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Martí-Vargas, JR, Garcia-Taengua, E, Caro, LA et al. (1 more author) (2014) Measuring specific parameters in pretensioned concrete members using a single testing technique. Measurement, 49. pp. 421-432. ISSN 0263-2241

https://doi.org/10.1016/j.measurement.2013.12.007

Measuring specific parameters in pretensioned concrete members using a single testing technique

Abbreviated title: Measuring in pretensioned concrete

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Abstract:

Pretensioned concrete members are designed and manufactured by using at least two materials: concrete and prestressing reinforcement. Also, two main stages must be considered: prestress transfer and member loading. Hence, the behavior of these members depends strongly on the reinforcement-to-concrete bond performance and prestress losses. In this paper, a testing technique to measure the specific parameters related with the involved phenomena is presented. The testing technique is based on the analysis of series of specimens varying in embedment length to simulate several cross sections at only one end of a pretensioned concrete member. Each specimen is characterized by means of the sequential release of the prestress transfer (detensioning) and the pull-out (loading) operation. The test provides data on prestressing force, transmission length (initial and long-term), anchorage length (without and with slip), reinforcement slips, bond stresses, longitudinal concrete strains, concrete modulus of elasticity, and prestress losses (instantaneous and time-dependent).

Keywords:

Concrete, Pretensioned, Test, Transmission, Anchorage, Prestress loss

1. Introduction

A lot of civil engineering structures have been made by using a pretensioning procedure. With this method of prestressing, pretensioned concrete members are designed and manufactured by using two materials: concrete and prestressing reinforcement. Also, two main stages must be considered: prestress transfer and loading. Prestressing reinforcement remains placed into the concrete and is always in tension. Concrete is initially precompressed by the prestressing reinforcement and can be decompressed and acquire tension stresses at loading. Stresses in both materials vary along the member length and through time. These variations are allowed only if there is sufficient bond between prestressing reinforcement and concrete.

First, the prestressing reinforcement is tensioned and concrete is cast. The prestressing reinforcement is released when sufficient strength is attained by concrete. Then, the prestressing force is transferred to concrete by bond. Later, when the member is loaded by externals actions, greater stresses in the prestressing reinforcement are activated by bond. As a result, tensile stresses in the prestressing reinforcement vary from zero at member ends to the effective stress –which is constant in the central zone of the member for each time. Effective stress is maximum just after prestress transfer, and decreases through time due to concrete creep and shrinkage and prestressing reinforcement relaxation. The difference between initial stress and stress at any time is defined as prestress loss. In addition, variations in prestressing reinforcement stresses along the member length appear when the member is put into service.

Therefore, the behavior of pretensioned concrete members depends strongly on the reinforcement-to-concrete bond performance [1-4] and prestress losses [5-7], and specific parameters related with these phenomena are established.

The aforementioned two main stages require setting up two bond lengths at the member ends: the transmission length (L_T) and the anchorage length (L_D) [8] (transfer length and development length [9]). L_T is the distance –from the member end– along which the prestress is built up in the prestressing reinforcement after prestress transfer. L_D is the distance required to transfer the ultimate tension force to the concrete. Fig. 1 illustrates these lengths and the idealized profile –based on the uniform bond stress hypothesis– of the prestressing reinforcement force along a pretensioned concrete member.

The relative displacements of the prestressing reinforcement into the concrete –slips– are also parameters related with the bond phenomenon [3,10-13]. These slips accumulate at the free end of the member at prestress transfer and can be measured and related to the L_T [14-16], but no condition regarding reinforcement slips is addressed for L_D in the main design codes [9,17,18]. For this reason, anchorage length definition can be based on two modes [19]: anchorage length –without slip– (L_A) and anchorage length with slip (L_S), that is, without and with slips at the free end of the member during the loading stage, respectively.

On the other hand, L_T depends on the concrete modulus of elasticity –among other factors [20,21]. Prestress loss due to elastic concrete shortening occurs at prestress transfer. Beyond L_T, the prestressing reinforcement force is the effective prestressing force which is determined by strain compatibility between the prestressing reinforcement and concrete.

It is worth noting that, for bonded applications, quality assurance procedures should be used to confirm that the prestressing reinforcement is capable of adequate bond [9]. However there are not minimum requirements for bond performance of prestressing reinforcement in [9] neither in [22,23]. Besides, there is no consensus on a standard test method for bond quality [8]. Methodological aspects are still being studied [24], in addition to the development of new sensors [25] and techniques [26].

Several experimental methodologies to characterize bond are offered: push-in test [10], pull-out test [27-29], push-pullout test [30], prestressing reinforcement end slip [15,16], longitudinal concrete strains profile [3], prestressing reinforcement force [31], and iterative process of flexural testing [32].

Regarding prestress losses, there are different experimental methods [7,33,34]: monitoring longitudinal concrete strains, determining crack initiation and crack re-opening loads, cutting the prestressing reinforcement into or using suspended weights on an exposed length, and inducing a hole drilled in the bottom flange of a member.

The purpose of this paper is to describe the development of a testing technique which allows the simultaneous measurement of the main specific parameters related with the bond phenomena and prestress losses concerning pretensioned concrete members. Particularly as exposed in section 2, the testing technique includes measurement of prestressing reinforcement force, prestressing reinforcement slips, and longitudinal concrete surface strains. Directly or by means a back-calculation from the test results as described in section 3, the tests provide data on prestressing force, transmission length (initial and long-term), anchorage length (without and with slip), bond stresses, prestressing reinforcement slips (free end slip, slips sequences and slips distribution), longitudinal concrete strains, concrete modulus of elasticity at prestress transfer, and prestress losses (instantaneous and time-dependent). By way of example, some experimental results obtained in several studies – conducted at the Institute of Concrete Science and Technology (ICITECH) at Universitat Politècnica de València (Spain)– are shown in section 4.

2. Testing technique

2.1. Overview

An experimental methodology based exclusively on the measurement of the prestressing reinforcement force was conceived: the ECADA[1] test method [31]. This test method was initially addressed to determine bond lengths [35]. After, a revised version (ECADA+ [36]) was developed to measure changes in these lengths through time. Each tested specimen is characterized by means the detensioning (prestress transfer) and the pull-out (loading) operations, which are sequentially performed. The bond lengths are obtained by analyzing series of specimens varying only in embedment length to simulate different cross sections at one end of a pretensioned concrete member. The feasibility of the test method has been verified for a short [37,38] and long-term analyses [39]. The test repeatability has been observed in two modes: (a) when a same effective prestressing force has been measured in specimens with different embedment lengths which are equal to or longer than L_T; and (b) when identical specimens have been tested.

[1] ECADA is the Spanish acronym for "Ensayo para Caracterizar la Adherencia mediante Destesado y Arrancamiento"; in English, "Test to Characterize the Bond by Release and Pull-out".

This test method may be extended to obtain other parameters besides bond lengths. For this purpose, the required instrumentation to measure prestressing reinforcement forces has to be complemented with other measuring devices, such as displacement transducers or micrometers to measure prestressing reinforcement slips at the ends of the specimens and strain gauges (electrical resistances or demountable mechanical points) to obtain the longitudinal concrete surface strains profile.

2.2. Experimental Set-up

The specimens are made and tested in a pretensioning frame with additional components at both ends, as shown in Fig. 2. In this way, each specimen simulates a cross section as part of one end of a member.

