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Prestressed Concrete Girder Bridges Using Large 0.7 Inch Strands

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***Abstract*—The National Bridge Inventory (NBI) includes more than 600,000 bridges within the United States of America. Prestressed concrete girder bridges represent one of the most widely used bridge systems. The majority of these girder bridges were constructed using 0.5 and 0.6 inch diameter strands. The main impediments to using larger strand diameters are: 1) lack of prestress bed capacities, 2) lack of structural knowledge regarding the transfer and development length of larger strands, and 3) the possibility of developing wider end zone cracks upon strand release.

This paper presents a study about using 0.7 inch strands in girder fabrication. Transfer and development length were evaluated, and girders were fabricated using 0.7 inch strands at different spacings. Results showed that 0.7 inch strands can be used at 2.0 inch spacing without violating the AASHTO LRFD Specifications, while attaining superior performance in shear and flexure.

***Keywords*—0.7 inch strands, prestress, I-girders, bridges.

I. Introduction and Literature Review

THE National Bridge Inventory (NBI) of the United States includes more than 600,000 bridges, including bridges located on interstate highways, US highways, state and county roads, and public accessible bridges on federal lands. According to the NBI survey in the period from year 1992 to year 2000, 1 in every 4 bridges in the United States is deficient, either structurally deficient or functionally obsolete. Structure deficient bridges include all bridges with severe deterioration in one or more of the bridge component (i.e. bridge substructure, bridge superstructure, or bridge deck). The deterioration is enough to reduce the load carrying capacity of the bridge. The majority of structural deficiency result from increasingly applied live loads, environmental attacks (i.e. scour, freeze and thaw cycles, etc.), and the use of deicing chemicals. The Federal Highway Administration (FHWA) and State Departments of Transportation (DOTs) are researching new construction materials to increase bridge life expectancy and reduce the bridge life cycle cost including high and ultra-high performance concrete, high grade steel, and large size prestressing strands.

Large diameter prestressing strands are used in cable-stayed bridges and mining applications in the United States and post-tensioned tendons in Europe and Japan. Seven-wire prestress strands of 0.7 inch diameter were introduced for the first time in pretensioned applications in North America on the Pacific Street and I-680 bridge in Omaha, Nebraska, as shown in Fig. 1.

Fig. 1 Pacific Street Bridge, Omaha, NE

Strands were located at a centerline distance greater than 2.0 inch due to lack of experience and specifications [1].The main impediments to using larger strands are: 1) lack of prestressing bed capacities, 2) lack of structural knowledge regarding the transfer and development lengths of larger strands, and 3) the possibility of developing wider end zone cracks upon strands release.

This paper presents a study about using larger 0.7 inch strands in girder fabrication, with welded wire reinforcement in shear [3]. Transfer and Development lengths of large strands were investigated and compared to the estimated results using AASHTO LRFD specifications. Full scale girders were fabricated using 0.7 inch

II. Analytical Investigation

The shear-friction concept is used to evaluate the development length of 0.7 inch diameter prestressing strands by considering the equilibrium of forces in the axial direction of the bottom row of prestressing strands in a precast/prestressed concrete girder, as shown in Fig. 2.

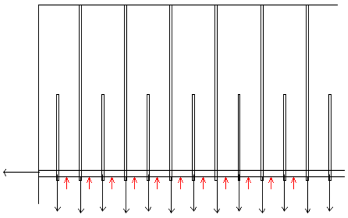

Fig. 2 Pullout Force acting on Strands Bottom Row at Section Ultimate Capacity

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Total force due to pretension =

$$F = A_{ps}\cdot f_{ps} \tag{1}$$

At ultimate load prior to strand slippage, a lateral crack, propagating in a horizontal plane passing by the strands, is assumed to develop through the bottom strand row. The resistance to strand pullout force is in effect through the transverse steel, as shown in Fig. 3.

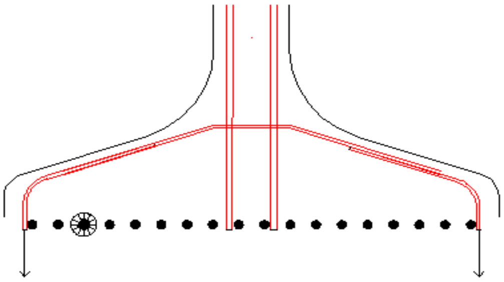

Fig. 3 Vertical force applied by transverse steel

Using the AASHTO LRFD shear-friction equation (5.8.4.1-1) [2] for evaluating nominal pullout resistance:

$$V_n = c\,A_{cv} + \mu\left[A_{vf}\,f_y + P_c\right] \leq 0.2\,f'_c\,A_c \tag{2}$$

