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Strand bond performance in prestressed concrete accounting for bond slip

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Abstract:

This paper presents the results of an experimental research program addressing the bond behavior of prestressing strands in pretensioned prestressed concrete members after anchorage failure has occurred. A test methodology based on measuring the prestressing strand force and strand end slip at the specimens' free end was employed. Transmission- and anchorage-length tests were performed on several series of prestressed specimens with different embedment lengths using twelve concrete mixes. Average bond stresses along the transmission length and the anchorage length were obtained for specimens with release strengths ranging from 24 MPa to 55 MPa. For the anchorage analysis, a parameter was developed that includes strand slip to be used in determining anchorage length. Based on the test results, an analysis to experimentally substantiate the Stress Waves Theory of Janney has been proposed. Additionally, the potential bond performance of prestressing strands after anchorage failure at the end regions has been suggested.

Keywords: concrete; strand; bond; prestress; failure; anchorage; development; transmission; transfer

1. Introduction

Prestressing strands have been widely used in precast pretensioned concrete structures and bridge construction. Sufficient strand bond is necessary in pretensioned prestressed concrete members to guarantee the transfer of prestressing force at release and to assure the ability of strand to develop stress increases when the member is overloaded. An accurate prediction of the lengths affected by the bond stresses in the end regions is necessary to avoid anchorage failures.

These requirements imply the establishment of two lengths: the transmission length and the anchorage length. FIB [1] defines the transmission length (transfer length according to ACI [2]) as the distance along which the prestress is built up in the prestressing strand after prestress transfer. Likewise, FIB [1] defines the anchorage length (development length in [2]) as the embedment length required to transfer the ultimate prestressing strand force to the concrete. Fig. 1 illustrates these lengths and the idealized profile of the prestressing strand stress at the end region of a pretensioned prestressed concrete member. Also shown in Fig. 1 is the complementary bond length [3] (flexural bond length in [2]) defined as distance from the transmission length to the anchorage length. A comparative study on the strand stress values developed along these lengths has been included in [4], and their implications through time have been analyzed in [5].

The necesessary bond mechanisms along these lengths may result in differential displacements (slips) between the prestressing strand and the concrete cross sections [6]. These slips accumulate at the free end of the prestressed member and can be measured (the end slip) and related to the transmission length [7].

Anchorage length is generally defined and calculated in terms of strand stress. In addition, Buckner [8] indicates that the maximum stress in the prestressing strand must be achieved with a minimum embedment length to prevent strand end slip. However, a limitation or an account for strand slip is not addressed in the main design codes [2,9,10].

On the other hand, it is generally accepted that strand force in the transmission zone does not vary (and therefore neither the end slips) when the applied loads increase strand force in the complementary bond length (Stress Waves Theory of Janney [11], see Fig. 1). According to this theory, when a pretensioned prestressed concrete member is overloaded, the strand force is at its maximum at the point of maximum moment. This increase of strand force diminishes toward the ends of the member. Strand force increases and then progresses towards the end of the member as a wave, as the magnitude of the moment increases. If this wave reaches the transmission zone, the bond resistance in this zone diminishes due to the reduction in strand diameter that occurs as strand force increases. Anchorage failure can then be expected by general bond slip.

Although it has not been directly verified, the Stress Waves Theory [11] is commonly considered as a hypothesis to determine anchorage length through an iterative flexural testing process. This process involves testing several members by applying concentrated loads at different distances from the member end [12]. With this method, the anchorage length of prestressing strand corresponds to the embedment length when the member achieves its nominal moment capacity and at the same time, the strand slips. An effective anchorage length shorter than the distance between the member end and the loading point has been observed in members with inclined bending cracks [13]. In some prestressed concrete flexural members, prestressing force may not be fully developed at sections of high moment, and there have been instances in which bond failures have been observed [14]. Moreover, it is suggested that preventing strand slip should be a criterion for design, since increasing strand stress beyond general bond slip has not been investigated experimentally [15]. Therefore, research is needed to understand bond behavior when strand slip continues after an anchorage failure.