To carry out tensioning, provisional anchorage and detensioning, a hollow hydraulic actuator with an end-adjustable anchorage device is placed at the pretensioning frame end related to the free end of the specimens. At the opposite end, the whole made up by a sleeve beyond the specimen embedment length, the end frame plate and an anchorage plate supported on the frame by two separators, it forms the Anchorage-Measurement-Access (AMA) system. Its design requirements are detailed in [31,36]. It carry out the simulation of member rigidity, it includes an anchorage device and the instrumentation to measure the prestressing reinforcement force, and it allows to pull the prestressing reinforcement from the pretensioning frame by using a second hydraulic actuator.

2.3. Instrumentation

In accordance with the ECADA/ECADA+ test method, the strictly necessary instrumentation devices are a hydraulic pressure sensor to control the tensioning and detensioning operations, and a hollow force transducer included in the AMA system to measure prestressing reinforcement force at all times during the test.

Complementarily, the prestressing reinforcement slips are measured simultaneously at both ends of a specimen by displacement transducers (in the test stages into the pretensioning frame) and by means of analogical micrometers (in the storage stage for analysis through time), while detachable mechanical gauges are used to obtain the longitudinal concrete surface strains at the prestressing reinforcement level.

The instrumentation devices used in the studies conducted at ICITECH laboratories are: pressure sensor Druck PDCR 4000 350 bar (accuracy ±0.08%), force transducers HBM C6A 500 kN (sensitivity 2 mV/V, accuracy class 0.5), linear displacement sensors Penny Giles SLS190/50/2K/L/50/01 (typical linearity 0.15%), micrometers Käfer 0-5 mm Ø58 (accuracy ±1 µm), and mechanical strain gauges (DEMEC points) spaced at 50 mm intervals with an extensometer Mayes Instruments 100 mm base length (accuracy ±5 µm).

Neither of these measurement devices introduces any distortion of the reinforcement-concrete bond phenomenon.

2.4 Specimen test procedure

The specimen test procedure includes the following main stages: (I) tensioning, (II) casting the concrete specimen, (III) preparing, (IV) transferring the prestress, (V) storing (only for analysis through time), and (VI) loading. With the equipment test set up as shown in Fig. 2, the step-by-step procedure are as follows ("LS" indicates step for long specimen –with embedment length clearly longer than L_T– instrumented with gauge points):

I) Tensioning

1. Lining up the prestressing reinforcement in the pretensioning frame with both anchorage devices at their ends (Fig. 3a).
2. Tensioning of the prestressing reinforcement by using the hydraulic actuator (Fig. 3b).
3. Acting on the prestressing reinforcement to avoid relaxation losses[2].
4. Anchoring provisional of the prestressing reinforcement by unscrewing the end-adjustable anchorage to mechanically block the hydraulic actuator (Fig. 3c).

II) Casting the concrete specimen

1. Specimen concreting and consolidating into the formwork mounted in the pretensioning frame, around the prestressing reinforcement (Fig. 3d).
2. Maintaining the selected conservation conditions to achieve the desired concrete properties at the time of testing.

III) Preparing

1. Demounting the formwork from the pretensioning frame.
2. (LS) Attaching gauge points by epoxy glue along both lateral sides of the specimen at the prestressing reinforcement level.

[2] Only for analysis through time, the prestressing reinforcement is overtensioned (e.g. at 82% of its specified strength over 10 minutes) prior to provisional anchoring.

3. Releasing the provisional anchorage: the hydraulic actuator recovers the actual prestressing reinforcement force (P_0, just before prestress transfer), and the end-adjustable anchorage is relieved and withdrawn by screwing (Fig. 3e).
4. Placing the displacement transducers at both ends of the specimen –at the free end and into the AMA system– (Fig. 3f).
5. (LS) Reading the initial set of distances between gauge points.

IV) Transferring the prestress

1. Detensioning: the hydraulic actuator is gradually unloaded and the prestressing reinforcement movement from the free end is produced by push-in. The prestressing force is transferred to the concrete, and the pretensioned concrete specimen is supported by the AMA system (Fig. 3g).
2. Stabilization period. The action between the pretensioned concrete specimen and the AMA system requires a stabilization period to guarantee the prestressing force measurement.
3. Measuring:
    i. the prestressing reinforcement force achieved (P_{Ti}) in the AMA system.
    ii. the prestressing reinforcement slips at both ends.
    iii. (LS) the actual set of distances between gauge points.

V) Storing (only for analysis through time)

1. Demounting the pretensioned concrete specimen with its coupled AMA system from the pretensioning frame (Fig. 3h).
2. Storing the demounted specimen under controlled conservation conditions (Fig. 3i).

3. Replacing the displacement transducers by analogical micrometers at both ends of the specimen.
4. At a given time *j*, subsequent measuring of:
    i. the prestressing reinforcement force (P_{Tj}) in the AMA system.
    ii. the prestressing reinforcement slips at both ends.
    iii. (LS) the set of distances between gauge points.

VI) Loading

1. If stage V) exists, remounting the pretensioned concrete specimen with its coupled AMA system in the pretensioning frame.
2. Coupling the second hydraulic actuator at the pretensioning frame (Fig. 3j).
3. Loading: the force in the prestressing reinforcement is gradually increased by loading the second hydraulic actuator which pulls the AMA system from the pretensioning frame.
4. Measuring: the maximum forces achieved before the prestressing reinforcement slips at the free end (P_A) and during the pull-out operation (P_S) are measured.
5. Finishing: loading is done until the prestressing reinforcement fractures, the concrete fails by splitting, or there is reinforcement slippage without reinforcement force increase.

A data acquisition system is used to obtain the complete curves force vs. slip at both ends of the specimen for the transferring the prestress and loading stages, in addition to the main prestressing reinforcement force values: P_0, P_{Tj}, P_A, and P_S (P_{Tj} values are obtained as direct readings from the force transducers by using an amplifier HBM MVD2555 with display).

3. Determination of specific parameters

The direct test results for a specimen are: prestressing reinforcement force, slips at both ends and longitudinal concrete strains. Directly or by means back-calculations from the test results using theory of mechanics concepts, and from a specimen as well as by comparing the test results to the embedment length from series of specimens tested under the same conditions, several specific parameters of pretensioned concrete members can be determined.

3.1 Bond lengths

The values of the bond lengths –transmission length (L_T), anchorage length (L_A), and anchorage length with slip (L_S)– are determined from series of specimens by plotting the measured prestressing reinforcement forces –at prestress transfer (P_{Ti}) and loading (P_A and P_S) stages– vs. embedment length. Fig. 4 shows an idealization of what these plots look like.

For the P_{Ti} values, the curves are expected to present an ascendent branch followed by a horizontal branch which corresponds to the effective prestressing force (P_E). L_T is determined as the embedment length of the specimen that marks the beginning of the horizontal branch. As shown in Fig. 4, this is the first specimen of the series with $P_{Ti} = P_E$.

For the P_A and P_S values, the curves are expected to present an ascendent branch in both cases (see Fig. 4). To analyze the anchorage behavior, a reference force (P_R) has to be established to represent the force that can be applied to the strand before failure. L_A is determined as the embedment length of the shortest specimen with $P_A \geq P_R$, whereas L_S is determined as the embedment length of the shortest specimen with $P_S \geq P_R$.

The resolution in determining bond lengths depends on the sequence of embedment lengths tested.

On the other hand, long-term values of the bond lengths at a time *j* can be determined in a similar manner, in this case from curves with P_{Tj} values –which depicts a lesser effective prestressing force ($P_{Ej} < P_E$) because of prestress losses– and the corresponding P_A and P_S values at time *j*.

