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16. Abstract

The use of 0.6-in. prestressing strand at a center-to-center spacing of 2 in. allows for the optimal implementation of High Strength Concrete (HSC) in precast, prestressed concrete bridge superstructures. For this strand configuration, partial debonding of strands is a desirable alternative to the traditional method of draping to alleviate extreme concrete stresses after prestress release. Experimental evidence suggests that existing code provisions addressing the anchorage of pretensioned strands do not adequately describe their behavior. In addition, the anchorage behavior of partially debonded strands is not fully understood.

Results are reported from a research study conducted to determine the anchorage behavior of 0.6-in. strands at 2 in. spacing in full-size, plant-cast AASHTO Type I I-beams. Concrete strengths ranged up to 15,000 psi. Strand featured either a bright mill finish or a rusted surface condition. A variety of strand debonding configurations were investigated. The use of pull-out capacities and strand draw-in measurements to predict the anchorage behavior of prestressing strands was also examined.

Along with recommended design procedures for anchorage of prestressing strand, a review of the evolution and shortcomings of existing code provisions is presented. The use of this strand configuration is concluded to be safe, and partial debonding of prestressing strands is shown to be an effective means of reducing stresses in the end regions of pretensioned beams.

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PRELIMINARY REVIEW COPY

CENTER FOR TRANSPORTATION RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

Research Project Summary Report 1388-S

Development Length of 0.6-in (15-mm) Diameter Prestressing Strand at 2-in (50-mm) Grid Spacing in Standard I-Shaped Pretensioned Concrete Beams

Authors: Robert W. Barnes, Ned H. Burns and Michael E. Kreger

Center for Transportation Research, The University of Texas at Austin, January 2000

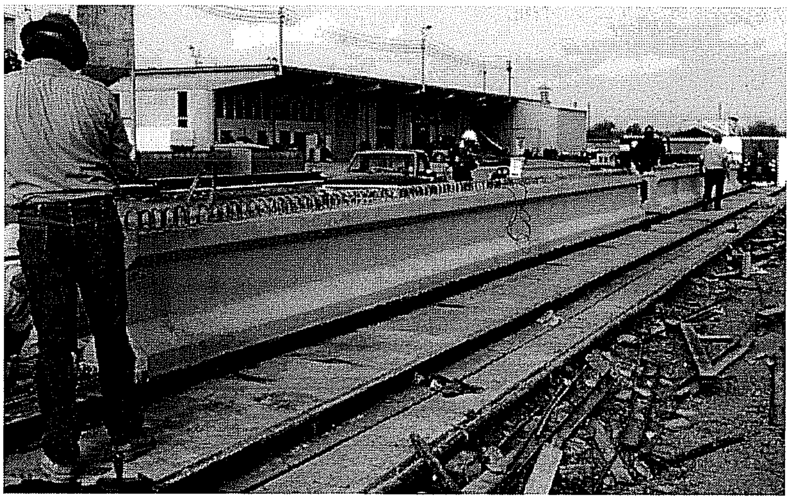
Anchorage of Large Diameter Prestressing Strands in Pretensioned Concrete I-Beams

The use of 0.6-in (15.2-mm) prestressing strand at a center-to-center spacing of 2 in (51 mm) allows for the optimal implementation of High Strength Concrete (HSC) in precast, prestressed concrete bridge superstructures. Because of the relatively large prestress forces developed with this strand configuration, partial debonding of strands is an attractive alternative to the more traditional method of draping strands for alleviating extreme concrete stresses in the end regions of pretensioned members.

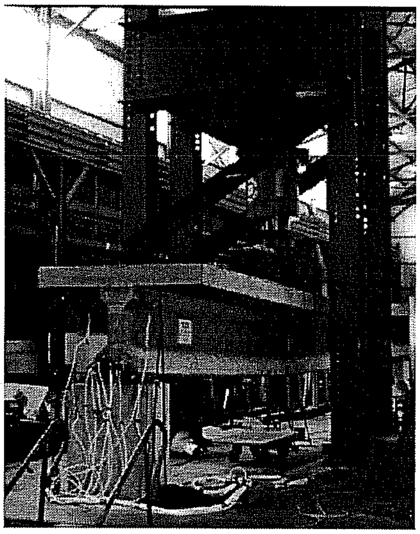
Recent experimental evidence suggests that the existing ACI and AASHTO code provisions that address the anchorage of pretensioned strands do not adequately describe the behavior of these strands. In addition, the anchorage behavior of partially debonded strands is not fully understood. At the time the research reported herein was initiated, the Federal Highway Administration (FHWA) had imposed a moratorium on the use of 0.6-in (15.2-mm) strand in pretensioned applications, thereby hindering the optimal implementation of HSC in pretensioned construction.

