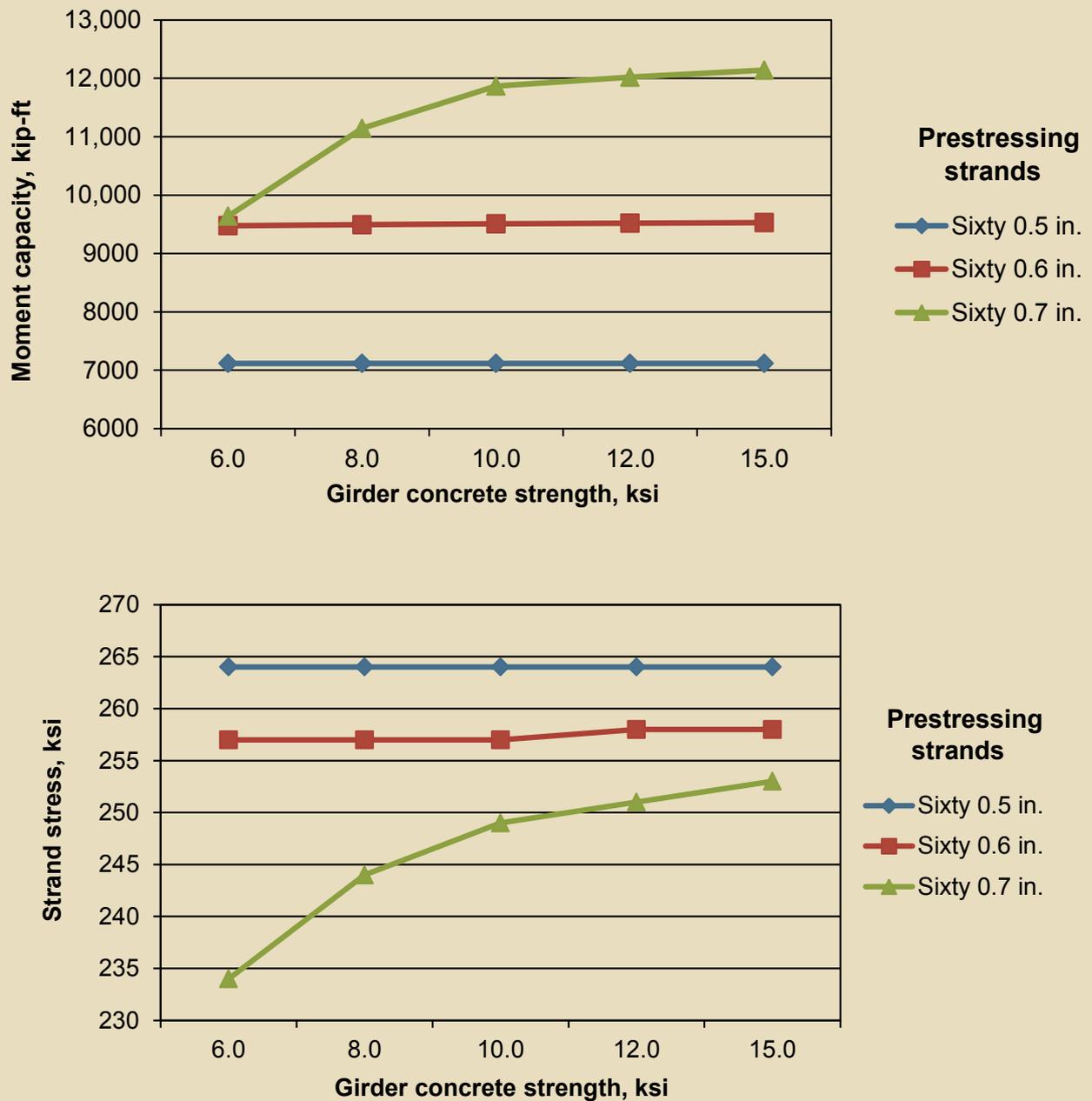


Figure 4. Effect of girder strength on ultimate moment capacity and ultimate strand stress when different strand diameters are used. Note: 1 kip-ft = 1.356 kN-m; 1 ksi = 6.895 MPa.

a simply supported bridge to span 87 ft (26.3 m) with 8 ft (2.4 m) spacing between girder lines designed according to AASHTO LRFD specifications. A total of twenty-four 0.7-in.-diameter (18 mm), Grade 270 (1860 MPa) prestressing strands tensioned to $0.75f_{pu}$ (where f_{pu} is the ultimate strength of prestressing steel) were placed at a horizontal spacing of 2.2 in. (56 mm) and a vertical spacing of 2.25 in. (57.2 mm). Shear reinforcement was two no. 4 (13M), Grade 60 (420 MPa) bars at 3 in. (76 mm) on center along

the girder length, while end-zone reinforcement was eight no. 6 (19M), Grade 60 bars spread over 8 in. (200 mm) at each girder end. Bottom-flange reinforcement of two no. 3 (10M), Grade 60 hairpins at 3 in. on center were placed along 45 in. (1140 mm) at each girder end. Two 0.5 in. (13 mm), Grade 50 (350 MPa) bearing plates were placed at each girder end and connected to the concrete by eight welded studs. **Figure 6** shows the girder reinforcement before concrete placement.