3.2 Effective prestressing force

The effective prestressing force is directly determined from the P_{Ti} and P_{Tj} values (see section 3.1). Besides, it can be obtained according to Eq. (1) from the prestressing reinforcement strain change ($\Delta\varepsilon_p$) beyond L_T accounted for just before prestress transfer until time *j*. This change is equal to the concrete strain change ($\Delta\varepsilon_c$) obtained at testing steps IV.3.iii (only prestress losses due to elastic concrete shortening are included) or V.4.iii (time-dependent prestress losses are also included). In Eq. (1), E_p and A_p are the modulus of elasticity and the area of the prestressing reinforcement, respectively, and the term $\Delta\varepsilon_p \cdot E_p \cdot A_p$ corresponds to the total prestress losses accounted for until time *j*.

$$P_{Ej} = P_0 - \Delta\varepsilon_p \cdot E_p \cdot A_p \quad (1)$$

3.3 Bond stresses

Based on the equilibrium of forces and the uniform bond stress distribution hypothesis which is generally accepted [2,4,9,40], the average bond stress (U_X) for a prestressing reinforcement force (P_X) developed along a length (L_X) can be obtained according to Eq. (2)::

$$U_X = \frac{P_X}{\Pi_p L_X} \quad (2)$$

Where Π_p is the prestressing reinforcement perimeter and the remaining parameters have to be consistently attributed to the cases of transmission, anchorage beyond L_T and anchorage with slip.

3.4 Prestressing reinforcement slips

Concerning prestressing reinforcement slips, the testing technique offers a lot of possibilities: slips sequences at both ends and slips distribution along bond lengths can be obtained in addition to the traditional free end slip value.

a) Free end slip

The free end slip (δ) allows determining L_T based on Eq. (3) [14]:

$$L_T = \alpha \frac{\delta E_p}{f_{pi}} \quad (3)$$

where α represents the shape factor of the bond stress distribution (α = 2 for uniform and α = 3 for linear descending; a 2.8 value is established in several standards [41-43]), E_p is the modulus of elasticity of the prestressing reinforcement and f_{pi} is the prestressing reinforcement stress immediately before release. In is worth noting that Eq. (3) is only applicable if the embedment length is equal to or longer than L_T.

b) Slips sequences

At prestress transfer, and according to the compatibility of strains condition between the prestressing reinforcement and concrete, slips do not occur beyond L_T. In this way, L_T (for both initial and long-term cases) is suitable to be determined from series of specimens by plotting the measured prestressing reinforcement slips –at one end at prestress transfer– vs. specimen embedment length. In these cases, the curves are expected to present a descendent branch followed by a horizontal branch. Again, L_T can be determined as the embedment length of the specimen that marks the beginning of the horizontal branch.

c) Slips distribution along transmission and anchorage lengths

The bond behavior can be characterized from curves prestressing force vs. slip. Two cases are expected from these curves for free end slip at prestress transfer: (a) for embedment length equal to or longer than L_T, an ascendent branch; and (b) for embedment length shorter than L_T, an ascendent branch followed by a horizontal branch starting at generalized slippage of the prestressing reinforcement.

Also, two cases are expected from these curves for end slip in the AMA system at loading: (a) for embedment length equal to or longer than L_T, increases in load and slips along the available embedment length beyond L_T; and (b) for embedment length shorter than LT, generalized slippage. Both cases are in agreement with the Stress Waves Theory [1,44].

In this way, by analyzing these curves at both ends for a complete series of specimens at both prestress transfer and loading stages, the slips distribution along bond lengths can be determined.

3.5. Longitudinal concrete strains

Longitudinal concrete strains can be obtained from the changes in distances between gauge points before and after prestress transfer (testing steps IV.3.iii or V.4.iii) by dividing them by gauge length. In correspondence with P_{Ti} values, a profile with an ascendent branch, followed by a practically horizontal branch, is depicted when these strains are plotted according to embedment length (Fig. 5). Concrete strains increase through time due to concrete creep and shrinkage, and this causes decreases –time-dependent prestress losses– in prestressing reinforcement force (P_{Tj} values). An approximate L_T value can be obtained from this profile directly as the distance from the free end to the beginning of the horizontal branch (Fig. 5) or by applying some adjustments [3]. In addition, prestress losses can be determined from the constant strain plateau (see section 3.2).

3.6 Concrete modulus of elasticity at prestress transfer

Eq. (4) accounts for prestress losses due to elastic concrete shortening at prestress transfer ($\Delta\varepsilon_{ci}$, concrete strain change at testing step IV.3.iii) and the transformed cross-section properties (initial steel modular and geometric ratios) to obtain the concrete modulus of elasticity at prestress transfer (E_{ci}) for a specimen with embedment length equal to o longer than L_T. In Eq. (4), A_c is the net cross-sectional area of the specimen.

$$E_{ci} = \frac{\dfrac{P_0}{\Delta\varepsilon_{ci}} - E_p A_p}{A_c} \qquad (4)$$

3.7. Prestress losses

Total prestress losses are directly determined from the P_{Ti} and P_{Tj} values by subtracting them to P_0. Besides, it can be obtained from the concrete strain change beyond L_T accounted for just before prestress transfer until the considered time j (see sections 3.2 and 3.5).

4. Applications

Several experimental studies using this testing technique have been conducted at the ICITECH laboratories [19,37-39]. Based on test equipment designed for prismatic concrete specimens pretensioned with a concentrically located single seven-wire prestressing strand, the main variables covered have been: concrete composition and strength, specimen cross-section, age at testing, release method, and level of prestress. Some aspects of these studies are shown in Fig. 6: a general view of a pretensioning frame (a), a series of tested specimens (b), and (c) instrumentation to obtain the longitudinal concrete surface strains.

In the following, some examples of experimental results regarding the testing technique are shown. Table 1 summarizes the main characteristics of the testing series of specimens used in the different analyses. Regarding the prestressing reinforcement, it was a low-relaxation seven-wire steel strand typified as UNE 36094:97 Y 1860 S7 13.0 [23]. According to the Spanish code [45] provisions for pretensioning, the maximum prestress level of 75% of specified strand strength was applied.

4.1 Analyses from prestressing reinforcement forces

Fig. 7 shows the prestressing reinforcement forces for series of specimens A. As it can be observed with increasing embedment length, the prestressing force transferred (P_{Ti}) increases until an effective prestressing force (P_E) of 132.5 kN which is achieved for the transmission length (L_T = 550 mm). The P_A forces increase from P_E until the reference force (P_R = 158 kN) when the embedment length increases from L_T to the anchorage length (L_A = 650 mm). For specimens with embedment length shorter than L_T, P_A coincides with the corresponding P_{Ti} which is in agreement with the Stress Waves Theory [1,44]. As expected, the P_S forces are greater than the P_A forces, and a shorter anchorage length –with slip– results (L_S = 500 mm). Generally, determining the bond lengths requires 6 to 12 specimens with different embedment lengths with a testing increment of 50 mm.

As the prestressing reinforcement was tensioned at a prestress level of 75 percent of its specified strength (1860 MPa), the prestressing reinforcement forces before prestress transfer (P_0) were around 140 kN for nominal diameter ϕ = 13 mm ($A_p = 0.194\pi\phi^2$ for seven-wire strands). Therefore, an instantaneous prestress loss about 7.5 kN (from P_0 to P_E) is measured (see Fig. 7).

