Bond of 13 mm prestressing steel strands in pretensioned concrete members

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Abstract

This paper presents an experimental research work to determine both the transmission and the anchorage lengths of seven-wire prestressing steel strands in different concrete mixes. A testing technique based on a bond behaviour analysis by measuring the force supported by the prestressing strand on a series of specimens with different embedment lengths has been used. Relationships between the average bond stress for both the transmission length and anchorage length as a function of the concrete compressive strength have been found. Equations to compute transmission and anchorage lengths of 13 mm prestressing strands have been obtained. The experimental results have been compared with the theoretical prediction from proposed equations in the literature and with experimental results from others authors.

Keywords

bond, concrete, strand, prestress, transmission length, anchorage length, transfer length, development length

1 Introduction

In pretensioned concrete members, the prestressing force in the reinforcement is transferred to the concrete by the bond in the end region of the member. Furthermore, when a pretensioned concrete member is loaded, the activation of bond stress increases the prestressing reinforcement force. Therefore, in pretensioned concrete members it is essential a correct design and an accurate prediction of the lengths affected in the end region of the member by means of the required bond stress.

In the end region of a pretensioned concrete member and after the prestress transfer operation, the stress in the prestressing reinforcement varies from zero at the free end to a maximum value (effective stress) along the distance, defined as the transmission length in agreement with the terminology presented in [1] (transfer length according to [2]). When a pretensioned concrete member is loaded, a complementary bond length beyond the transmission length is required to develop the corresponding reinforcement stress from the effective prestress. The embedment length from the free end required to reach a design stress is known as the anchorage length [1] (development length according to [2]). The anchorage length is obtained as the sum of the transmission length and the complementary bond length.

Several theoretical and experimental works about bond and transmission, and on anchorage lengths of prestressing reinforcement, have been conducted over the years. Bond strength, as well as transmission and anchorage lengths, depend on several factors [1,3]: concrete strength at the time of the prestress transfer, initial reinforcement stress, concrete cover, prestress transfer process condition, reinforcement geometry, reinforcement surface condition, concrete strength at the time of loading, etc. However, no consensus has been reached on the main parameters to be considered in the equations to calculate both transmission and anchorage lengths. An example of this is ACI Code 318–11 [2], provisions for transmission (transfer) and anchorage (development) lengths which are not a function of concrete strength. On the other hand, Eurocode 2 [4] and Model Code 2010 [5] provisions for transmission and anchorage lengths include concrete properties.

Nowadays, it is assumed that bond performance is essential for an adequate response of pretensioned prestressed concrete applications. ACI 318–11 [2] indicates that the quality assurance procedures for bonded applications should be used to confirm that the bond properties of reinforcement are adequate. However, there are no minimum requirements for the bond performance of prestressing strands in [2], or in standards like in [6,7].

In spite of the large number of experimental research works carried out, there is no consensus on a standard test method for bond quality [1]. Recently, an experimental methodology has been developed, the ECADA test method, which is based on both the measurement and analysis of the force supported by the reinforcement in specimen series with different embedment lengths [8], and its feasibility has been verified [9].

The purpose of this research study is to develop an analytical bond model to predict the transmission and anchorage lengths of 13 mm prestressing steel strands for bond characterization. To this end, an experimental program to determine transmission and anchorage lengths, as well as the average bond stress along both the transmission length and the complementary bond length in twelve concretes of different compositions and properties, by means of the ECADA test method, has been set up. The experimental results have been compared with other theoretical and experimental studies found in the literature.

2 Background

According to [10], the uniform bond stress distribution hypothesis is an unattainable limit since a portion zone that behaves in an elastic way will always exist in both the transmission length and the complementary bond length. An analytical bond model for anchorage length that considers both the plastic and elastic zones along the transmission and complementary bond lengths was proposed in [11]. These elastic zones are located one after the other at the end of the transmission length, and also at the beginning of the complementary bond length. However, a plastic response along the almost entire transmission length [12,13], and a very small elastic zone in the case of complementary bond length [14], have been reported.

Currently, the uniform bond stress distribution hypothesis is generally accepted by several Codes [2,4,5] and authors [15-28], which assumes linear variations of the prestressing reinforcement stress for both the transmission and complementary bond lengths, resulting in a bilinear model.