The cohesion between strands and concrete is assumed as zero (different materials), and no permanent compressive force is acting on the strands. Equation (2) can be rewritten as:

$$V_n = \mu\left[A_{vf}\,f_y\right] = \mu . A_{ts}\cdot f_{tsy} \tag{3}$$

From equilibrium of forces, acting on the strand row in the axial direction:

$$A_{ps}\cdot f_{ps} = \mu . A_{ts}\cdot f_{tsy} \tag{4}$$

Thus, the required area of transverse reinforcement along the developed length can be calculated as:

$$A_{ts} = \frac{A_{ps}\cdot f_{ps}}{\mu . f_{tsy}} \tag{5}$$

By considering the bearing pressure on the concrete around the strands along the horizontal crack line:

$$P_{bearing} = \frac{A_{ts}\cdot f_{tsy}}{A_{bearing}} \tag{6}$$

Forces are in equilibrium in the vertical direction, as shown in Fig. 3. The area of bearing is considered as the horizontal projection of the circumferential area of strands. Thus:

$$A_{bearing} = n_{ps}\cdot L_d\cdot d_{ps} \tag{7}$$

The concrete bearing capacity can be calculated according to the AASHTO LRFD provisions as. The concrete bearing capacity can be calculated according to the AASHTO LRFD provisions as:

$$P_{bearing}\cdot A_{bearing} = A_{ts}\cdot f_{tsy} = 0.2 f'_c\cdot A_c \tag{8}$$

Equation (8) can be rewritten as:

$$\frac{A_{ts}\cdot f_{tsy}}{n_{ps}\cdot d_{ps}\cdot L_d} \leq 0.2\,f'_c \tag{9}$$

III. EXPERIMENTAL INVESTIGATION

In order to validate the use of shear friction theory in calculating the amount of confinement required for the development of 0.7in. diameter prestressing strands without violating the current AASHTO LRFD equations, pullout test program for prestressed specimens is conducted. In this research program prestressed specimens were designed, and pullout testing was performed to assess the bond quality of confined prestressed strands. It was predetermined to continue the test until one of the following modes of failure is achieved:

1. Strand slippage: where strand starts to slip prior to its rupture. This slippage could be an abrupt or gradual slippage. Slippage prior to strand rupture is considered as an indication of confinement inadequacy.
2. Strand rupture: where strand is broken at a load greater than its ultimate capacity of 79.4 kips (equivalent to tensile strength of 270 ksi). Rupture of strands indicates its full development under the existing amount of confining steel.

A. Specimens Design and Fabrication

Square prisms with 7in. side dimension were used to perform the pullout testing of 0.7in. strands. Required confinement for strand development was calculated according to (5) as follows:

$$A_{ts} = \frac{A_{ps}\cdot f_{ps}}{\mu . f_{tsy}} = \frac{0.294\times 270}{1.4\times 60} = 0.95 in^2$$

Grade 60 square ties were used for strand confinement. Ties had a side dimension of 5 in., and a diameter of 0.375 in^2. The minimum number of ties required for strand development was:

$$N_{ties} = \frac{0.95}{2 \times 0.11} = 5 \text{ ties.}$$

The stress developed in confining steel upon reaching ultimate pullout force, considering the use of 5 ties as confining steel bars is:

$$f_{tsy} = \frac{A_{ps} \cdot f_{ps}}{A_{ts} \cdot \mu} = \frac{0.294 \times 270}{2 \times 0.11 \times 5 \times 1.4} = 51.5 ksi$$

The minimum length of concrete specimen was calculated according to (9) as follows:

$$\frac{A_{ts} \cdot f_{tsy}}{n_{ps} \cdot d_{ps} \cdot L_d} \leq 0.2 f'_c$$

Thus:

$$L_d = \frac{A_{ts} \cdot f_{tsy}}{n_{ps} \cdot d_{ps} \cdot 0.2 \cdot f'_c} = \frac{5 \times 2 \times 0.11 \times 51.5}{1 \times 0.7 \times 0.2 \times 8} = 50 in.$$

A minimum specimen length of 4 ft. (48 in.) was considered for the pullout test.

Self-consolidating 8000 psi concrete mix was used in casting specimens. The 8000 psi concrete strength represents the minimum concrete strength according to precast/prestressed concrete industry common practice in most of the States. The concrete mix was ordered and casted the same day of pretensioning the strands.

B. Pullout Test Setup

Pullout testing of pretensioned specimens was designed to be done horizontally for safety purposes. A 9 inch grip insert was used for strand gripping. The 2 grip halves were placed around the strand, confined by a metal frame, and firmly griped to the strand by a 30 ton load applied by using a hydraulic jack. A 0.7 inch chuck was directly seated at the end of the grip insert to prevent any slippage. The evenly distributed jack loading acting on the grip, and the grip length were enough to eliminate the stress concentration resulting in premature strand failure. The test setup and strand gripping are shown in Fig. 4.