By using Eq. (2), the average bond stresses U_T = 4.5 MPa and U_S = 6 MPa are obtained when the values L_T and P_E, and L_S and P_R, respectively, are used jointly with Π_p ($\Pi_p = 1.33\pi\phi$ for seven-wire strands). In addition, an average bond stress U_C = 2.6 MPa is obtained to characterize the behavior along a length $L_C = L_A - L_T$ considering the corresponding P_A forces.

Regarding the long-term behavior, Fig. 8 depicts the results for series of specimens B after 6 months. The time-dependent behavior shows changes in the effective prestressing force (from P_E = 132.5 kN to P_{Ej} = 119.5 kN) and also in L_T: the P_{Tj} value is smaller for the first specimen after 6 months, and greater and similar P_{Tj} values are measured in the remaining longer test specimens, that is, there is change in the embedment length that marks the beginning of the horizontal branch. Therefore for this series and time interval, L_T varies from 500 to 550 mm and time-dependent prestress losses about 13 kN are measured. In a general case, this process may be done with other specimens by following the embedment length sequence, and also cases with no changes in L_T through time exist.

4.2 Analyses from prestressing reinforcement slips

Fig. 9 shows free end slips for the specimens of series B with embedment length equal to or longer than the initial L_T (500 mm). Similar tendencies and values are observed for all the specimens, except for the specimen with the shorter embedment length (500 mm) which presents a greater slip one month after prestress transfer. This is in agreement with the change in L_T registered from the prestressing reinforcement force measurements (see Fig. 8). Complementarily, Fig. 10 depicts the L_T results obtained from forces as well as by Eq. (3) – with α = 2.8– from the free end slips just after prestress transfer and after 6 months. As observed, the L_T from slips vary for the different embedment lengths and with time, resulting in average L_T values of 544 mm (initial) and 608 mm (long-term; the specimen with 500 mm embedment length is excluded in this case). Therefore for this series and time interval, a L_T change of 64 mm is obtained from slips, which is of the order than 50 mm in accordance with the results from the prestressing reinforcement forces.

On the other hand, Fig. 11 shows the complete curves prestressing force transferred vs. free end slip for a series of specimens C including very short embedment length to characterize bond at prestress transfer. Two cases can be distinguished:

a) For embedment lengths shorter than 400 mm, it is observed a bilinear response with an ascendent branch until a certain slip value (δ_p, peak-slip) that marks the beginning of the generalized slippage until a final slip (δ_f).

b) For embedment lengths equal to or longer than 400 mm, the slip increases progressively while the prestressing force is transferred to the concrete; no peak-slip value appears, and the final slip obtained is the free end slip (δ) which is suitable to be used in Eq. (3).

Fig. 12 depicts the final slips at prestress transfer for the specimens of series C. As it can be observed with increasing embedment length, the final slip decreases until a slip (δ) of 1 mm (in average). In this way, L_T (400 mm in this case) can be directly obtained from the sequence of slips.

Besides, and according to the L_T definition, after prestress transfer the slip is zero beyond L_T and it is maximum at the free end of the member. For an embedment length shorter than L_T, the δ_p is the maximum slip compatible with the prestressing force transferred that can be assumed along the available embedment length. Therefore, the δ_p points can be arranged according to the embedment length –from the end of L_T (400 mm in this case) towards the free end– as shown in the Fig. 13. In this way, the slip distribution along L_T is obtained without distorting the bond phenomenon.

4.3 Analyses from longitudinal concrete strains

Fig. 14 shows the longitudinal concrete strains profiles at several ages for specimen D. The results corresponds to average values from the readings from two opposite specimen faces, and the strain change for each 100 gauge length is assigned to its center point sequentially from the free end.

From the profile corresponding at prestress transfer, an approximate L_T of 400 mm is directly observed. Beyond L_T, constant strains plateaus with increasing concrete strains through time are depicted.

An average concrete strain $\Delta\varepsilon_{ci}$ = 0.00071 result in the plateau at prestress transfer. By using Eq. (4), with a specimen gross cross-sectional area (A_g) of 100x100 mm^2 ($A_c = A_g - A_p$), P_0 = 143 kN and E_p = 203.35 GPa, the concrete modulus of elasticity at prestress transfer (E_{ci}) is 18.23 GPa.

Regarding prestress losses, they can be obtained as $\Delta\varepsilon_p \cdot E_p \cdot A_p$ (see Eq. (1)). For instantaneous prestress losses, $\Delta\varepsilon_p = \Delta\varepsilon_{ci}$ = 0.00071 and it results 14.9 kN. Time-dependent losses and total prestress losses can be obtained from subsequent profiles. For a 12 months interval, time-dependent prestress losses are obtained from $\Delta\varepsilon_p = \Delta\varepsilon_{c,12} - \Delta\varepsilon_{ci}$, resulting in 25.4 kN ($\Delta\varepsilon_{c,12}$ = 0.00192); and total prestress losses are obtained from $\Delta\varepsilon_p = \Delta\varepsilon_{c,12}$, resulting in 40.3 kN (also as 14.9 + 25.4 = 40.3 kN).

5. Conclusions

In this study, a testing technique to measure simultaneously prestressing reinforcement forces and slips and concrete strains in pretensioned concrete specimens has been developed. The testing technique reproduces sequentially the prestress transfer and loading stages and simulates the behavior at one end of a member. From the test results, directly o by means back-calculations using theory of mechanics concepts, several specific parameters concerning pretensioned concrete members can be determined. This testing technique allows obtain additional knowledge about bond behavior of prestressing reinforcement and prestress losses for a better determination of transmission and anchorage lengths and the available prestressing force at different cross-sections of a pretensioned concrete member. Regarding both initial and long-term behavior, the testing technique shows satisfactory experimental results. In this way, the testing technique possess good qualities for application to the precast concrete industry: pretensioned concrete members can be characterized for design, production process and quality control.

Acknowledgements

The content of this paper is part of the research that the Institute of Concrete Science and Technology (ICITECH) at Universitat Politècnica de València is currently conducting in conjunction with PREVALESA and ISOCRON. This study has been funded by the Ministry of Education and Science/Science and Innovation and ERDF (Projects BIA2006-05521 and BIA2009-12722). The authors wish to thank the aforementioned companies as well as the technicians at the concrete structures laboratory of the Universitat Politècnica de València for their cooperation. Finally, the authors wish to pay their respects to C.A. Arbeláez.