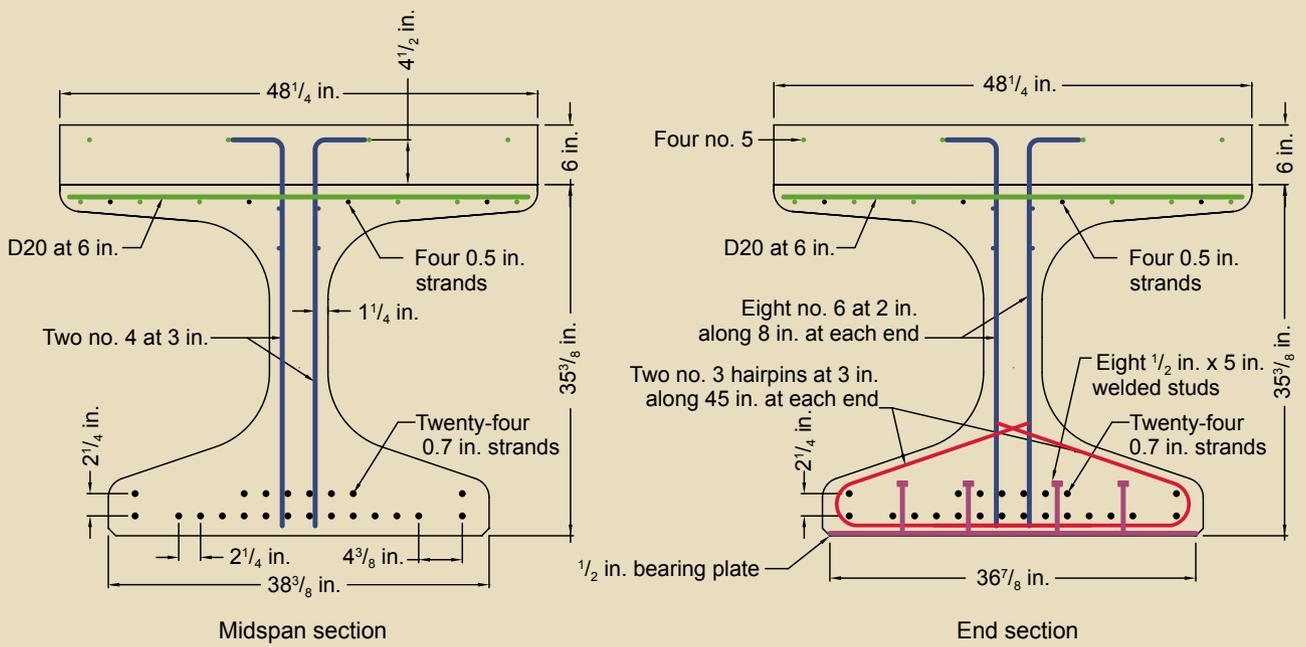


Figure 5. Girder A sections and reinforcing details. Note: no. 3 = 10M; no. 4 = 13M; no. 5 = 16M; no. 6 = 19M; 1 in. = 25.4 mm.



Figure 6. End-zone reinforcement.

The girder was made of self-consolidating concrete (SCC) with specified 1-day compressive strength of 6 ksi (41 MPa) and 28-day compressive strength of 8 ksi (55 MPa). SCC was used because it is the present practice for fabricating bridge girders in Nebraska. Upon reaching the specified release strength, strands were detensioned using a flame cut due to the unavailability of gradual release at the prestressing bed used for girder production. Girder ends experienced a few cracks that were narrow and short and therefore did not represent any concern. This cracking might be due to the lack of anchorage of the end-zone reinforcement at the bottom flange. **Figure 7** shows the end zone of girder A immediately after detensioning.

Then, 6 ksi (41 MPa) concrete diaphragms were cast at each girder end. Eight strands were bent and embedded in each end diaphragm, a common practice in I-girder bridge construction in Nebraska. Also, a 6-in.-thick (150 mm), 8 ksi (55 MPa) concrete deck was placed over the full width of the girder top flange to simulate the composite section that has a 4 ksi (28 MPa) concrete deck and NU900 girder with 8 ft (2.4 m) spacing.

The challenges associated with the fabrication of girder A can be categorized into two groups: handling larger-diameter strands and jacking and release of strands with higher prestressing force.¹² Because the stiffness of a round bar is a function of its moment of inertia, 0.7-in.-diameter (18 mm) strands are 85% stiffer than 0.6-in.-diameter (15 mm) strands. Having these stiffer strands shipped in the same coils used in shipping smaller-diameter strands caused difficulties in uncoiling the strands and threading them through the bulkheads. However, we anticipate that as 0.7-in.-diameter strands become common, these difficulties will be overcome. Also, strand manufacturers could use larger coils for shipping 0.7-in.-diameter strands to facilitate handling.

The other group of challenges relates to jacking and releasing strands with higher prestressing force. The required prestressing force for tensioning at 75% ultimate strength is 59.5 kip (265 kN) for the 0.7-in.-diameter (18 mm) strands. In addition, anchorage seating losses of about 3.5 kip (15.6 kN) per strand must be added to the required initial force for this production line. The total force required was therefore approximately 63 kip (280 kN) per strand. This exceeded the 50 kip (222 kN) capacity of the monostrand jack used for this girder, which was designed for 0.6-in.-diameter (15 mm) strands. The solution was to increase the monostrand jack capacity by upgrading the pump valves, which provided a jacking capacity that exceeded the required prestressing force.

Two types of chucks were used for this girder: single use and reusable. Both have an outer diameter of 2 in. (50 mm). The total lengths of the reusable and single-use chucks are 4½ in. (114 mm) and 2⅛ in. (54 mm), respec-



Figure 7. End-zone cracking in girder A.

tively. The single-use chucks are cheaper and work well for the dead end but not for the jacking end. The jaws of the single-use chucks seat onto the strand during jacking and cannot be released for incremental jacking.

Reusable chucks, similar to standard 0.6 in. (15 mm) reusable chucks, are available for the 0.7-in.-diameter (18 mm) strand. The reusable chucks worked well during prestressing; however, some were not easily removable after prestressing. After the strands were tensioned to the desired force, fabrication continued without any unusual difficulties. No strands were debonded or draped in this girder.

Design and fabrication of girder B

Girder B was also a 40-ft-long (12.2 m) NU900 that spanned 39 ft (11.9 m). **Figure 8** shows the cross-section and reinforcement details. This section has adequate flexural and shear capacities for a simply supported bridge to span 87 ft (26.3 m) with 12 ft (3.6 m) spacing between girder lines, designed according to AASHTO LRFD specifications. The girder was pretensioned using thirty 0.7-in.-diameter (18 mm), Grade 270 (1860 MPa), low-relaxation prestressing strands spaced at 2 in. (50 mm) and tensioned to $0.66f_{pu}$ due to the limited capacity of the prestressing bed. Four partially prestressed (19.6 ksi [131 MPa]),