What We Did...

The research study encompassed the transfer and development length testing of thirty-six plant-cast, AASHTO Type I (Texas Type A), pretensioned concrete I-beams. Transfer length testing was performed at the plant; both immediate and long-term transfer lengths were measured. Transfer lengths were determined from measured concrete surface strains. Corresponding values of strand draw-in were also measured. Pull-out tests were performed in an effort to quantify strand bond quality. Development length tests were performed on thirty of the beams at the Phil M. Ferguson Structural Engineering Laboratory at The University of Texas at Austin. Development length testing of the remaining six beams was carried out at Texas Tech University. In an effort to achieve ultimate tendon elongation values exceeding 3.5 percent, a cast-in-place, composite deck was added to each beam prior to development length testing.



Pair of I-beam specimens prior to prestress release



Development length testing of composite beam specimen

Three different levels of beam concrete strength were investigated. Compressive strengths at prestress release varied from 4000 to 11,000 psi (27 to 76 MPa). Strengths at time of development length testing ranged from 5700 to 14,700 psi (39 to 102 MPa). Specimens were reinforced with strands having either a "bright" or a "rusted" surface condition. Various strand debonding schemes were tested. Some specimens contained strands that were all fully bonded, while other specimens featured percentages of debonded strands ranging up to 75 percent. The study included a limited investigation of the effect of horizontal web reinforcement on anchorage behavior.

What We Found ...

General

1. Prestressing strands with a diameter of 0.6 in (15.2 mm) may be safely used at a center-to-center spacing of 2 in (51 mm).
2. Staggered debonding of strands is an effective method for selectively reducing concrete stresses in the end regions of pretensioned concrete members and may be effectively implemented as an alternative to draping strands.
3. The bond behavior exhibited by seven-wire strands has varied greatly in different research studies. The bond quality of prestressing strand appears to vary from manufacturer to manufacturer. Because of this significant lack of uniformity and the lack of an established performance standard, very conservative relationships must be used to model anchorage behavior for design.
4. Existing ACI and AASHTO specifications concerning the anchorage behavior of fully bonded prestressing strand are unconservative. They also do not adequately address the adverse effects resulting from the reduced effective prestress at debonded sections and the interaction of shear and moment near the debond points.
5. Increased concrete strength enhances the anchorage capacity of prestressing strand, and this relationship should be reflected in Code expressions for transfer and development length. Larger bond stresses may be developed due to the increased concrete stiffness and tensile strength along the transfer length. Also, the cracking resistance of anchorage zones increases slightly with increasing tensile strength.
6. Extending and/or modifying the existing design rules for terminating mild steel tension reinforcement to the design of partially debonded prestressing tendons offers the potential simplification of the design of these tendons while more accurately reflecting their behavior. However, the conservatism of applying such a method has yet to be experimentally determined.

Strand Pull-Out Testing

1. The Moustafa Pull-Out Test, in conjunction with Logan's performance benchmark, accurately indicated the excellent bond behavior of the strands used in this study with respect to the existing ACI/AASHTO transfer and development length relationships.
2. Properly consolidated concrete is vital to adequate bond performance. Particular care should be taken to ensure the workability and proper consolidation of HSC when casting pretensioned products.

Transfer Length Testing

1. On average, transfer lengths are indirectly proportional to the square root of the concrete strength at release, $\sqrt{f'_{ci}}$.
2. Transfer length can increase significantly in the first few weeks after release. Average increases in this study ranged from 10 to 20 percent. Increases in a few specimens exceeded 50 percent. All significant increase appears to occur in the first 28 days after release.
3. Surface weathering of prestressing strand can reduce transfer length, but this effect is not reliable enough to incorporate into design.
4. Although sudden prestress release has been shown to adversely affect transfer length in previous studies, which featured specimens constructed with normal strength concrete, varying the method of prestress release had minimal influence on the transfer length of bright strand specimens constructed of concrete with release strengths exceeding 7000 psi (48 MPa) in this study. This indicates that HSC is less susceptible to the influence of prestress release method.
5. Transfer lengths of partially debonded strands are no longer than those of fully bonded strands.

6. Very short transfer lengths are possible. When performing design checks of allowable stresses for the Service Limit State, a transfer length of less than $10d_b$ should be assumed. Assuming a length of zero enhances conservatism and simplifies calculations without unduly sacrificing economy.