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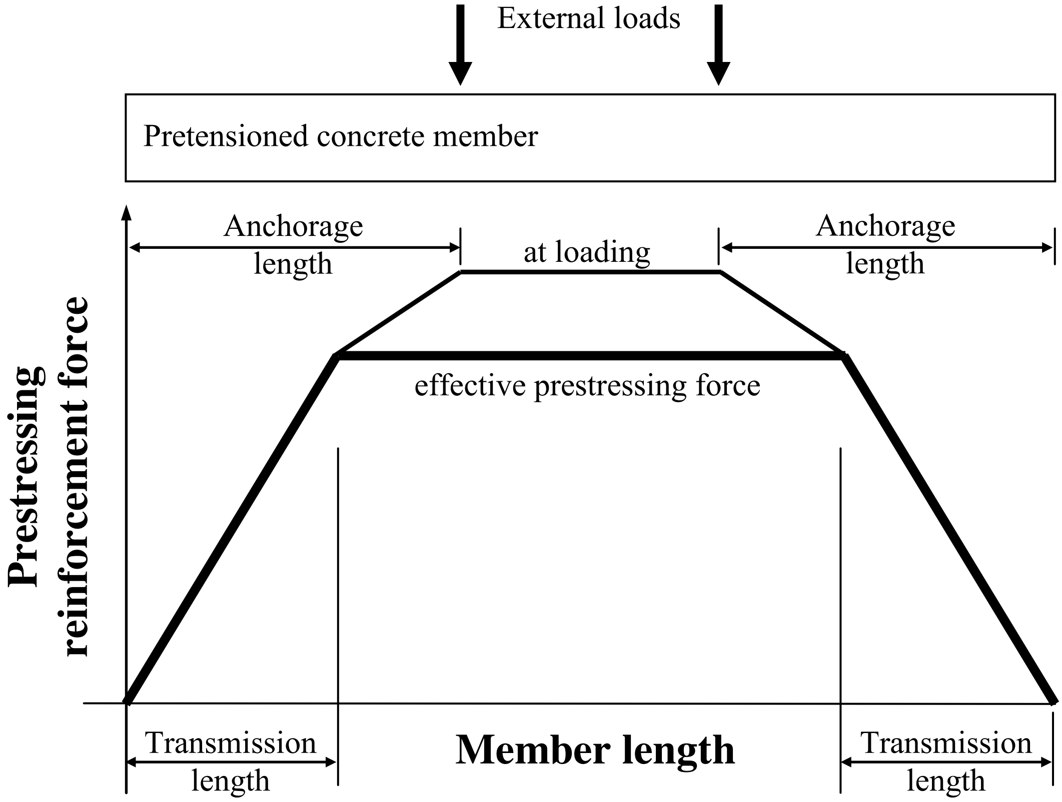
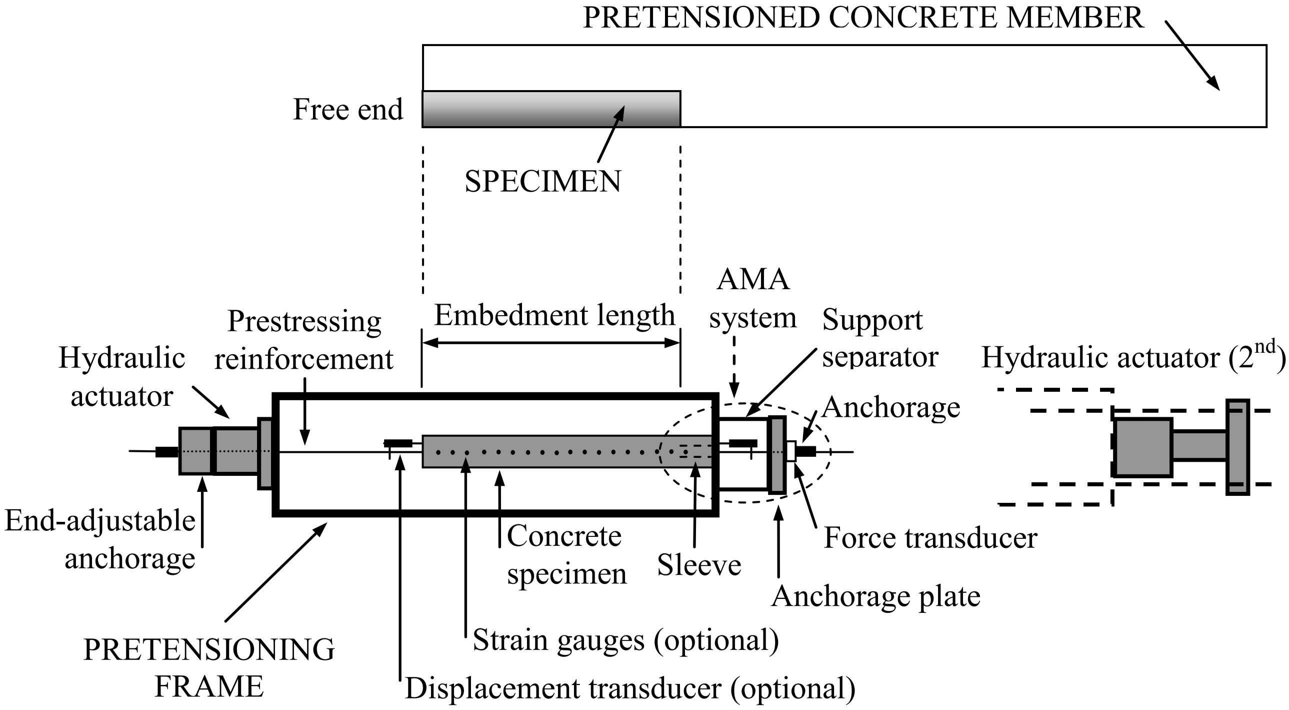
List of figure captions

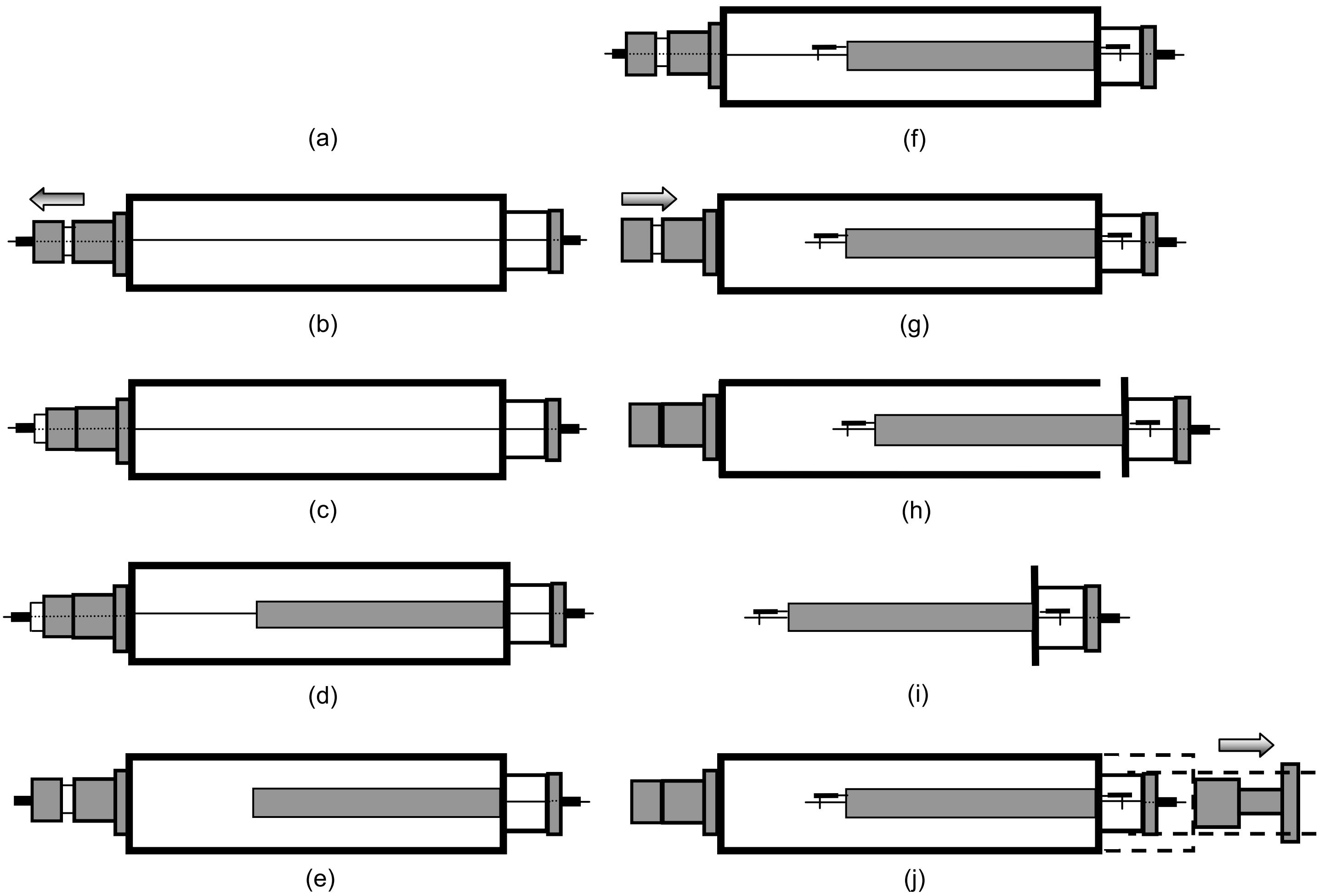
Figure(s)