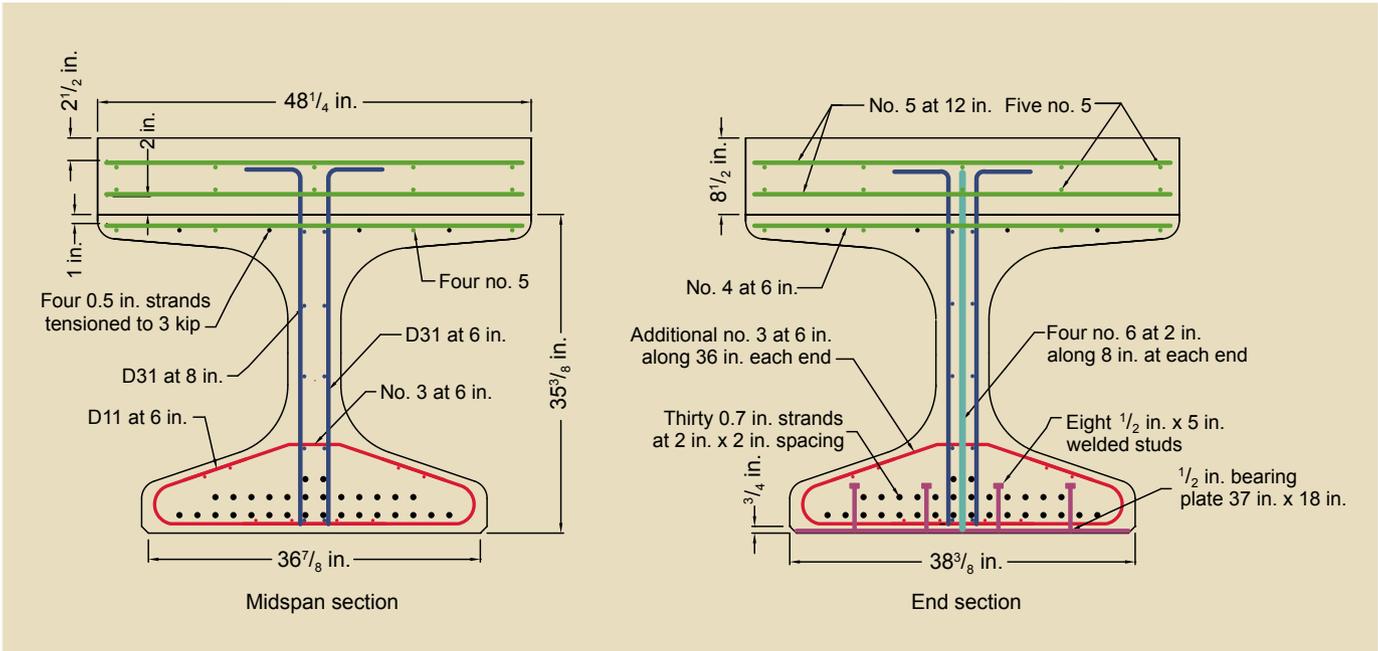


Figure 8. Girder B sections and reinforcing details. Note: no. 3 = 10M; no. 4 = 13M; no. 5 = 16M; no. 6 = 19M; 1 in. = 25.4 mm; 1 kip = 4.448 kN.

0.5-in.-diameter (13 mm) strands were placed in the top flange to control cracking at release, in addition to four no. 5 (16M), Grade 60 (420 MPa) bars used as compression reinforcement. The shear reinforcement consisted of two orthogonal welded-wire reinforcements (WWRs) made of D31 (MD200) at 6 in. (150 mm) spacing in the horizontal direction and 8 in. (200 mm) spacing in the vertical direction. The end zone was reinforced using four no. 6 (19M), Grade 60 bars at 2 in. (50 mm) spacing along the girder axis. Two 5-in.-thick (13 mm), Grade 50 (350 MPa) steel plates were placed at the girder ends and anchored using eight 0.5-in.-diameter headed studs on each plate. The bottom flange was reinforced using two D11 (MD 70) WWR at 6 in. (150 mm) spacing and a no. 3 (10M) cap bar to enclose the prestressing strands along the entire girder length, in addition to a no. 3 bar at 6 in. spacing along 3 ft (0.9 m) from the girder ends. **Figure 9** shows the girder reinforcement before concrete placement.

The girder was made of high-strength concrete that has a specified 1-day concrete compressive strength of 12 ksi (83 MPa) and 28-day concrete compressive strength of 15 ksi (104 MPa). Upon reaching the specified release strength, strands were detensioned using a flame cut similar to girder A; however, girder ends did not experience any visible cracks (**Fig. 10**). This was primarily due to the significantly higher concrete strength at release and the adequate anchorage of end-zone reinforcement at the bottom flange. Then, 6 ksi (41 MPa) concrete diaphragms were cast at each girder end. Ten strands were bent and embedded in the end diaphragms. An 8.5-in.-thick (216 mm), 12 ksi concrete deck was placed over the top



Figure 9. End-zone reinforcement detail of girder B.



Figure 10. End-zone cracking in girder B.

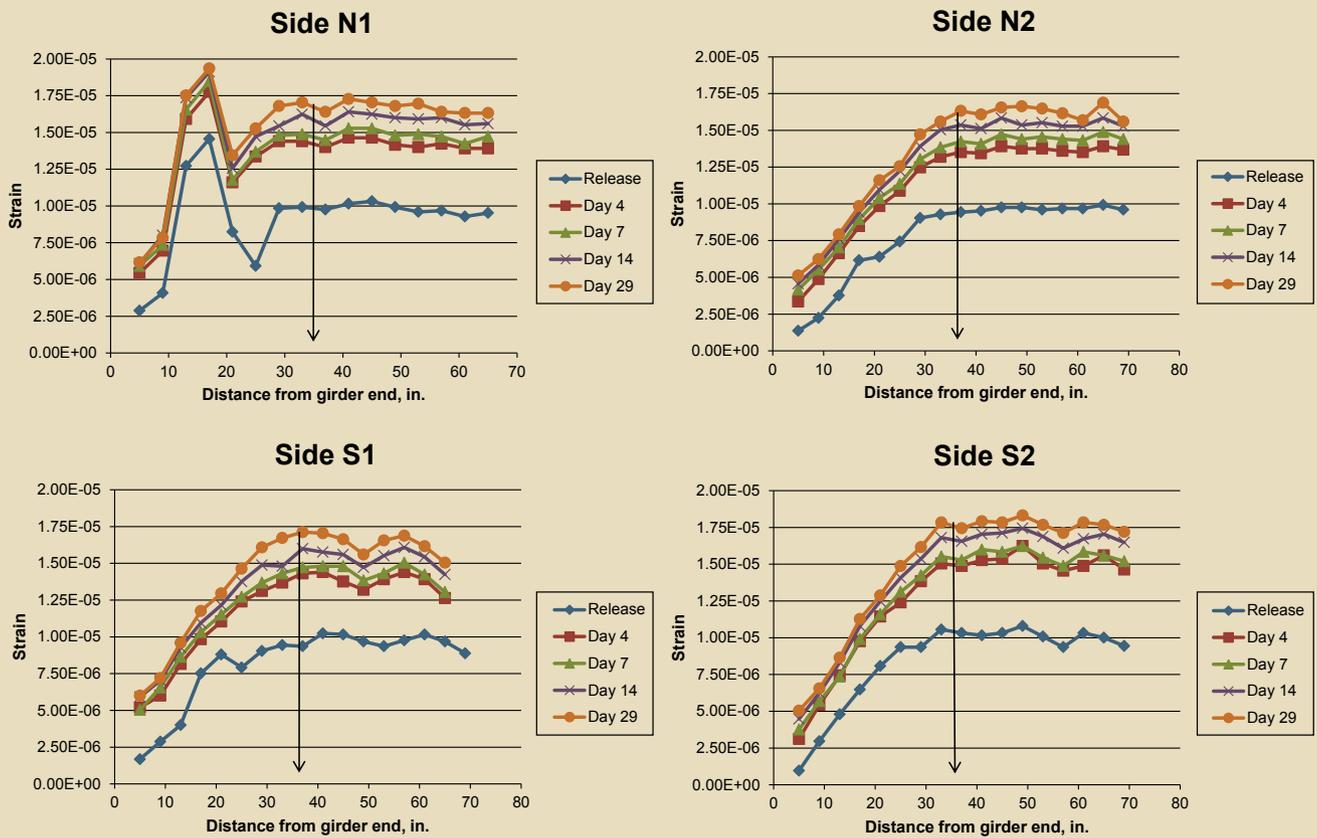


Figure 11. Strain versus distance for detachable mechanical gauge readings on girder A. Note: 1 in. = 25.4 mm.

flange of the girder to simulate the composite section that has a 4 ksi (28 MPa) deck and NU900 girder with 12 ft (3.6 m) spacing.