2. Objectives

Experimentally verifying the Stress Waves Theory of Janney [11] and analyzing the bond behavior of prestressing strands after anchorage failure has occurred are the aims of the research program. These purposes require an important condition for testing: the sequential performance of the prestress transfer stage and the anchorage loading stage on a same test specimen. Thus, the anchorage length can be determined on specimens in which the prestress transfer has been previously carried out with the same procedures used in practice of pretensioned prestressed concrete members.

To achieve these objectives, the ECADA test method [16,17], which is based on measuring the strand force, is a viable option. Researchers have suggested defining anchorage length based on two modes [18]: without strand slip at the free end of the member during the loading stage (anchorage length -without slip-, L_A), and accepting strand slip at the free end when a prestressed concrete member is loaded (anchorage length with slip, L_{AS}).

As part of the research program, prestressed specimens using 12 concrete mixes with compressive strengths at prestress transfer ranging from 24 MPa to 55 MPa were cast.

Transmission and anchorage lengths and examination of bond behavior after anchorage failure was assessed. All specimens contained 13 mm seven-wire prestressing steel strand.

3. Bond mechanisms and models

Strand bond behavior depends on several mechanisms developed between the strand surface and the surrounding concrete along the transmission and anchorage lengths: chemical adhesion, friction and mechanical action [1]. The adhesion is destroyed when slip of any magnitude occurs. After slip occurs, the friction mechanism and the mechanical action are activated. Bond stresses are caused by radial compressive stresses around the prestressing strand due to prestress transfer. These radial compressive stresses are the response of the surrounding concrete to the Hoyer effect [19] -strand diameter increase upon transfer of prestress force to member- and to the displacement of the prestressing strand when a slip occurs [6]. However, the increase of prestressing strand stress at loading involves an unfavorable contribution of the Poisson effect by decreasing the strand diameter. This fact reduces the frictional bond mechanism, increasing the importance of the mechanical action [20,21]. The mechanical action in prestressing strands is notably different than that in wires (see Fig. 2) because their helical shape allows for a bond stress increase when additional slip occurs.

High bond stresses at transfer can cause bond failures due to the surrounding concrete splitting [12,23]. Bond failures may also result from bursting failures and in spalling failures [1,9]. These failures may cause a complete loss of bond, especially when no confining reinforcement exists [24]. In these cases, the effective prestressing force may be redeveloped by bond at a distance from the damaged location [25].

High bond stresses at loading may cause anchorage failures by strand slip [26] and concrete splitting [27]. In beams, the increased strand force resulting from equilibrating internal shear forces also increases the force in the strand, most significantly along the transfer length. Failure to account for this action has resulted in both splitting and strand slip failures.

Strand anchorage failures can lead to an abrupt flexural or shear failure in prestressed concrete members [23]. The member may also collapse after general bond slip due to combined bon-flexure-shear failure modes [20,27,28]. The additional confining action of the transverse reinforcement favourably influences the anchorage capacity in these cases [13,29].

Uniform bond stress distribution along the transmission and the complementary bond lengths has been assumed by several authors and codess [30,31]. This assumption results in bilinear models which imply a linear variation of the prestressing stress as shown in Fig. 1. The slopes of the curves are proportional to the induced bond stresses within each zone.

In contrast with these models and with the Stress Wave Theory [11], the Norsk Standard 3473 [32] and Bruggeling [33] consider it possible that greater bond stresses may develop in the transmission zone when a prestressed concrete member is loaded.

Fig. 3 illustrates the Norsk Standard model [32] for strands gradually released with no transverse reinforcement. According to this model, increases of strand stress by external forces beyond the effective stress involve uniform bond stress increases along the whole of the anchorage length. Consequently, the bond stress along the transmission length increases approximately 15-30% over its initial value after prestress transfer (depending on the initial prestress level and prestress losses).

On the other hand, Bruggeling [33] establishes the anchorage length directily without a complementary bond length beyond the transmission length. According to Bruggeling [33], the mean bond strength value along the transmission length is proportional to $0.13f_{cm}$ (f_{cm}: mean concrete compressive strength at release) for gradually released strands, and the ultimate bond strength equally distributed over the whole anchorage length is proportional to $0.18f_{cm}$. Therefore, a bond strength improvement in the transmission zone from the prestress transfer stage to the anchorage stage is inferred according to a ratio of 1.4 (0.18/0.13).