External loads
Pretensioned concrete member
Anchorage length
at loading
Anchorage length
effective prestressing force
Prestressing reinforcement force
Transmission length
Member length
Transmission length

Figure(s)


PRETENSIONED CONCRETE MEMBER
Free end
SPECIMEN
AMA
system
Embedment length
Prestressing
reinforcement
Hydraulic
actuator
Support
separator
Hydraulic actuator (2nd)
Anchorage
End-adjustable
anchorage
Concrete
specimen
Sleeve
Force transducer
Anchorage plate
PRETENSIONING
FRAME
Strain gauges (optional)
Displacement transducer (optional)

Figure(s)



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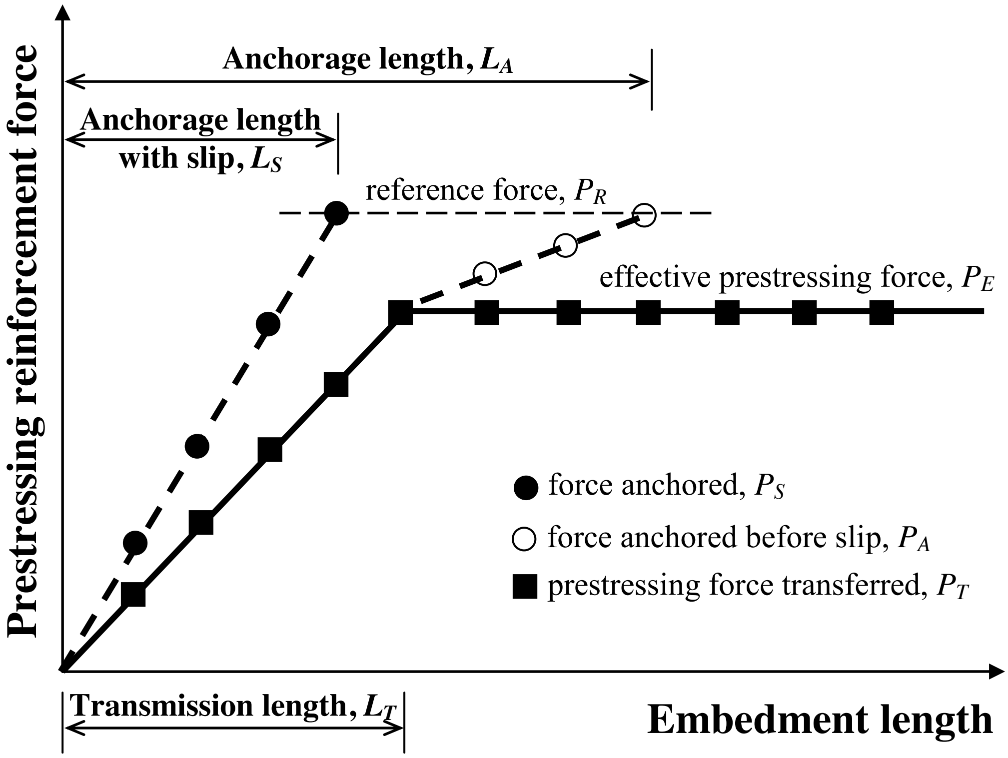
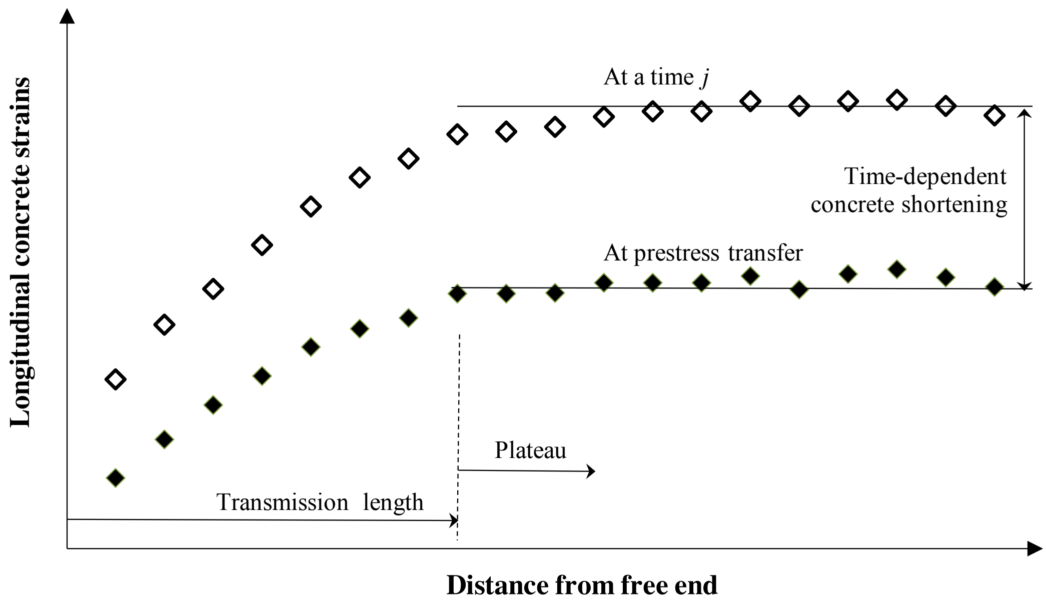


Prestressing reinforcement force
Anchorage length, L_A
Anchorage length with slip, L_S
reference force, P_R
effective prestressing force, P_E
force anchored, P_S
force anchored before slip, P_A
prestressing force transferred, P_T
Transmission length, L_T
Embedment length

Figure(s)



At a time j
Time-dependent
concrete shortening
At prestress transfer
Longitudinal concrete strains
Plateau
Transmission length
Distance from free end