Fabrication of girder B did not present any challenges to the production team because they became familiar with handling 0.7-in.-diameter (18 mm) strands in the fabrication of girder A. No strands were debonded or draped in this girder.

Testing of girders A and B

To measure the transfer length of 0.7-in.-diameter (18 mm) strands, detachable mechanical (DEMEC) gauges were placed at the ends of girder A along the sides of the bottom flange at the elevation of the centroid of prestressing strands. These gauges were attached to the concrete surface before release using rapid-set glue. The number of DEMEC gauges used in each side was 19 at 4 in. (100 mm) spacing to ensure accurate readings and cover the predicted transfer length of 42 in. (1070 mm). DEMEC readings were taken at 1, 7, 14, 21, and 28 days using a caliper gauge. The change in the measured distance between DEMEC gauges was used to calculate the strain in the concrete at different ages.

The transfer length can be determined using the 95%

average maximum strain (AMS) method as noted by Russell and Burns.⁷ After prestress release, the prestressed concrete strain is zero at the girder ends, then increases and becomes relatively constant as the distance from the girder end increases and the strand fully transfers its force to the girder. The point at which the strain becomes constant distinguishes where all of the prestressing forces are transferred to the concrete. The transfer length can be determined by measuring the distance from the girder end to the point at which 95% of the maximum concrete strain is achieved. **Figure 11** shows the strain profiles obtained from DEMEC gauge readings on the sides (1 and 2) of the girder ends (S and N).

According to Fig. 11, the average transfer length of 0.7-in.-diameter (18 mm) strands calculated using the AMS method was approximately 35 in. (890 mm). This value matches the value $50d_b$ predicted using the American Concrete Institute's (ACI's) *Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary (ACI 318R-08)*.¹³ It is slightly less than the $60d_b$ predicted using 2007 AASHTO LRFD specifications. Another observation in Fig. 11 is the change in strain with time. This is primarily due to shrinkage and creep of the concrete, which is more rapid at early ages. Similar strain profiles were developed for girder B. However, the average transfer length of 0.7-in.-diameter strands calculated using the

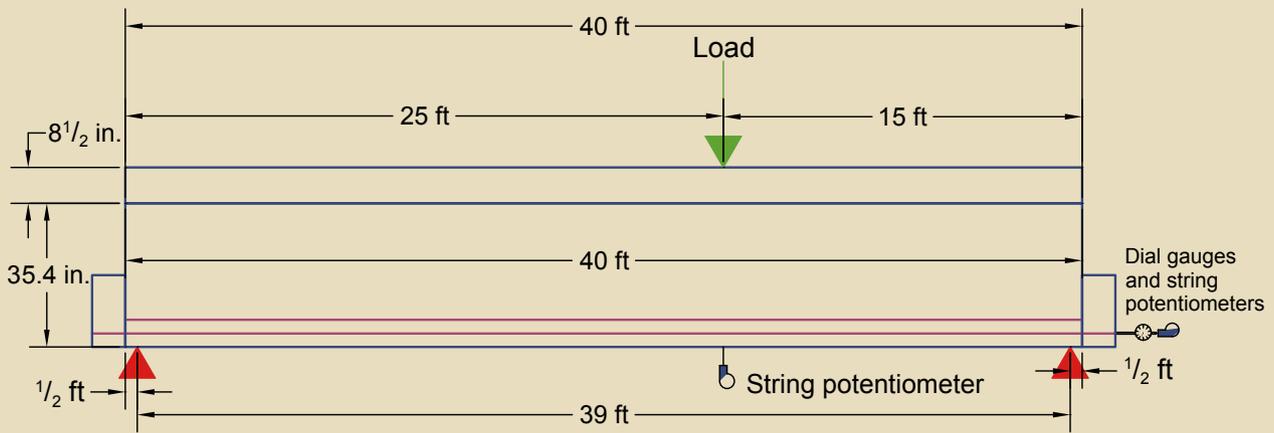


Figure 12. Test setup for girders A and B. Note: P = applied load. 1 in. = 25.4 mm; 1 ft = 0.305 m.

AMS method was 27 in. (690 mm), which is less than that of girder A due to the high compressive and bond strength of the concrete used in girder B.

Girders A and B were designed according to the AASHTO LRFD specifications to carry a point load 15 ft (4.5 m) from the girder end (**Fig. 12**). This is because 15 ft is the predicted development length of 0.7-in.-diameter (18 mm) strands according to AASHTO LRFD specifications' section 5.11.4.2. For girder A, the theoretical flexural capacity of the composite section was estimated at 5476 kip-ft (7424 kN-m), which corresponds to a point load of 582 kip (2590 kN), including the weight of the girder. For girder B, the theoretical flexural capacity of the composite section was estimated at 7295 kip-ft (9890 kN-m), which corresponds to a point load of 779 kip (3460 kN), including the weight of the girder. These theoretical capacities were estimated using strain compatibility and specified material properties. Figure 12 also shows the test setup for the two girders.

String potentiometers (ST-POTs) were used to measure the deflection of the girder directly under the load. Also, ST-POTs and analog dial gauges were attached to the strands extending from end diaphragms to measure strand-end slippage during development-length testing. Strand slippage under the ultimate load indicates bond failure, or the inability to develop the strand within the predicted length. If the girder developed ultimate flexural capacity without strand slip or brittle bond failure, then it can be concluded that the actual development length is equal to or less than the predicted value.

To determine the ultimate capacity of the two girders more accurately, actual material properties were determined through testing. **Figure 13** shows the compressive strength of the concrete used in girders A and B versus time. This figure indicates that the actual concrete compressive strengths of girders A and B at the time of testing were 7.9 ksi (54 MPa) and 17.4 ksi (120 MPa), respectively. **Fig-**

ure 14 also shows the actual stress-strain diagram of the 0.7-in.-diameter (18 mm) strands used in pretensioning the two girders. **Table 1** lists the measured load at 1% strain, peak load, modulus of elasticity, and ultimate elongation for the three tested specimens as well as those specified by ASTM A416-06 and AASHTO M203-07. Actual concrete and strand properties were used in predicting the ultimate flexural capacity of the two girders.

Figure 15 shows the load-deflection curves for development length testing of girders A and B. This figure indicates that the maximum load carried by girder A was 600 kip (2670 kN), which is higher than the value predicted using specified and actual material properties. However, the failure mode was not flexural as expected. Web-shear cracking occurred at a load of approximately 250 kip (1110 kN) and propagated as the load increased through the bottom flange. Sudden, brittle shear failure occurred at the ultimate load due to inadequate anchorage of shear reinforcement in the bottom flange, which resulted in a complete separation between the web and bottom flange (**Fig. 16**). A different anchorage detail was adopted in the shear reinforcement of girder B to avoid a similar premature shear failure.