In order to obtain the equilibrium of a prestressing reinforcement, the transfer bond force over the transmission length and the anchorage bond force along the complementary bond length must equal the force in the prestressing reinforcement according to Eq. (1) and Eq. (2), respectively; consequently, the anchorage length can be obtained from Eq. (3):

$$U_T \Sigma_p L_T = \sigma_{p1} A_p \tag{1}$$

$$U_C \Sigma_p L_C = (\sigma_{p2} - \sigma_{p1}) A_p \tag{2}$$

$$L_A = L_T + L_C = \frac{\sigma_{p1} A_p}{U_T \Sigma_p} + \frac{(\sigma_{p2} - \sigma_{p1}) A_p}{U_C \Sigma_p} \tag{3}$$

where

U_T = average bond stress along the transmission length

U_C = average bond stress along the complementary bond length

Σ_p = perimeter of prestressing reinforcement

L_T = transmission length

L_C = complementary bond length

σ_{p1} = effective stress in prestressing reinforcement after prestress transfer

σ_{p2} = stress in prestressing reinforcement at loading

A_p = cross-sectional area of prestressing reinforcement

L_A = anchorage length

Fig. 1 shows the idealized increase of the prestressing reinforcement stress with the embedment length from the free end according to the bilinear model presented.

According to Fig. 1 ($L_A = L_T + L_C$), several equations based on experimental results have been proposed by several codes and authors to predict the transmission and the anchorage lengths. Table 1 shows some of these equations for seven-wire prestressing strands. For each reference, the equations for transmisson length (Equations (a)) and for complementary bond length (Equations (b)) are indicated, resulting in the corresponding equation for anchorage length as Equation (c) = Equation (a) + Equation (b). Complementary bond length is deduced as $L_C = L_A - L_T$ for the case of reference [15]. Once the notation of the different equations has been adapted from their original form to SI Units, then:

ϕ = nominal diameter of prestressing strand

σ_{pt} = initial prestress in prestressing strand prior to release

σ_{pi} = effective stress in prestressing strand just after prestress transfer

σ_{pa} = maximum stress in strand at loading (for design stress [5], at nominal strength [2])

σ_{pcs} = effective stress in prestressing strand after all prestress losses

f_{ci} = concrete compressive strength at time of release

f_{cl} = concrete compressive strength at loading

f_c = concrete compressive strength at 28 days

It should be noted that Table 1 includes several equations for transmission length: $\sigma_{p1} = \sigma_{pi}$ [4,5,16-20,23,24] and others $\sigma_{p1} = \sigma_{pcs}$ [2,11]. Some cases correspond to the variations proposed for the ACI Code provisions, which first appeared in 1963 [29] and were derived from Eq. (3) taking into account U_T = 2.76 MPa and U_C = 0.94 MPa [30]. This equation has remained up to date in [2] and is applied for all types of concrete in spite of a considerable number of proposed changes that includes concrete strength [11,16,21,24]. In addition, several authors [16,17,19-21,24] consider that the use of term σ_{pi}, rather than σ_{pcs}, to compute transmission length is more rational, and in [17,19,20,22] the U_T = 2.76 MPa is retained resulting in greater transmission lengths.

For design purposes, it is generally considered that the transmission length (with $\sigma_{p1} = \sigma_{pi}$ or $\sigma_{p1} = \sigma_{pcs}$) established at the time of the prestress transfer does not significantly change with time. The anchorage length prediction takes into account the term $\sigma_{p1} = \sigma_{pcs}$ in the complementary bond length in all the cases presented in Table 1, except in [25] ($\sigma_{p1} = \sigma_{pt}$). This exception is considered in [25] to obtain the best coefficient of correlation (R^2) in several simple regression models based on measured complementary bond lengths (R^2 = 0.47 when $\sigma_{p1} = \sigma_{pcs}$ and R^2 = 0.69 when $\sigma_{p1} = \sigma_{pt}$; for transmission length, R^2 = 0.40 is obtained).