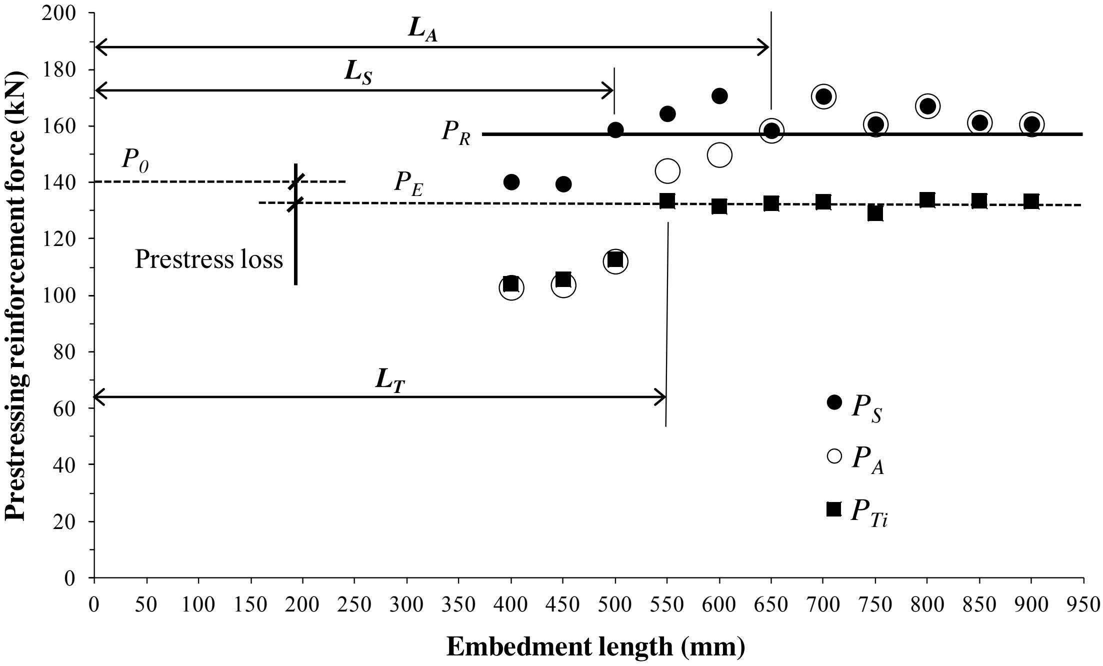
Figure(s)

(a)

(b)

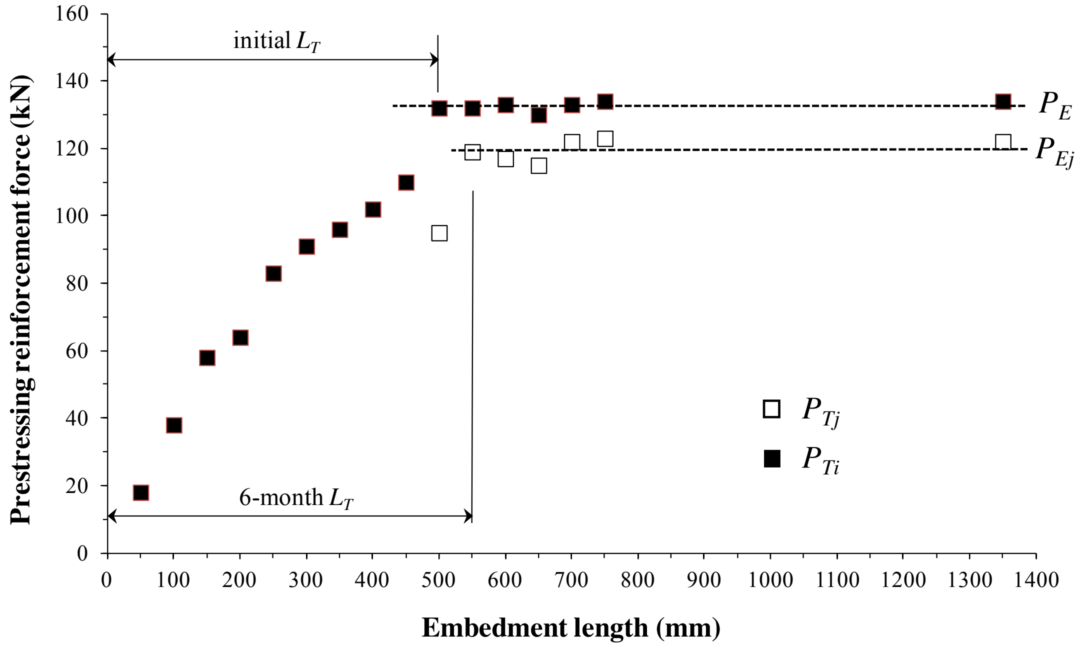
(c)

Figure(s)



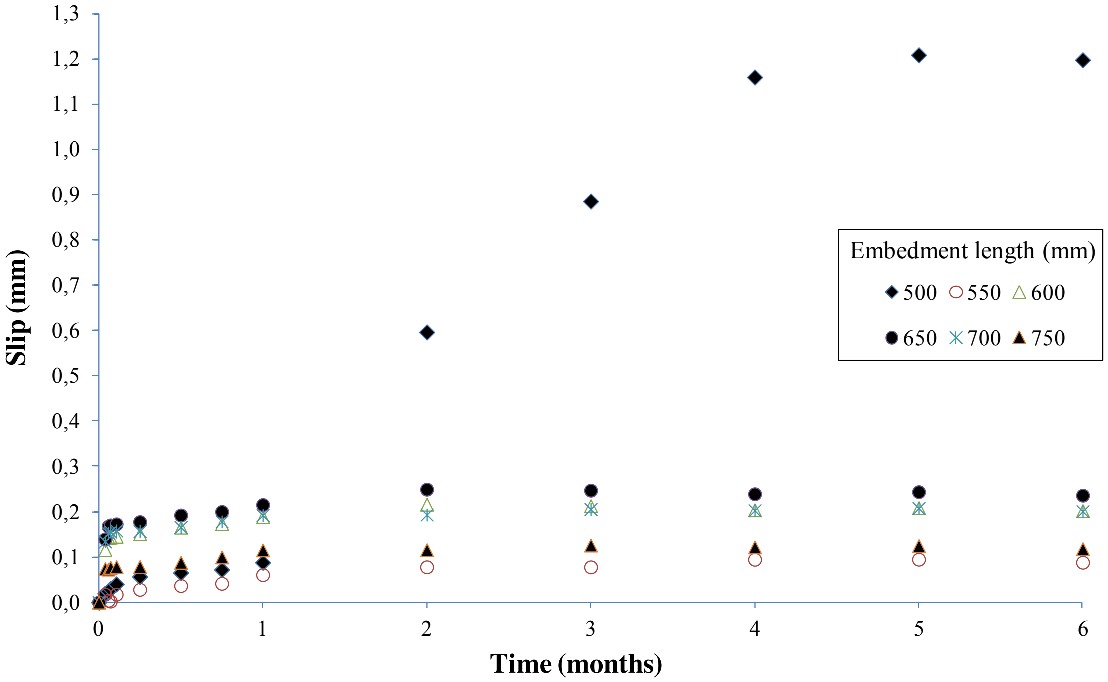
L_A
L_S
P_R
P_0
P_E
Prestress loss
L_T
P_S
P_A
P_{Ti}
Prestressing reinforcement force (kN)
Embedment length (mm)
0
20
40
60
80
100
120
140
160
180
200
0 50 100 150 200 250 300 350 400 450 500 550 600 650 700 750 800 850 900 950

Figure(s)