Figure 15 also indicates that the maximum load carried by girder B was 800 kip (3560 kN), higher than that predicted using specified material properties but slightly less than predicted using actual material properties. This load did not cause the girder to fail; however, the test was stopped as the maximum capacity of the loading frame and jacks was reached. **Figure 17** shows the shear and flexural cracks of girder B under the maximum load. The girder was unloaded, as shown in the rebounding portion of the load-deflection curve, and loaded again 10 ft (3 m) from the support for shear capacity testing.

Figure 18 plots the average strand slip measurements taken by ST-POTs and analog dial gauges while loading.

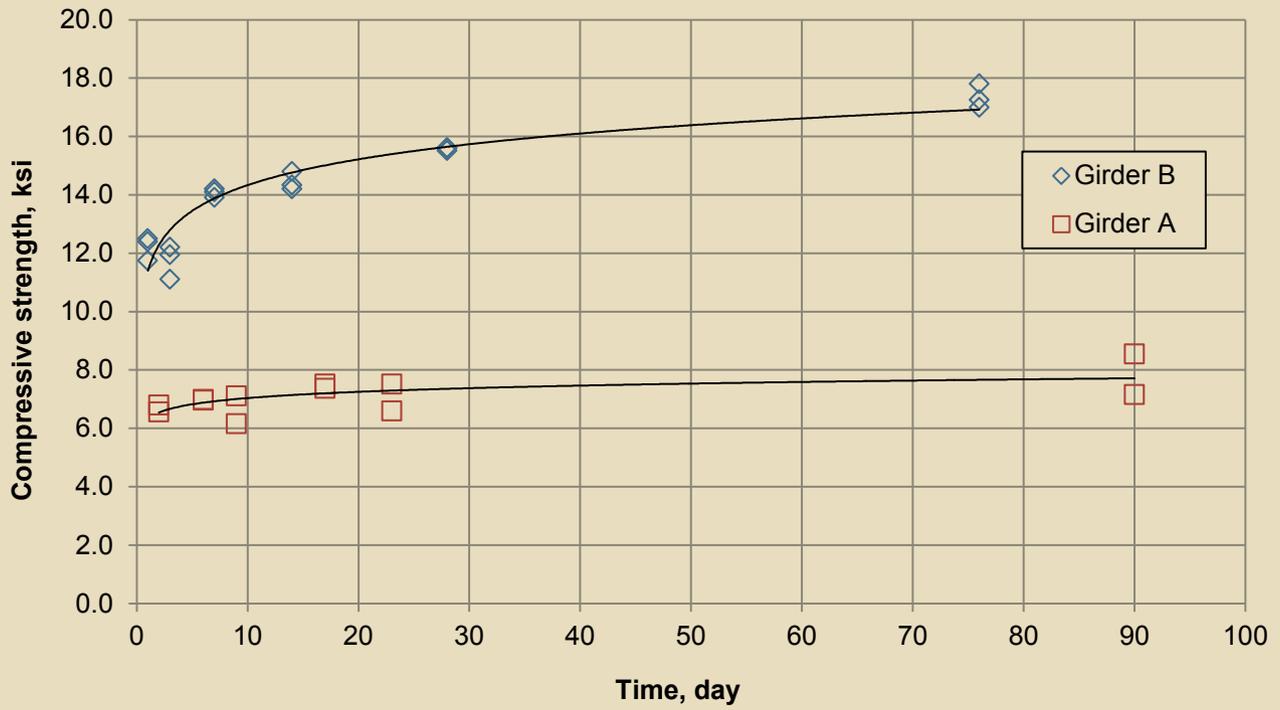


Figure 13. Concrete compressive strength gain for girders A and B. Note: 1 ksi = 6.895 MPa.

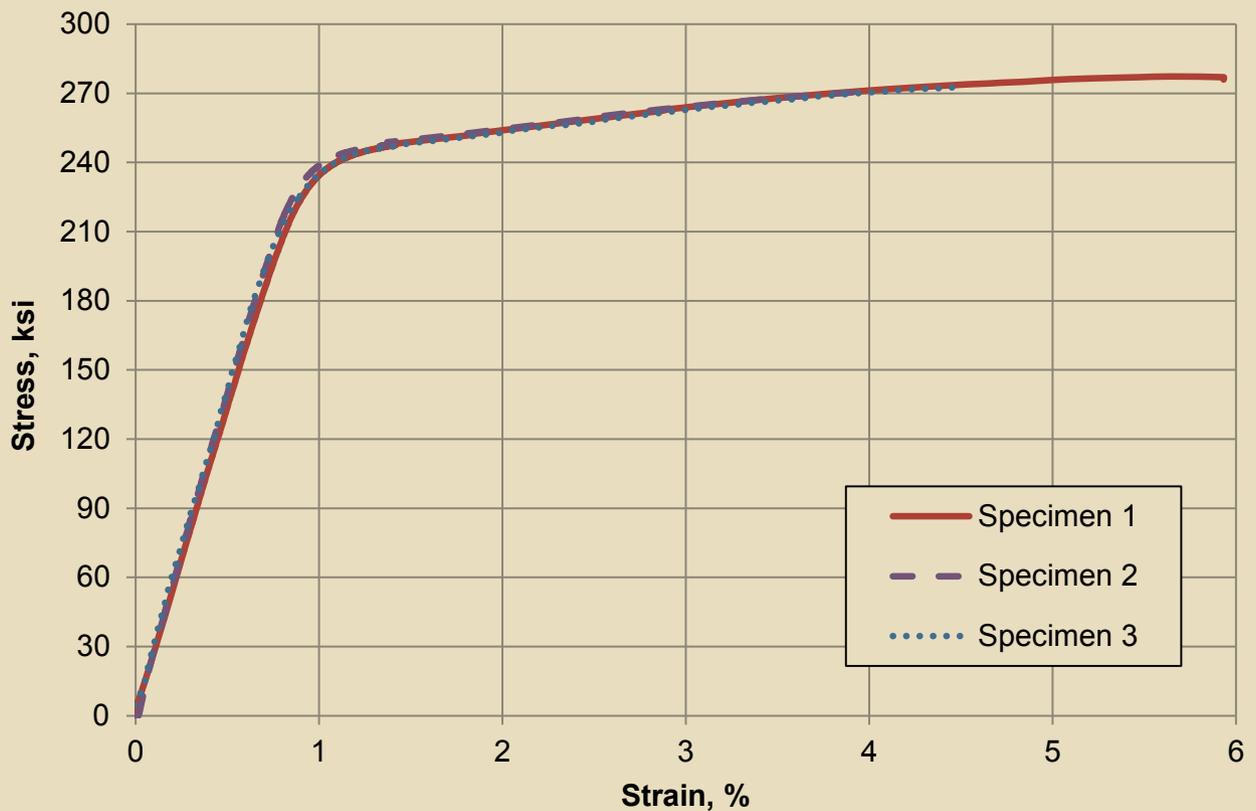


Figure 14. Stress-strain diagram of three 0.7-in.-diameter strand specimens. Note: 1 ksi = 6.895 MPa.