Fig. 2, 3 and 4 present the transmission length, complementary bond length, and anchorage length of a seven-wire 13 mm prestressing steel strand, respectively. These lengths have been predicted from the equations in Table 1 for concrete compressive strength at the time of prestress transfer f_{ci}, which is equal to 30 MPa and 50 MPa in these comparisons. The following relationships have been adopted: $\sigma_{pt} = 0.75 f_{pu}$ (f_{pu} = 1860 MPa, specified tensile strength of prestressing strand), $\sigma_{pi} = 0.93\sigma_{pt}$, $\sigma_{pcs} = 0.8\sigma_{pt}$, $\sigma_{pa} = 0.9 f_{pu}$ and $f_{cl} = 1.5 f_{ci}$. For the α_{p2} factor included in the MC2010 [5] to consider the action effect to be verified in design (α_{p2} = 1 for calculation of anchorage length when moment and shear capacity is considered; α_{p2} = 0.5 for verification of transverse stress in anchorage zone), a value of α_{p2} = 0.75 has been adopted by the authors from the established values α_{p2} = 1 and α_{p2} = 0.5 for the upper bound and lower bound values of transmission length, respectively. With α_{p2} = 0.75, the provisions for the transmission length from [4,5] coincide.

Fig. 2, 3 and 4 show the wide ranges of predicted values by means of different equations of transmission length, complementary bond length and anchorage length, respectively. In addition, it may be seen that these lengths are always decreased when concrete strength increases for the lengths predicted from those equations which are related to concrete strength. The ratios of the lengths obtained for both concrete compressive strengths are shown in the figures.

Regarding to the experimental results of transmission and anchorage lengths obtained in the literature, the values of the transmission lengths for 13 mm prestressing steel strands are around 600-700 mm, with minimum values of 330-350 mm [21,24] and maximum of 1800 mm [11]. Anchorage length values are often above 2000 mm [11,19], although some are also around 700 mm [21]. Moreover, the U_T/U_C ratios to characterize the different bond situations have been determined theoretically and experimentally [20,27,31].

3 Test procedure and instrumentation

The ECADA test method consists in sequentially analysing the transmission and anchorage process of the strand in pretensioned concrete specimens. Specimens are made in pretensioning frames with an adjustable strand anchorage as shown in Fig. 5. At the opposite end, an Anchorage-Measurement-Access (AMA) system is placed to simulate the sectional stiffness of the specimens. The test equipment is completed with a hydraulic jack that can be placed at the pretensioning frames ends.

The force in the strand is controlled and registered while the test is being carried out by means of a hollow force transducer placed in the AMA system. Relative displacements between the strand and concrete are also continuously measured and registered by means of a displacement transducer at the free end of the specimen. A pressure transducer completes the instrumentation and is used to control the hydraulic jack. No internal measuring devices are used in the specimens tested in order to not distort the bond phenomenon.

Once the equipment test is set up as shown in Fig. 5, with the hydraulic jack connected to the frame at the free end, the different test procedure phases are as follows:

a) Preparation stage.

- Lining up the strand in the frame.
- Tensioning the strand. The hydraulic jack pulls the anchorage plate and separates it from the adjustable strand anchorage.

- Anchorage of the strand. The adjustable strand anchorage is set up to contact the anchorage plate thus bearing the force introduced into the strand. The hydraulic jack is then unloaded.
- Specimen cast. The concrete is mixed, placed into the form prepared in the frame, and consolidated.
- The specimen is cured to achieve the desired concrete properties and is then demoulded before testing.

b) Testing stage.

- Prestress transfer. The hydraulic jack is loaded to recover the force in the strand supported by the adjustable strand anchorage which is relieved. The strand prestress transfer takes place at a controlled speed through the unloading of the hydraulic jack. The prestressing force is transferred to the concrete and the concrete specimen is supported at the stressed end of the frame.
- Stabilization period. The force in the strand after release (P_T) is measured.
- Pull-out operation. The hydraulic jack is positioned to increase the force in the strand by separating the anchorage plate of the AMA system from the frame. The maximum force achieved during the pull-out operation before the strand slip at the free end (P_A) is measured.

4 Experimental program

An experimental program to determine the transmission and anchorage lengths of a 13 mm prestressing steel strand in different concrete mixes has been carried out.