Requirements regarding trand slip have not been explicitly established in the Norsk Standard provisions [32] or by Bruggeling [33] for the defined lengths.

4. Bond test method

In this research program, the ECADA test method was used to investigate strand bond [16,17]. This method measures the prestressing strand force during strand release (prestress transfer). Pull-out testing was sequentially performed on the same test specimens. Prestressed concrete specimens with varying embedment lengths were cast to determine both transmission and anchorage lengths.

The research program also recommends improvements to the test method. These improvements include measuring strand end slip at the free end of the specimens during loading, and defining two anchorage lengths: anchorage length -without slip- (L_A) and anchorage length with slip (L_{AS}). In the first case, the criterion to determine the anchorage length was based on the force achieved immediately before strand end slip occurs. In the second case, only the strand force achieved was considered in determining anchorage length.

4.1 Test equipment

The specimens were tested in prestressing frames with additional components at both ends as shown in Fig. 4. An AMA (Anchorage-Measurement-Access) system was placed at the pull-out end to simulate the sectional rigidity of the specimen during the prestress transfer. This system allowed for increases in strand force during the anchorage loading phase. An adjustable strand anchorage was placed at the transmission end to facilitate strand tensioning and release. To complete the testing program, six prestressing frames and 2 hydraulic actuators were employed.

4.2 Measurement

The ECADA test method requires a force transducer and a pressure sensor to obtain the necessary measurements. The force transducer was located at the end of the AMA system. With the force transducers, strand force was measured during all test phases: tensioning, provisional anchorage, detensioning, and loading. The pressure sensor controlled the force exerted by the hydraulic actuator.

A displacement transducer was placed at the free end of the each test specimen (see Fig. 4). This transducer detected free end slip during the anchorage loading and measured strand movement when slip occurred. Neither of these measurement devices interfered with the strand-concrete bond interface.

4.3. Specimen test procedure

The specimen test procedure included stages for preparation, prestress transfer (release) and anchorage capacity (loading) analysis. Fig. 5 illustrates a test specimen at the loading stage. The different phases for each stage are detailed below.

4.3.1 Test preparation

a) The prestressing strand was placed in the prestressing frame and was anchored at both ends.
b) The hydraulic actuator was positioned at the transmission end of the prestressing frame.
c) The prestressing strand was tensioned and provisionally anchored by using the adjustable strand anchorage.
d) The hydraulic actuator was removed.
e) The concrete was cast into the mold located in the prestressing frame. The concrete was allowed to cure until the desired concrete properties were achieved.

4.3.2 Prestressing force transfer

a) The hydraulic actuator was positioned at the transmission end of the prestressing frame to recover the actual prestressing strand force (P_0).
b) The adjustable strand anchorage device was released.
c) The hydraulic actuator was gradually unloaded, and the prestressing force was transferred to the concrete.

d) The prestressed concrete specimen was supported at the end plate of the prestressing frame included in the AMA system, and the prestressing strand force (P_T) was measured after a stabilization period.

4.3.3 Anchorage capacity

a) The hydraulic actuator was positioned at the pull-out end of the prestressing frame.

b) A displacement transducer was placed at the free end of the test specimen.

c) The force in the prestressing strand was gradually increased by loading the hydraulic actuator which separated the strand end anchorage at the AMA system from the prestressing frame.

d) The maximum force achieved during the pull-out operation before strand slip at the free end (P_A) was measured.

e) The maximum force achieved during the pull-out operation (P_{AS}) was measured.

f) Testing was complete when the prestressing strand fractured, the concrete split, or there was excessive strand slippage.

4.4. Test analysis of specimen series

Once the specimens were tested, the transmission and the anchorage lengths were determined by comparing the measured prestressing force to the specimen embedment length. Fig. 6 shows an idealization of the expected curves. Determining the transmission and anchorage lengths required testing 6 to 12 specimens with different embedment lengths at 50 mm increments.

For the transferred prestressing force values (P_T), the curves are expected to present a bilinear tendency (see Fig. 6), with an ascendent initial branch and a practically horizontal branch corresponding to the effective prestressing force (P_E, maximum prestressing force value determined by strain compatibility between the prestressing strand and concrete). The transmission length (L_T) corresponds to the shorter specimen embedment length that marks the beginning of the horizontal branch. As shown in Fig. 6, this is the point where $P_T = P_E$.