Table 1. Material properties of three 0.7-in.-diameter (18 mm) strand specimens

Specimen identification	Load at 1% strain, lb	Peak load, lb	Elongation, %	MOE, ksi
1	70,600	81,700	5.9	27,100
2	71,200	79,800	4.0	28,400
3	69,500	80,300	4.5	28,500
Average	70,433	80,600	4.8	28,000
ASTM A416-06/AASHTO M203-07	71,500	79,400	3.5	n.a.

Source: ASTM A416-06. *Standard Specification for Steel Strand, Uncoated Seven-Wire for Prestressed Concrete*. American Association of State Highway and Transportation Officials (AASHTO) M203. 2007. *Standard Specification for Steel Strand, Uncoated Seven-Wire for Concrete Reinforcement*. Note: MOE = modulus of elasticity; n.a. = not applicable. 1 lb = 4.448 N; 1 ksi = 6.895 MPa.

This plot indicates that the maximum average strand slip in girder A, which occurred at the ultimate load of 600 kip (2670 kN), was 0.01 in. (0.25 mm), while the maximum average strand slip in girder B occurred at maximum load of 800 kip (3560 kN) and was 0.008 in. (0.2 mm). These values are less than the precision of the measuring devices, which is 0.01 in., which means that the 0.7-in.-diameter (18 mm) strands in girders A and B were fully developed within the length specified by the current AASHTO LRFD specifications. **Table 2** summarizes the results of the two tests in terms of the applied load and bending moment and compares them with the predicted values using specified and actual material properties. Table 2 also presents the maximum strand stress in the two tests, which is close to the ultimate

strength of 270 (1860 MPa).

Application of 0.7-in.-diameter strands

The Pacific Street Bridge over Interstate 680 in Omaha, Neb., is the first bridge in the United States to use 0.7-in.-diameter (18 mm) prestressing strands in pretensioned concrete girders. The bridge was built in August 2008 as a replacement for an existing bridge due to the deteriorating condition and substandard width of its superstructure.

The old bridge was 74 ft (22.6 m) wide and had four spans

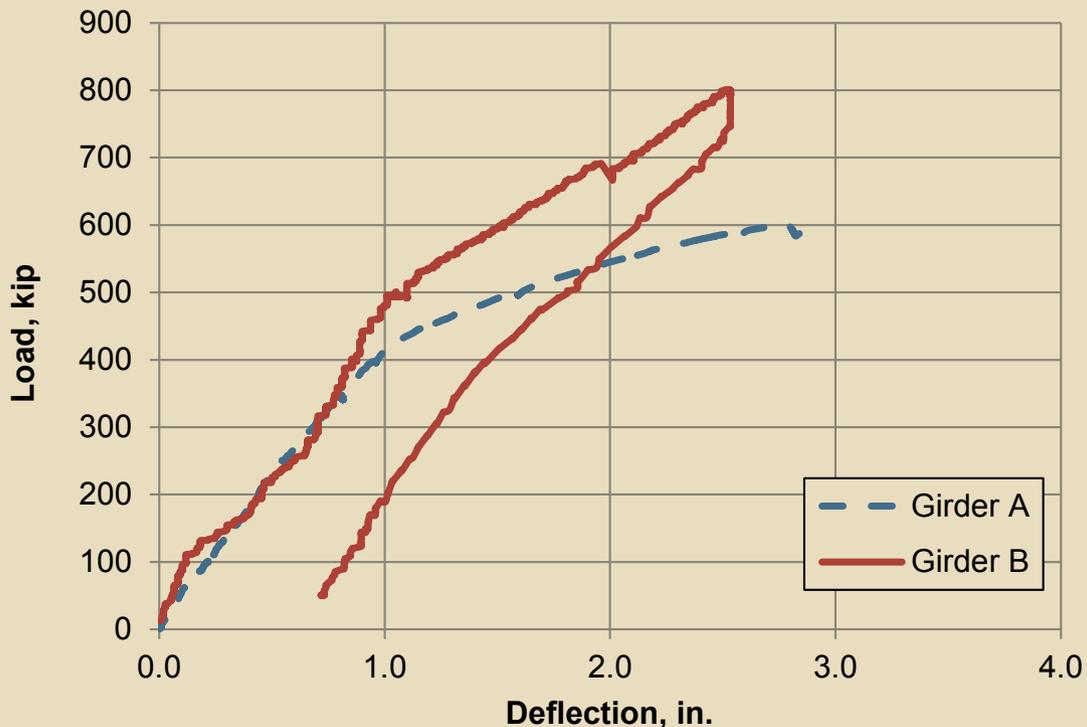


Figure 15. Load-deflection diagrams for girders A and B. Note: 1 in. = 25.4 mm; 1 kip = 4.448 kN.



Figure 16. Failure of girder A.

that were 44.5 ft (13.6 m), 73 ft (22.3 m), 73.5 ft (22.4 m), and 30 ft (9.2 m). Each span consisted of 11 steel I-girders at 7 ft (2.1 m) spacing. The new bridge consists of two identical spans that are 98 ft (29.9 m) long with a 17° skew angle.

The bridge has six traffic lanes with a total width of 105 ft 8 in. (32.2 m). The bridge superstructure consists of twenty NU900 I-girders (ten for each span) that are 35.4 in. (900 mm) deep and spaced at 10 ft 8 in. (3.3 m). Each girder was pretensioned using thirty 0.7-in.-diameter (18 mm) strands spaced at 2 in. (50 mm) horizontal spacing and 2.5 in. (63 mm) vertical spacing. Because the design and production of the bridge girders were completed before testing girder B, the smaller strand spacing was not allowed.

Figure 19 shows the completed bridge. The elegant slenderness of this high-performance concrete bridge is obvious in the photograph. The main challenge in this project was to design a two-span concrete alternative to the four-span steel bridge while maintaining the same vertical clearance. This challenge necessitated the use of high-strength concrete and large-diameter strands. The average concrete compressive strength was 11,000 psi (76 MPa) at 28 days, exceeding the specified minimum strength of

10,000 psi (69 MPa).

Overnight release strengths averaged approximately 7000 psi (48 MPa). This combination of 0.7-in.-diameter (18 mm) strands with high-strength concrete resulted in an efficient use of both materials.



Figure 17. Cracking of girder B under maximum load.