Specimens cross-sections were 100 x 100 mm^2 with a concentrical single prestressing strand. Tests were carried out on twelve different concrete mixes with water/cement ratios (w/c) ranging from 0.3 to 0.5, cement content (C) from 350 to 500 kg/m^3 and a compressive strength at the time of testing f_{ci} ranging from 24 to 55 MPa. The concrete components were: cement CEM I 52.5 R [32], crushed limestone aggregate 7/12, washed rolled limestone sand 0/4 and a polycarboxylic ether superplasticiser. All the concrete mixes were designed with a constant gravel/sand ratio of 1.14.

The prestressing strand was a low-relaxation seven-wire steel strand, 13 mm in diameter, at a prestress level of 75 percent of the guaranteed ultimate strength (1860 MPa), specified as UNE 36094:97 Y 1860 S7 13.0 [6]. The main characteristics were taken from the manufacturer: diameter, 12.9 mm, section, 99.69 mm^2, nominal strength, 192.60 kN, yield stress at 0.2%, 177.50 kN, and modulus of elasticity, 196.70 GPa.

All the specimens were subjected to the same consolidating and curing conditions. The prestress transfer was gradually performed at 24 hours after casting to avoid dynamic shock effects [33,34]. A 2-hour stabilization period from the prestress transfer was established. The pull-out operation was carried out after this stabilization period (consequently, $f_{cl} = f_{ci}$) to reach a reference force (P_R) of 158 kN in the prestressing strand, corresponding to the strand's nominal yield strength at 0.1% [6].

5 Determining transmission and anchorage lengths

With the ECADA method, both the transmission and anchorage lengths are determined by measuring and analysing the force supported by the strand in a series of pretensioned concrete specimens with different embedment lengths [8,9]. By way of example, Fig. 6 shows the results of transferred prestressing and pull-out forces versus the embedment length for a concrete mix design.

The transferred prestressing force values after stabilization period P_T are ordered according to specimen embedment lengths (Fig. 6). The obtained curves present a bilinear tendency, with an ascendent initial branch and a sensibly horizontal branch corresponding to the effective prestressing force P_E ($P_E = \sigma_{pi}A_p$). Transmission length L_T corresponds to the shorter specimen embedment length with $P_T = P_E$; that is, it corresponds to the shorter specimen embedment length that marks the beginning of the horizontal branch.

The pull-out force values P_A are ordered according to the specimen embedment lengths (Fig. 6). The obtained curves present an ascendent trend. Anchorage length L_A corresponds to the shorter specimen embedment length of the test specimens in which the reference force P_R in the strand is reached in the pull-out operation without a strand slip at the free end of the specimen; that is, it corresponds to the first specimen of the series with $P_A \geq P_R$. The complementary bond length is obtained as $L_C = L_A - L_T$.

The resolution in determining the transmission and anchorage lengths will depend on the sequence of the specimen lengths tested. For the specimen embedment length equal to the measured transmission length, the force reached during the pull-out operation before the strand slip (P_{A^*}) is slightly greater than the effective prestressing force P_E. This fact indicates that the transmission length obtained for the adopted embedment length sequence is somewhat longer than the real transmission length.

6 Results and discussion

6.1 Test results

For each specimen, the prestress transfer and the pull-out of the strand operations performed with the ECADA test method have been carried out sequentially. For each concrete mix, transmission and anchorage lengths are determined from a series of specimens with different embedment lengths.

Table 2 summarizes the main results for all the concrete mix designs. The effective prestressing force P_E is the average value of the force in the prestressing strand in those specimens with an embedment length equal to or longer than the transmission length obtained by the ECADA test method for each concrete mix design after the stabilization period.

6.2 Proposed bond model

The average bond stresses values along both transmission and complementary bond lengths from the measured data in this study, according to Eq. (1) and Eq. (2), are obtained from the following equations:

$$U_T = \frac{P_E}{\Sigma_p L_T} \tag{18}$$

$$U_C = \frac{P_A - P_{A*}}{\Sigma_p L_C} \tag{19}$$

P_E in Eq. (18) was chosen instead of P_{A*} to directly consider the results obtained after the stabilization period of the prestress transfer from the embedment length sequence tested at a resolution of 50 mm. In this way, slighter average bond stresses than the real ones were determined for the transmission zone. The P_{A*} value will coincide with the P_E value if the transmission length is a multiple point of the embedment length resolution.