Draw-In Testing

1. Mast's draw-in theory correctly indicated the excellent bond behavior of the strands used in this study with respect to the existing ACI/AASHTO transfer and development length relationships.
2. Draw-in measurements may be used to indicate trends in bond behavior, and to indicate gross deficiencies in bond quality.
3. The correlation of obtained transfer lengths and draw-in values indicates that a detailed, statistical study must be performed and a large database of results must be developed before instituting any quality control system that relies on draw-in to establish the adequacy of bond in pretensioned members.
4. The use of draw-in measurements to calculate the transfer length of partially *debonded* strands is difficult and not recommended.

Development Length Testing

1. Concrete strength and strand surface condition exhibited little influence on the flexural bond length portion of the development length.
2. The presence of horizontal web reinforcement yielded only slightly improved performance compared to that of companion specimens lacking this reinforcement. However, none of the specimens exhibited a premature shear failure due to loss of bond, therefore little demand was exerted on the horizontal web reinforcement in this test program. Where present, horizontal web reinforcement reduced crack widths.
3. For partially debonded strands, prevention of general bond slip requires that no cracking cross the bonded portion of the strands within the transfer length or closer to the transfer length than $20d_b$. If this condition is satisfied, debonded strands will exhibit bond capacity comparable to that of fully bonded strands.
4. Up to 75 percent of strands may be debonded so long as the following conditions are satisfied:
   - cracking is prevented in or near the transfer length
   - the ACI/AASHTO rules for terminating tensile reinforcement are applied to the bonded length of prestressing strand
5. The susceptibility to cracking of regions with debonded strands may be assessed by calculating principal stresses under ultimate loads and satisfying the limits recommended below.

The Researcher Recommends ...

Transfer Length

For seven-wire prestressing strand, the transfer length, l_t, should be calculated as:

$$l_t = \frac{5}{4}\frac{f_{pt}}{\sqrt{f'_{ci}}}d_b$$

where the stresses are in ksi and the lengths are in inches. The resulting value defines the maximum extent of the transfer length. For purposes of calculating member strength, the effective prestress force transferred to the concrete from a bonded prestressing strand should be assumed to vary linearly from zero at the initiation of bond to a maximum over a distance equal to this transfer length.

For purposes of design in which conservatism dictates the selection of a lower-bound value for transfer length, such as when comparing concrete stresses to permissible values, a transfer length no longer than $10d_b$ should be assumed.

Development Length

For seven-wire prestressing strand, the development length, l_d, should be calculated as:

$$l_d = \frac{5}{4}\left[\frac{f_{pt}}{\sqrt{f'_{ci}}} + f_{ps} - f_{pe}\right]d_b$$

where the stresses are in ksi and the lengths are in inches.

Section 12.9.2 of ACI 318-99 (and corresponding Section 9.28.2 of the AASHTO Standard Specification) should be deleted. Establishment of the debonded lengths of prestressing tendons should be subject to code provisions that regulate the termination points of cutoff bars.

With the deletion of Section 12.9.2, or the clarification that the included language only applies to fully bonded strands, the provisions of Sections 12.10, 12.11, 12.12 become applicable to partially debonded strands. For typical simply supported, pretensioned members the specific provisions discussed below are most pertinent. Suggested changes to reflect application to partially debonded strands are shown in brackets.

> **12.10.2** — Critical sections for development of reinforcement in flexural members are at points of maximum stress and at points within the span where adjacent [bonded] reinforcement terminates, or is bent. Provisions of 12.11.3 must be satisfied. (AASHTO Standard 8.24.1.2; LRFD 5.11.1.2.1)
>
> **12.10.3** — [Bonded] reinforcement shall extend beyond the point at which it is no longer required to resist flexure for a distance equal to the effective depth of the member or $12d_b$, whichever is greater, except at the supports of simple spans and at free ends of cantilevers. (AASHTO Standard 8.24.1.2.1; LRFD 5.11.1.2.1)
>
> **12.10.4** — Continuing reinforcement shall have an embedment length not less than the development length l_d beyond the point where bent[, debonded,] or terminated tension reinforcement is no longer required to resist flexure. (AASHTO Standard 8.24.1.2.2; LRFD 5.11.1.2.1)
>
> **12.10.5** — [Bonded] flexural reinforcement shall not be terminated in a tension zone unless one of the following conditions is satisfied (AASHTO Standard 8.24.1.4):
>
> > **12.10.5.1** — Shear at the cutoff [or debonding] point does not exceed two-thirds that permitted, including shear strength of shear reinforcement provided.
> >
> > **12.10.5.2** — Stirrup area in excess of that required for shear and torsion is provided along each terminated [or debonded] bar[, strand,] or wire over a distance from the termination [or debonding] point equal to three-fourths the effective depth of the member. Excess stirrup area A_v shall be not less than $60b_w s/f_y$. Spacing s shall not exceed $d/8\beta_b$ where β_b is the ratio of area of reinforcement cut off [or debonded] to total area of tension reinforcement at the section.
> >
> > **12.10.5.3** — For No. 11 bar and smaller, [and prestressing strand,] continuing reinforcement provides double the area required for flexure at the cutoff [or debonding] point and shear does not exceed three-fourths that permitted.