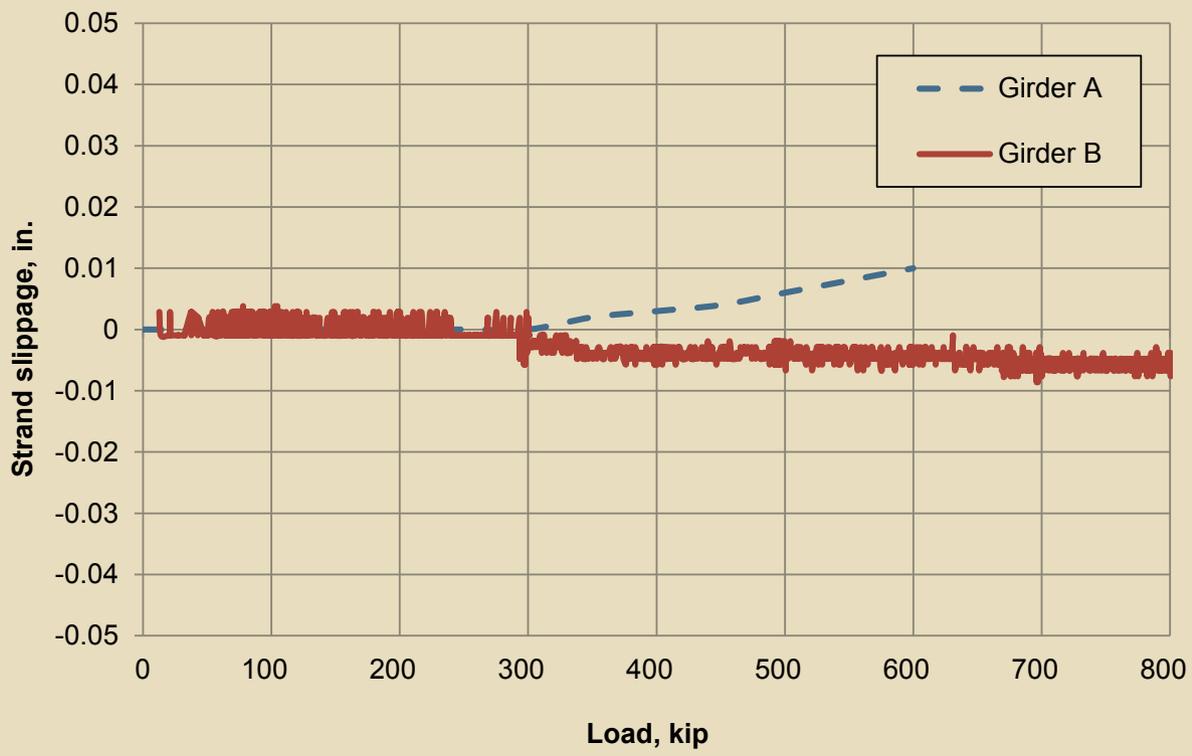


Figure 18. Strand slip versus load for girders A and B. Note: 1 in. = 25.4 mm; 1 kip = 4.448 kN.

The availability of this large size of strand was not a problem, though several challenges were associated with the size and stiffness of the strand itself, such as uncoiling the strand, retooling the opening in the bulkheads, feeding the strand through the bulkheads, and acquiring larger chucks and hold-down devices for depressing strands. The producer resolved all these difficulties in a safe and efficient manner and did not experience any problems. However, due to the unavailability of hold-down devices for 0.7-in.-diameter (18 mm) strands, debonding the strands was used instead of depressing the strands to meet stress requirements at release.

In addition to the introduction of this large strand diameter, a threaded-rod continuity system was another innovative feature of this project. A threaded-rod continuity system allows I-girders to be continuous for deck weight and live loads, which represent two-thirds of total bridge loads. A threaded-rod continuity system is an economical and

practical way to improve the load-carrying capacity of I-girders, reduce girder deflection, and minimize deck cracking over intermediate supports. This results in the optimal use of materials, an increased span-to-depth ratio, and improved durability.

In this project, the concrete girders were connected over the intermediate support using 10 Grade 150 (1030 MPa) high-strength threaded rods of 1³/₈ in. (35 mm) diameter above the top flange to each girder. The connection between girders was placed with the intermediate diaphragm to make the girders continuous before placing the deck. Longitudinal unbonded, monostrand post-tensioning was applied to the cast-in-place concrete deck to enhance deck durability. A total of thirty-six 0.6-in.-diameter (15 mm) encapsulated strands were used at 3 ft (0.9 m) spacing to control deck cracking and allow early opening to traffic. This simple and economical method of post-tensioning

Table 2. Comparing predicted and actual flexural capacities for girders A and B

Girder identification	Predictions using specified properties		Predictions using measured properties		Actual values obtained from testing		f_{ps} , ksi
	M_n , kip-ft	P , kip	M_n , kip-ft	P , kip	M_n , kip-ft	P , kip	
Girder A	5476	582	5560	591	5639	600	262
Girder B	7295	779	7590	812	7483	800	265

Note: f_{ps} = average stress in prestressing steel; M_n = nominal moment capacity; P = applied load; . 1 kip = 4.448 kN; 1 kip-ft = 1.34 kN-m; 1 ksi = 6.895 MPa.

was done by the general contractor without need for a specialty contractor.

Conclusion

This paper presents an investigation conducted to introduce the use of 0.7-in.-diameter (18 mm), Grade 270 (1860 MPa), low-relaxation strand in pretensioned concrete bridge girders. Two full-scale NU900 I-girders were designed using 0.7-in.-diameter strands at different strand spacing and concrete strengths. The two girders were produced to identify production challenges associated with such large-diameter strands. Transfer and development length of 0.7-in.-diameter strands were evaluated experimentally and compared with the values predicted using the AASHTO LRFD specifications' provisions for 0.5-in.-diameter (13 mm) and 0.6-in.-diameter (15 mm) strands. The main conclusions of this study can be summarized as follows:

- The production challenges of using large-diameter strands are mainly those associated with handling a heavier and stiffer strand. Extra caution is needed while pulling the strand out of the spool and feeding it along the bed. The availability of strands and chucks is not a problem. Minor modifications may be needed to enlarge the bulkhead openings and increase the prestressing capacity of the jacking equipment or prestressing bed.
- The average transfer length of 0.7-in.-diameter (18 mm) strands is approximately 31 in. (790 mm), which is closer to the $50d_b$ transfer length predicted using the ACI 318-08 expression than the $60d_b$ predicted using the AASHTO LRFD specification expression. However, the authors do not recommend any revisions to AASHTO LRFD specifications.
- The 0.7-in.-diameter (18 mm) strand can be fully developed within the length predicted by the 2007 AASHTO LRFD specifications. This conclusion applies for the values of concrete strength, strand spacing, and bottom-flange confinement reinforcement adopted in this study. Based on the results of the experimental investigation presented herein, the following cases were verified:
 - For a concrete strength of 8 ksi (55 MPa) and confinement reinforcement of no. 3 (10M) bars at 3 in. (75 mm) along at least 45 in. (1140 mm) from the girder end, 0.7-in.-diameter (18 mm) strands can be spaced at 2.2 in. (56 mm) horizontally \times 2.25 in. (57.2 mm) vertically.
 - For a concrete strength of 15 ksi (104 MPa) and confinement reinforcement of no. 3 (10M) bars at 3 in. (75 mm) along 3 ft (0.9 m) from the gir-



Figure 19. Pacific Street Bridge.

er end and no. 3 (10M) bars at 6 in. (150 mm) elsewhere, 0.7-in.-diameter (18 mm) strands can be spaced at 2 in. (50 mm) horizontally and vertically.