Fig. 4 Pullout test setup and strand gripping

The pullout test included four 4 ft. specimens, five 5 ft. specimens, and four 6 ft. specimens. The results of ultimate pullout force compared to the required force for strand rupture according to ASTM A416 [4] are presented in Fig. 5. Strand pullout tests for all tested specimens had similar mode of failure. Progressive rupture of the seven wires was initiated upon reaching the strand ultimate stress, followed by a sudden thrust of the gripping device from the load cell upon full strand rupture.

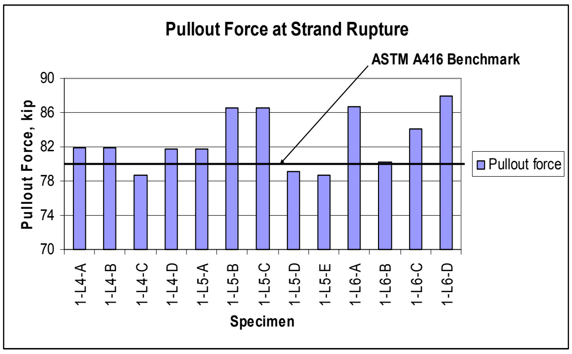

Fig. 5 Strand pullout test results

The transfer length was calculated by the 95% Average Maximum Strain (AMS) method [4].Once the strain profile for the transfer zone was drawn, using values of readings at days 1, 3, 7, 16, and 28, the strain values that lain in the strain profile plateau were identified, and the value of the average maximum strain was calculated using the arithmetic mean of these values. According to the 95% AMS method, the value of the transfer length at any time is identified by the distance of the point where the compressive strain profile intersects the horizontal line representing the 95% of the average maximum strain. Example of the strain profile readings is shown in Fig. 6.

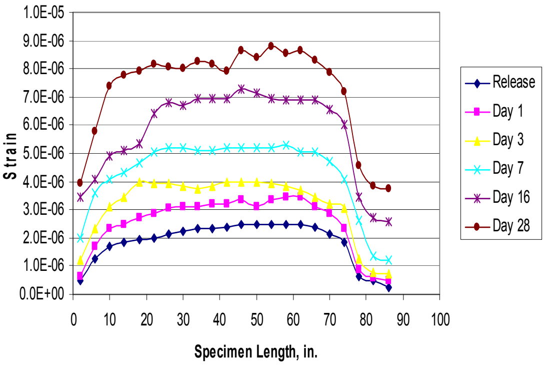

Fig. 6 Transfer length readings

C. Full Scale Girder Testing

Two full-scale girder testing was precast using 0.7in. prestressing strands. First girder, denoted as girder A, represents the first precast/prestressed girder fabricated using 0.7in. strands at a centerline spacing of 2.0in. in North

America. The second girder, denoted as girder B, was used in constructing the Pacific St. and I-680 bridge in Omaha, Nebraska [1]. Girder B was produced using strands at a centerline spacing of 2.5 inch. The following represents the girder design and testing results.

Girder A – First I-Girder Fabricated with 0.7in. Strands in North America

The first precast/prestressed I-girder fabricated with 0.7in. prestressing strands at centerline spacing of 2.0 in. was made in Coreslab, Omaha, Inc. The I-girder had a depth of 35.4 inch, with a 1 inch thick haunch, and a 7.5 in. deck. Its bottom flange contained 30-0.7in. straight prestressing strands. Welded wire fabric (WWR) was used for girder shear reinforcement. 2 6x6 – D31xD31 meshes were used. The girder end zone reinforcement contained 4#6 bars at 2in. spacing. Strands at the bottom flange were confined by D11 WWR at 6in. spacing. Additional confinement of #3 bars was placed at 6in. spacing for 36in. at each girder end [5]. The section details of the I-girder are shown in Fig. 7. According to the current AASHTO LRFD equation for development length estimation

$$L_d == 1.6 \times \left(270 - \frac{2}{3}.160 \right).0.7 = 183in$$

The girder was tested to its ultimate capacity with a point load acting on 15 ft (180 in.) from its end, as shown in Fig. 8. The load point of action existed at a distance from the girder end equal to the development length, and no slippage was noticed on the strands. According to (5), the amount of steel required for full development of the strands is 11.3 in^2