For the pull-out forces values (P_A and P_{AS}), the curves are expected to present ascendent tendencies (see Fig. 6). A reference force (P_R) was established to analyze the anchorage behavior. The anchorage length (L_A) corresponds to the shorter specimen embedment length of the test specimens in which P_R is achieved in the pull-out operation without strand slip at the free end of the specimen, that is, to the first specimen of the series with $P_A \geq P_R$. The anchorage length with slip (L_{AS}) corresponds to the shorter embedment length of the test specimens in which P_R is achieved in the pull-out operation, that is, to the first specimen of the series with $P_{AS} \geq P_R$.

The complementary bond length (L_C) results as the reduction of the transmission length to the anchorage length ($L_C = L_A - L_T$).

5. Experimental program

An experimental program was developed to verify the Stress Waves Theory [11] and to analyze the bond behavior in prestressed concrete members after anchorage failure has occurred by bond slip. The materials, concrete mixture proportions, and specimens are discussed in detail below.

5.1 Materials

Specimens were cast using twelve different concretes with water to cementitious material ratios (w/cm) ranging from 0.30 to 0.50, cement contents from 350 to 500 kg/m^3, and concrete compressive strengths at strand release (f_{ci}) from 24 to 55 MPa. All concrete mixtures were composed of: cement CEM I 52.5 R [34], crushed limestone aggregate 7-12 mm, washed rolled limestone sand 0-4 mm and a polycarboxylic ether high range water reducer. All mixtures contained a constant gravel/sand ratio of 1.14. Table 1 summarizes the concrete mixture designs and also includes the tested specimen embedment lengths (see section 4).

Low–relaxation, seven-wire steel strand with a 13 mm nominal diameter and a pitch of 190 mm was used for all specimens. The strand had a guaranteed ultimate strength 1860 MPa and specified as UNE 36094:97 Y 1860 S7 13.0 [35]. The strand manufacturer provided the following information about the strands: diameter of 12.9 mm, section of 99.69 mm^2, ultimate strength of 1932 MPa, yield stress at 0.2% of 1780 MPa, and modulus of elasticity of 196.70 GPa.

5.2 Specimens and test parameters

The test specimens had a cross section of 100 x 100 mm^2 with a centered single strand. The prestressing strand was used in the as-received condition (free of rust and free of lubricant). For all specimens, the strands were tensioned to 1395 MPa, equal to 75 percent of the nominal ultimate strand strength.

All specimens received identical consolidation and curing conditions. The prestress transfer was gradually performed 24 hours after concrete casting. A two hour stabilization period after prestress transfer was allowed before determining the transferred prestressing force (P_T).

For the anchorage analysis, a force P_R of 158 kN was chosen to represent the force that can be applied to the strand before failure.

In the experimental research, the moment corresponding to a strand slip of 0.1 mm (first slip) at the free end was used to determine the anchorage length -without slip- (L_A). Previous research has used strand slip values of 0.025 mm [27] and 2 mm in [36].

6. Test results and discussion

The transmission and anchorage lengths were determined by testing a series of specimens cast with each concrete mixture proportion. Shown in Fig. 7 are the test results for concrete C-350/0.50.

Table 2 summarizes the transmission and anchorage length results and the corresponding prestressing strand forces (ratios in terms of the nominal ultimate strand strength have been included parenthetically) for all concrete mixtures. The effective prestressing force P_E is the average value of the strand force in specimens with an embedment length equal to or longer than the corresponding measured transmission length. As shown in Table 2, the P_A and P_{AS} are slightly greater than P_R because of the 50 mm embedment length increments. As observed, the anchorage length with slip (L_{AS}) obtained for all concrete mixtures was always shorter than the anchorage length (L_A), and the anchorage length with slip (L_{AS}) was less than the transmission length (L_T) for 9 of the 12 cases.