The effect of concrete strength on the average bond may be illustrated by redefining U_T and U_C as [11,21,24]:

$$U_T = U'_T\,(f_{ci})^{\alpha} \tag{20}$$

$$U_C = U'_C\,(f_{ci})^{\alpha} \tag{21}$$

In order to determine U'_T and U'_C and the appropiate α exponent, several regression analyses of the test results have been carried out by substituting U_T and U_C in Eq. (18) and Eq. (19), respectively, for Eq. (20) and Eq. (21). Fig. 7 and 8 show the obtained adjustments. Therefore, the proposed equations for both transmission and complementary bond lengths derived from the test results of this study are:

$$L_T = \frac{P_E}{\Sigma_p 0.4 f_{ci}^{2/3}} \tag{22}$$

$$L_C = \frac{P_A - P_{A*}}{\Sigma_p 0.25 f_{ci}^{2/3}} \tag{23}$$

From the adjustments, the obtained U_T/U_C ratio is 1.6 (0.4/0.25); consequently, anchorage length can be obtained from Eq. (24):

$$L_A = \frac{2.5}{\Sigma_p f_{ci}^{2/3}} \left[P_E + 1.6 \left(P_A - P_{A*} \right) \right] \tag{24}$$

Fig. 9, 10 and 11 show the comparisons of the predicted values from Eq. (22), Eq. (23) and Eq. (24), respectively, versus the measured transmission lengths, complementary bond lengths and anchorage lengths. The quality of the adjustments is comparable to that obtained in [24]. Therefore, the 50 mm resolution applied to determine these lengths from the sequences of specimen lengths is reliable.

In this experimental study for the bond characterization of 13 mm prestressing steel strand, the testing loading time coincides with the time of the prestress transfer ($f_{cl} = f_{ci}$). For $f_{cl} > f_{ci}$, the U_C values can be expected to be above the obtained U_C values. As a result, when $f_{cl} > f_{ci}$, Eq. (23) is conservative for the complementary bond length prediction, while Eq. (24) proves conservative for the anchorage length prediction.

According to the notation used in Table 1, Eq. (22) and Eq. (24) can be rewritten as Eq. (25) and Eq. (26), respectively:

$$L_T = \frac{2.5 A_p \sigma_{pi}}{\Sigma_p f_{ci}^{2/3}} \tag{25}$$

$$L_A = \frac{2.5 A_p}{\Sigma_p f_{ci}^{2/3}} \left[\sigma_{pi} + 1.6 \left(\sigma_{pa} - \sigma_{pa*} \right) \right] \tag{26}$$

Term σ_{pa*} in Eq. (26), obtained as P_{A*}/A_p, coincides with σ_{pi} when $P_{A*} = P_E$ in the ECADA test methodology. For a general case, σ_{pa*} should be replaced with σ_{pi} in Eq. (26).

In order to obtain equations for design, additional experimental works on transmission and anchorage lengths with $f_{cl} > f_{ci}$ should be conducted, and term σ_{pa*} in Eq. (26) should be replaced with σ_{pcs}. Moreover, the 95 percent confidence intervals for the transmission and anchorage lengths should be established.

6.3 Comparison with others research works and code provisions

The experimental results obtained in this study have been compared with the theoretical predictions obtained from the equations included in Table 1 and the proposed equations by considering the experimental conditions of this study in all cases. For this purpose, the following relationships have been adopted: $\sigma_{pt} = 0.75f_{pu} = 1395$ MPa, $\sigma_{pi} = \sigma_{pcs} = 1310$ MPa (obtained on average as P_E/A_p), $\sigma_{pa} = 0.9f_{pu} = 1674$ MPa (implies $P_A = 166.88$ kN, average $L_A = 725$ mm and average $L_C = 192$ mm by extrapolation with the experimentally obtained U_C values) and $f_{cl} = f_{ci} = 38.7$ MPa.

Fig. 12 shows the comparison for the average bond stresses along both the transmission and anchorage lengths, while Fig. 13 shows the comparison for transmission length and anchorage lengths. These figures also include the average values obtained for U_T (4.6 MPa), U_C (2.8 MPa), L_T (533 mm) and L_A (725 mm).