Additional research is being conducted to determine the minimum concrete strength and degree of confinement required to fully develop 0.7-in.-diameter (18 mm) strands at 2 in. (50 mm) spacing that satisfy the AASHTO LRFD specifications for transfer and development length.

Acknowledgments

The authors thank the Nebraska Department of Roads (NDOR) for its financial and technical support of this project. The authors are also very thankful to Coreslab Structures Inc. of Omaha, Neb.; Ivy Steel & Wire of St. Joseph, Mo.; InSteel Industries Inc. of Mt. Airy, N.C.; and Chryso Inc. of Charlestown, Ind., for donation of materials and technical support. Special acknowledgment goes to the graduate students who participated in various tasks of the project, in particular Marc Maguire, Nick Reiser, and Alec Stubbe.

References

1. Hanson, N. W., and P. H. Kaar. 1959. Flexural Bond Tests of Pretensioned Prestressed Beams. *Journal of the American Concrete Institute*, V. 55, No. 7 (January): pp. 783–803.
2. Lane, S., and D. Rekenhaller. 1998. The Ties That Bind: The 10-Year Fight for 0.6-Inch Diameter Strands. *Public Roads*, V. 61, No. 5 (March): pp. 27–29.
3. Buckner, C. D. 1995. A Review of Strand Development Length for Pretensioned Concrete Members, State of the Art Report. *PCI Journal*, V. 40, No. 2 (March–April): pp. 84–105.
4. James, B. 2001. Narrows Bridge, Perth, WA. *The Newsletter of Engineering Heritage Australia*, No. 11 (June): pp. 44–65.



5. ASTM A416. 2006. *Standard Specification for Steel Strand, Uncoated Seven-Wire for Prestressed Concrete*. West Conshohocken, PA: ASTM International.
6. American Association of State Highway and Transportation Officials (AASHTO). 2007. *Standard Specification for Steel Strand, Uncoated Seven-Wire for Concrete Reinforcement*. Specification M203. Washington, DC: AASHTO.
7. Russell, B. W., and N. H. Burns. 1996. Measured Transfer Lengths of 0.5 and 0.6 in. Strands in Pretensioned Concrete. *PCI Journal*, V. 41, No. 5 (September–October): pp. 3–4.
8. Russell, H. G., J. S. Volz, and R. N. Bruce. 1997. *Optimized Sections for High-Strength Concrete Bridge Girders*. FHWA-RD-95-180. Washington, DC: Federal Highway Administration.
9. Vadivelu, J., and Z. Ma. 2008. Potential Impact of 0.7-inch Strands on Precast/Prestressed Concrete Bridge I-Girders: Spacing of Large Diameter Strands. In *2008 PCI National Bridge Conference*. CD-ROM.
10. Nebraska Department of Roads (NDOR). 2008. *NDOR Bridge Office Policies and Procedures*. Lincoln, NE: NDOR.
11. AASHTO. 2007. *AASHTO LRFD Bridge Design Specifications, 4th Edition—2008 Interim Revisions*. 4th ed. Washington, DC: AASHTO.
12. Reiser, N. P. 2007. *Innovative Reinforced/Prestressed Concrete Bridge Superstructure Systems*. MS thesis, University of Nebraska–Lincoln.
13. American Concrete Institute (ACI) Committee 318. 2008. *Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary (ACI 318R-08)*. Farmington Hills, MI: ACI.

Notation

- b_w = width of girder web
- d_b = nominal strand diameter
- d_v = shear depth
- f'_c = girder 28-day concrete strength
- f'_{cd} = deck 28-day concrete strength
- f'_{ci} = girder concrete strength at release
- f_{pe} = effective stress in prestressing steel
- f_{ps} = average stress in prestressing steel
- f_{pu} = ultimate strength of prestressing steel
- h = overall height of the girder
- k = development-length magnification factor = 1.0 for pretensioned panels, piling, and other pretensioned members with a depth less than or equal to 24.0 in. (610 mm), otherwise 1.6
- l_d = development length
- l_t = transfer length
- M_n = nominal moment capacity
- P = applied load
- V_n = nominal shear capacity

About the authors



George Morcous, PhD, P.Eng., P.E., is an associate professor at the Charles W. Durham School of Architectural Engineering and Construction at the University of Nebraska–Lincoln in Lincoln, Neb.



Kromel E. Hanna, PhD, is a post-doctoral fellow in the Department of Civil Engineering at the University of Nebraska–Lincoln.



Maher K. Tadros, PhD, P.E., is an emeritus Professor of Civil Engineering at the University of Nebraska–Lincoln and principal of e.construct.USA.

Abstract

Since the Federal Highway Administration (FHWA) allowed the use of 0.6-in.-diameter (15 mm) strands at 2 in. (50 mm) minimum spacing in 1996, they have been increasingly used in the production of pretensioned concrete bridge girders. For several years, 0.7-in.-diameter (18 mm) strands have been successfully used in cable bridges and for mining applications. Using these large-diameter strands in pretensioned concrete girders at 2 in. spacing will result in an increase of approximately 35% in the prestressing force compared with the same number of 0.6-in.-diameter strands, which will, consequently, allow for longer spans, shallower structural depth, and wider girder

spacing. For the same prestressing force, using 0.7-in.-diameter strands results in fewer strands to jack and release, fewer chucks, and greater flexural capacity due to the lower center of gravity of the strands.

In this paper, the design and production challenges of using 0.7-in.-diameter (18 mm) strands in pretensioned concrete bridge girders are discussed. Two full-scale NU900 I-girders pretensioned using twenty-four and thirty 0.7-in.-diameter strands were fabricated and tested to address production concerns and evaluate transfer length, development length, and end-zone cracking associated with such large-diameter strands. Positive production experience and predictable test results indicated that 0.7-in.-diameter strands can be used with no major changes to the current production practices or design criteria according to the current American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*. Also, the design and construction of the Pacific Street Bridge over Interstate 680 in Omaha, Neb., the first pretensioned concrete bridge to use 0.7-in.-diameter (18 mm) strands, is summarized.

Keywords

Bridge girder, development length, end-zone cracking, prestressing strand, transfer length.

Review policy

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

Reader comments

Please address any reader comments to journal@pci.org or Precast/Prestressed Concrete Institute, c/o PCI Journal, 200 W. Adams St., Suite 2100, Chicago, IL 60606. 