6.1 Stress Waves Theory verification

As observed in Fig. 7:

a) The prestressing force transferred (P_T) increases as embedment length increases until the transmission length is achieved.

b) From the transmission length (L_T = 550 mm in this case) forward, the transferred prestressing force values are essentially constant and independent of the embedment length ($P_T = P_E$.).

c) The force achieved at first slip during the pull-out operation (P_A): i) coincides with the corresponding prestressing force transferred P_T when specimen embedment length is shorter than the measured transmission length; ii) is greater than the effective prestressing force P_E when specimen embedment length is longer than the measured transmission length, and the obtained P_A value increases from P_E until P_R when the embedment length increases; and iii) for the specimen embedment length equal to the measured transmission length, P_A essentially coincides with the effective prestressing force P_E.

d) The values of maximum strand force achieved during the pull-out operation (P_{AS}) are greater than the strand force values at first slip (P_A) in specimens with embedment length shorter or equal than the anchorage length (L_A). In specimens where the embedment length was longer than L_A, the strands frequently ruptured.

The aforementioned facts have been observed for all series of specimens tested and they indicate that, after prestress transfer and sequentially the anchorage loading is performed:

a) for cases where embedment length is shorter than the measured transmission length, the increase of the prestressing strand force is only possible if strand end slips occur;

b) for cases where embedment length is longer than the measured transmission length, the prestressing strand force can be increased without strand end slip;

c) for cases where the embedment length equals the measured transmission length, the increase in the prestressing strand force from the effective prestressing force causes strand end slips, and $P_A = P_E$: the Stress Waves Theory is directly verified by testing a prestressed concrete specimen with embedment length equal to the transmission length, and performing the anchorage loading sequentially after the prestress transfer on the same specimen.

6.2 Bond performance

As shown in Fig. 7, when the embedment length equals the transmission length (550 mm), the strand force achieved during the pull-out operation at first slip (P_A) is slightly greater than the effective prestressing force P_E. This difference is due to the fact that the resolution in determining the transmission and anchorage lengths depends on the interval (50 mm increments) of the specimen lengths tested [37,38]. Also, in the design of the ECADA test equipment [16,17], the strand force measured in the AMA system after release is slightly greater than the effective prestressing force in the specimen. This is because the rigidity of the AMA system is slightly greater than the sectional rigidity of the specimens. Consequently, as shown in Fig. 8, the measured transmission length ($L_{T,ECADA}$) is somewhat longer than the actual transmission length ($L_{T,actual}$).

To account for the difference between measured and actual, an adjusted line to the P_A points of specimens with embedment length equal to or longer than L_T and shorter than L_A (see the idealized upper line in Fig. 7) can be used, as follows (see Fig. 8): a) a new transmission length ($L_{T,adj}$) is determined by extending the adjusted line to the free end to intercept the P_E value; b) a new anchorage length ($L_{A,adj}$) is determined from the P_R value; c) the new complementary bond length ($L_{C,adj}$) is obtained as $L_{C,adj} = L_{A,adj} - L_{T,adj}$. Table 3 summarizes the equations for the adjusted lines and the subsequent corrected values ($L_{T,adj}$, $L_{A,adj}$, and $L_{C,adj}$) for each concrete mixture proportion tested.

Based on the equilibrium of the prestressing strand force achieved in the different stages and the induced bond stresses that characterize each phenomenon (transmission, anchorage, and anchorage with slip), the average bond stress values are obtained from the following equations:

$$U_T = \frac{P_E}{\left(\frac{4}{3}\pi\phi\right)L_{T,adj}} \tag{1}$$

$$U_C = \frac{P_R - P_E}{\left(\frac{4}{3}\pi\phi\right)L_{C,adj}} \tag{2}$$

$$U_A = \frac{P_R}{\left(\frac{4}{3}\pi\phi\right)L_{A,adj}} \tag{3}$$

$$U_{AS} = \frac{P_{AS}}{\left(\frac{4}{3}\pi\phi\right)L_{AS}} \tag{4}$$

Where:

U_T = average bond stress along the transmission length

U_C = average bond stress along the complementary bond length

U_A = average bond stress along the anchorage length
U_{AS} = average bond stress along the anchorage length with slip
P_E = effective prestressing force
P_R = reference force for the anchorage analysis
P_{AS} = maximum strand force anchored during the pull-out operation
ϕ = nominal diameter of prestressing strand
$L_{T,adj}$ = transmission length (adjusted)
$L_{C,adj}$ = complementary bond length (adjusted)
$L_{A,adj}$ = anchorage length (adjusted)
L_{AS} = anchorage length with strand end slip

Based on the results for the specimens cast with concrete C-350/0.50, Fig. 9 illustrates the prestressing strand forces for the different adjusted lengths defined in this work. The slopes of the curves correspond to bond forces per unit length and are related to bond stresses around the strand perimeter (see Eq. (1) to (4)). The average bond stress associated with each length is also plotted in Fig. 9.

Table 4 summarizes the average bond stress along each defined length for all concrete mixture proportions. These bond stresses were calculated using Eq. (1) to Eq. (4). Table 4 also includes bond stress ratios and their average values. In all cases, U_T is greater than U_C, U_A has values between U_T and U_C, and U_{AS} is greater than U_T.

The average U_T/U_C ratio obtained in this work is 1.9 which is in the order of experimental results reported by other authors. Currently it is considered that beyond the transmission length the bond strength is half the value available within the transmission length [8]. Similar experimental results are found for beams in [13] ($U_T/U_C = 2$) and in [28] ($U_T/U_C = 1.4$), and for cylindrical concrete specimens in [39] ($U_T/U_C = 2$).

The average U_{AS}/U_T ratio of 1.3 implies that, in agreement to [32,33], there is a bond strength improvement in the transmission zone from the prestress transfer stage to the anchorage stage.

The average U_{AS}/U_C ratio of 2.5 implies that a potential bond performance after anchorage failure, by bond slip, is neglected in the traditional bilinear bond models that do not consider strand end slip at the end regions of pretensioned members.

Finally, the average U_{AS}/U_A ratio of 1.5 proves that the mechanical action exerted by developing strand end slip increases bond strength along L_{AS} (anchorage length with slip) when compared to the bond strength along L_A (anchorage length -without slip-). This contribution provides beneficial effects at the end zones of pretensioned members by improving their strength and ductility after anchorage failure occurs. Moreover, as shows Fig. 10, it can be observed that the U_{AS}/U_A ratio increases when concrete compressive strength increases.

7. Conclusions

The research program examined the transmission and anchorage length of pretensioned prestressed concrete specimens. The research also analyzed the bond behavior after an anchorage failure by general bond slip. Specimens containing 13-mm seven-wire prestressing steel strand were tested using the ECADA test method. The following conclusions may be drawn from this experimental research:

- For specimens with embedment length shorter or equal to the transmission length, the maximum strand force anchored without strand end slip coincides with the transferred prestressing force.
- For specimens with an embedment length longer than the transmission length, the anchored strand force without strand end slip is greater than the transferred prestressing force. This strand force in the anchorage length increases when embedment length increases.
- The Stress Waves Theory of Janney has been experimentally verified by testing a pretensioned specimen with an embedment length equal to the transmission length while performing the anchorage loading sequentially after prestress transfer. The maximum strand force anchored without end slip coincides with the effective prestressing force, and increases in strand force during the pull-out stage involve strand end slips.
- For all cases, the average bond stress along the transmission length (U_T) is greater than the average bond stress along the complementary bond length (U_C). The obtained U_T/U_C ratio is 1.9, which is in accordance with experimental results reported by other authors.
- For all cases, the average bond stress along the anchorage length with slip (U_{AS}) is greater than the average bond stress along the transmission length (U_T). The obtained U_{AS}/U_T ratio is 1.3, which implies that there is a bond strength improvement in the transmission zone from the prestress transfer stage to the anchorage stage.
- The obtained U_{AS}/U_C ratio is 2.5, which implies the existence of a potential bond performance after an anchorage failure by bond slip. Therefore, there is some bonding capacity which is neglected in the traditional bilinear bond models that do not consider strand end slip at the end regions of pretensioned members.

- The obtained U_{AS}/U_A ratio is 1.5, which proves that the mechanical action contribution exerted after anchorage failure by general bond slip enhances bond strength along the anchorage length.
- The U_{AS}/U_A ratio increases when concrete compressive strength increases.

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