Fig. 12 depicts the wide ranges of predicted values. For U_T, Eq. (6a) and Eq. (11a) provide a good prediction of the experimental results of this study. For U_C, results are greater than the predicted values. Only the prediction made by Eq. (8b) with $k = 2$ stands out in the set of predictions as it comes closer to the obtained results.

The predicted U_T/U_C ratios are 1.5 to 7, as observed in Fig. 12, with an average value of 4. A ratio of 4.0 was derived to correlate transmission to pullout bond stress-slip relationships [27]. Other theoretical studies [20] indicate values of 1 to 8 for the U_T/U_C ratio, with an average value of 2.4. Moreover, experimentals results with U_T/U_C = 1.4 (in beams) are presented in [21], and are offered in [31] with U_T/U_C = 2 (in cylindrical concrete specimens). The U_T/U_C ratio obtained in this work is 1.6, similar to the aforementioned experimental results and the prediction by Eq. (8) with k = 2.

Fig. 13 shows that Eq. (6a) and Eq. (11a) offer a good prediction of the average measured L_T in this study. Generally, the measured transmission length is overvaluated by the remaining equations, with predictions that provide transmission length values more than twice the measured transmission lengths. Similar experimental results for transmission length are presented in [15,16,18,23,24].

For anchorage lengths, and in agreement with the greater U_C in relation to that predicted, the tests results are distinguised by short lengths (see Fig. 13), resulting in a poor prediction of the experimental anchorage lengths from the equations found in the literature. Similar experimental results are found in [11] for coated strands, and in [20] for uncoated strands with f_{ci} = 48 MPa and f_{cl} = 65 MPa.

The predicted L_T/L_A ratios are 0.34 to 0.71, as observed in Fig. 13, with an average value of 0.5. The L_T/L_A ratio obtained from the equations proposed in this study is 0.69 (L_T/L_A = 528/ 763 –the experimental ratio is L_T/L_A = 533/725 = 0.73-), indicating that the complementary bond lengths obtained are relatively short. In addition to the proposed equations, the predicted ratio of 0.71 by Eq. (8) with k = 2 is the best prediction of the experimental L_T/L_A ratio.

7 Conclusions

An experimental program to determine transmission and anchorage lengths and the average bond stress along both the transmission length and the complementary bond length of 13 mm prestressing steel strand has been conducted by means of the ECADA test method. The influence of concrete strength on transmission and anchorage lengths has been analyzed.

The main conclusions drawn from this experimental study are:

- An increase of the concrete compressive strength at the testing time results in an increase of the bond stress along both the transmission and complementary bond lengths. However, this fact is not considered in the current ACI 318 Code provisions.
- An average bond stress along the transmission length as a function of the concrete compressive strength at the time of the prestress transfer has been obtained as $U_T = 0.4\, f_{ci}^{2/3}$.
- An average bond stress along the complementary bond length as a function of the concrete compressive strength at loading has been obtained as $U_C = 0.25\, f_{cl}^{2/3}$.
- The obtained U_T/U_C ratio is 1.6, which is in agreement with other experimental results reported by other authors.
- With these relationships for U_T and U_C, the estimation of the transmission length, the complementary bond length, and the anchorage length is a good adjustment to the lengths measured for the 50 mm resolution in the specimen lengths sequences, and is reliable.
- The following equation to predict the transmission length of 13 mm prestressing steel strand is proposed:

  $$L_T = \frac{2.5 A_p \sigma_{pi}}{\Sigma_p f_{ci}^{2/3}}$$

- The following equation to predict the anchorage length of 13 mm prestressing steel strand when the testing loading time coincides with the prestress transfer time is proposed:

$$L_A = \frac{2.5 A_p}{\Sigma_p f_{ci}^{2/3}} \left[\sigma_{pi} + 1.6 \left(\sigma_{pa} - \sigma_{pi} \right) \right]$$

- The test results obtained in this study have been compared with the theoretical predictions obtained from the different equations proposed by several authors and codes to determine transmission and anchorage lengths. Predictions give transmission and anchorage lengths values that vary considerably and differ from each other.
- The predicted transmission length generally overvestimates the measured transmission length, with predictions that provide transmission length values more than twice the measured transmission lengths.
- From the experimental results of this study a high L_T/L_A ratio has been obtained.

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