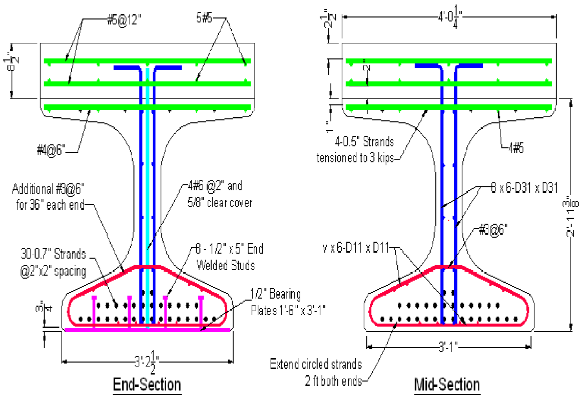

Fig. 7 Girder cross section

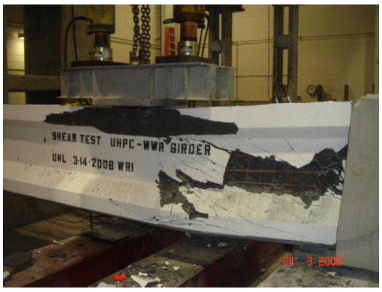

Fig. 8 Girder test (limit state)

Transverse reinforcement in the first 10ft. of the girder includes the following:

- Shear Reinforcement:

$$A_{ts} = 0.31 \times 2 \times 27 = 16.74in^2$$

- Confinement rebars:

$$A_{ts} = 19 \times 2 \times 0.11 = 4.18in^2$$

The area of confinement resulting from the confinement and shear reinforcement is greater than the required area for girder development. Thus, strands are fully developed at a distance less than that estimated by AASHTO LRFD development length equation.

Girder B - Pacific St. Bridge Project NU900 I-Girder

Similar dimension I-girder was designed and tested in the preparation for the pacific street bridge project [1] the girder contained 24-0.7in. prestressing strands in the bottom flange, located at a centerline spacing of 2.25 inch, and 4-0.5in. partially stressed strands in the top flange. Strands were released after 24 hours of pouring Girder B. No large end zone cracks appeared upon strand release. The girder transverse reinforcement included the following:

– 4 #6 bars for end zone reinforcement.
– 2 #4 @ 3 in. spacing for shear reinforcement.
– 15 # 3 hairpins for strand confinement at the bottom flange (first 45 in. of the girder ends). The cross-section of the girder is shown in Fig. 9.

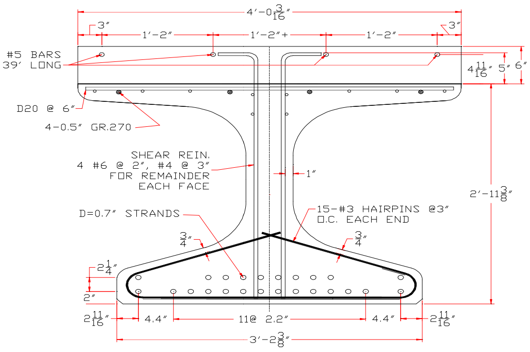

Fig. 9 Girder B cross section [1]

According to (5), the amount of transverse reinforcement required for strand development is 13.2in^2. The quantity of transverse reinforcement is calculated as follows:

- End zone reinforcement = 8#6 bars = 2.31in^2
- Area of hairpins used in confinement =

$$15 \times 2 \times 0.11 = 3.3 in^2$$

- Area of shear reinforcement = 0.4 in^2 @ 3in.

Required area of shear reinforcement to be used in developing the strands = 13.23-2.31-3.3 = 7.62 in

Number of shear reinforcement lines = 7.62/0.4= 20 lines. Shear reinforcement was placed after the end zone reinforcement was placed. Thus, the required shear reinforcement lines existed at distance = $4 \times 2 + 20 \times 3 = 68 in.$ from the girder end

The girder was tested by a point load at a distance of 14 ft (from the centerline of the end bearing). The girder achieved its theoretical flexure capacity before failure was achieved. Girder failure happened by concrete crushing, while no strand slippage was observed. Strands were fully developed in a distance shorter to that estimated by AASHTO LRFD specifications provisions.

IV. SUMMARY AND CONCLUSIONS

This research investigated the effect of confinement on transfer and development length of prestressing strands. The results were used to introduce the large 0.7 in. strands in the precast/prestressed concrete industry. The shear-friction concept was used to quantify the effect of strand confinement on the development length. Demec discs were used to evaluate the transfer length of 0.7in. strands. Prestressed prismatic specimens were used to conduct pullout tests for experimental justification. The following results were achieved:

1. Shear-friction concept could be used to quantify the effect of confinement on development length of strands.
2. Confinement can be used to reduce the development length of prestressed strands.
3. The current AASHTO LRFD specifications and ACI code equations conservatively estimate the transfer length of 0.7in. strands.

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