Until further research can establish a reliable indication of the post-slip anchorage capacity of prestressing tendons, adequate anchorage of debonded strands can only be guaranteed by preventing cracking across the bonded length of strand inside or within $20d_b$ of the transfer length. This is best accomplished by calculating the principal tensile stresses at the beginning and end of this region. For members, such as I-beams, U-beams, or box beams, in which the debonded strands are contained within the flange, the tensile stress at the extreme fiber should be limited to a value equal to $6\sqrt{f'_c}$, and the principal tensile stress at the junction of the web and the flange containing the strands should be limited to $4\sqrt{f'_c}$. These expressions are in psi units; the corresponding limits are $\frac{\sqrt{f'_c}}{2}$ and $\frac{\sqrt{f'_c}}{3}$, respectively, in MPa units. For other members, the principal tensile stresses in this region should be limited to $4\sqrt{f'_c}$ (in psi units) between the centroid and the extreme tensile fiber; the corresponding limit is $\frac{\sqrt{f'_c}}{3}$ in MPa units. Gross section properties may be used in the calculation of the principal stresses.

Bond fatigue should be prevented by preventing tensile stress within the same length (l_t plus $20d_b$) under service level loadings. As long as the conditions in the previous paragraph are met for the ultimate loads, however, this consideration should not control design. It may only become critical if transfer length cracking and the resulting general bond slip are allowed under ultimate loads.

If the above conditions are met for the anchorage of debonded strands, Section 12.9.3 of ACI 318-99 (and the corresponding language in AASHTO Standard Section 9.28.3 and LRFD Article 5.11.4.3), which requires the doubling of the development length for debonded strands in members designed for tension under service loads, is unnecessary. Likewise, the rules in Article 5.11.4.3 that limit the percentage of debonded strands in the member and in each horizontal row are unnecessary if the above conditions are satisfied.

Design Process

The following general steps should be taken when designing the reinforcement pattern for pretensioned concrete members. These steps are described in more detail in Report 1388-1.

1. Design of midspan section for flexural resistance
2. Determination of strand debonding lengths and configuration
3. Strength limit state performance checks
4. Service Limit State checks
5. Calculation of prestress forces at sections where strands are not fully developed

Further Research

1. The results of various test programs have revealed tremendous variability in the bond behavior of prestressing strands. There is significant evidence to suggest that strand produced by one manufacturer may perform quite differently than that produced by another. Researchers should continue to investigate this problem by attempting to identify the source of the discrepancy and/or establishing a performance test for measuring strand bond quality. If a reliable performance standard can be adopted, the variability of bond behavior can be reduced. With more predictable bond behavior, expressions for transfer and development length can more accurately model the behavior of all strands.
2. If a safe, reliable estimate of the post-slip strength of prestressing strand can be established, anchorage design of pretensioned members with debonded strands can be greatly simplified. Such an estimate might be used to formulate an expression for development length that allows for the presence of cracking in the transfer length. Partially debonded strands could then be designed by simply using rules identical or comparable to the rules presently used for the design of cutoff bars. Tedious stress computations would no longer be necessary.
3. The effects of shear on bond resistance of pretensioned strand are not addressed in present code expressions. Likewise, the existing provisions do not reflect the extra embedment length that is required to prevent premature shear failures where bonded tension reinforcement terminates in a flexural member. The principles and rules developed for reinforced concrete construction need to be extended or adapted for use in pretensioned members.
4. It has been hypothesized that strands near the top of the member casting position will exhibit reduced bond capacity relative to those cast near the bottom, as is known to be the case with reinforcing bars. This effect has yet to be quantified for prestressing strands however.

For More Details...

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The research was documented in the following report:

Report 1388-1, *Development Length of 0.6-Inch Prestressing Strand in Standard I-Shaped Pretensioned Concrete Beams*, unpublished.

To obtain copies of the above report, contact the Research and Technology Transfer Section, Construction Division, (512) 465-7644.

TXDOT IMPLEMENTATION STATUS

JANUARY 2000...

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This research was performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration. The content of this report reflects the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TXDOT. This report does not constitute a standard, specification or regulation, nor is it intended for construction, bidding, or permit purposes. Trade names were used solely for information and not for product endorsement. The engineer in charge was Ned Burns, P.E. (Texas No. 20801).

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