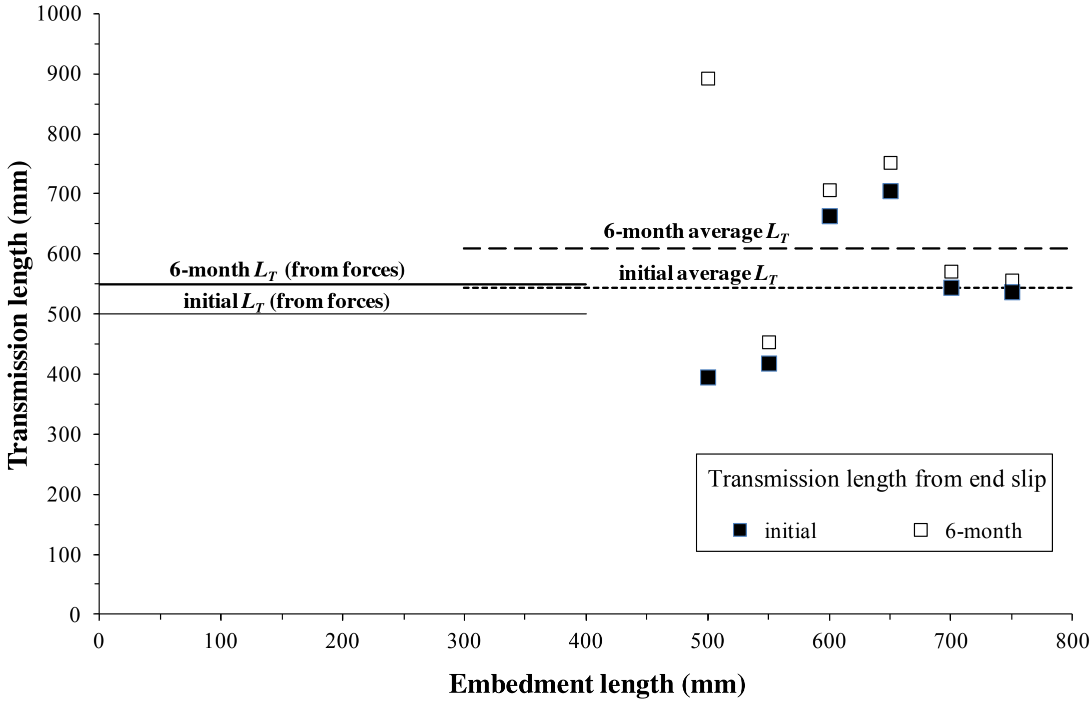
160
140
120
100
80
60
40
20
0
Prestressing reinforcement force (kN)
initial L_T
6-month L_T
P_E
P_{Ej}
P_{Tj}
P_{Ti}
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Embedment length (mm)

Figure(s)

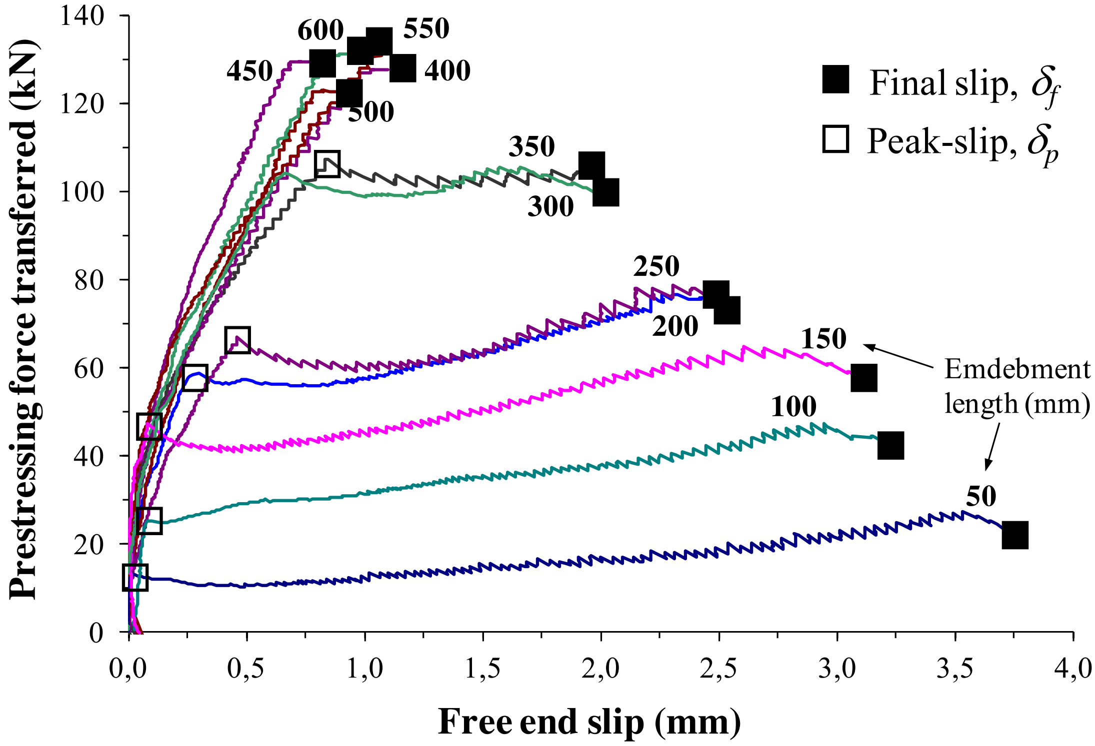


1,3
1,2
1,1
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
Slip (mm)
0
1
2
3
4
5
6
Time (months)
Embedment length (mm)
500
550
600
650
700
750

Figure(s)

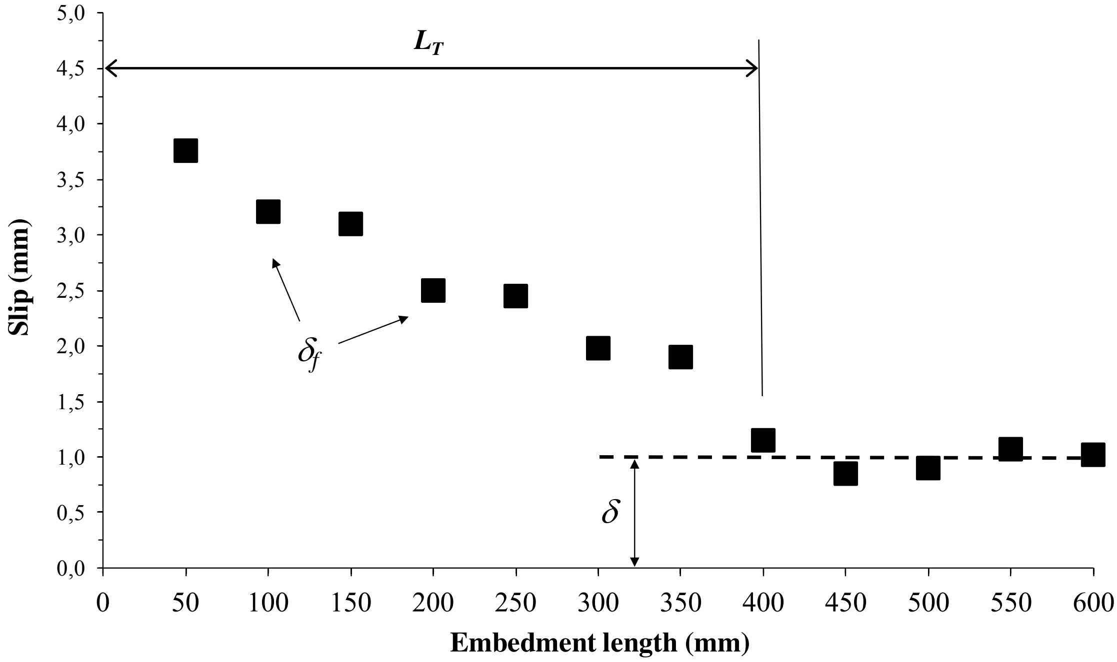

1000
900
800
700
600
500
400
300
200
100
0
Transmission length (mm)
6-month average L_T
6-month L_T (from forces)
initial average L_T
initial L_T (from forces)
Transmission length from end slip
initial
6-month
0
100
200
300
400
500
600
700
800
Embedment length (mm)

Figure(s)



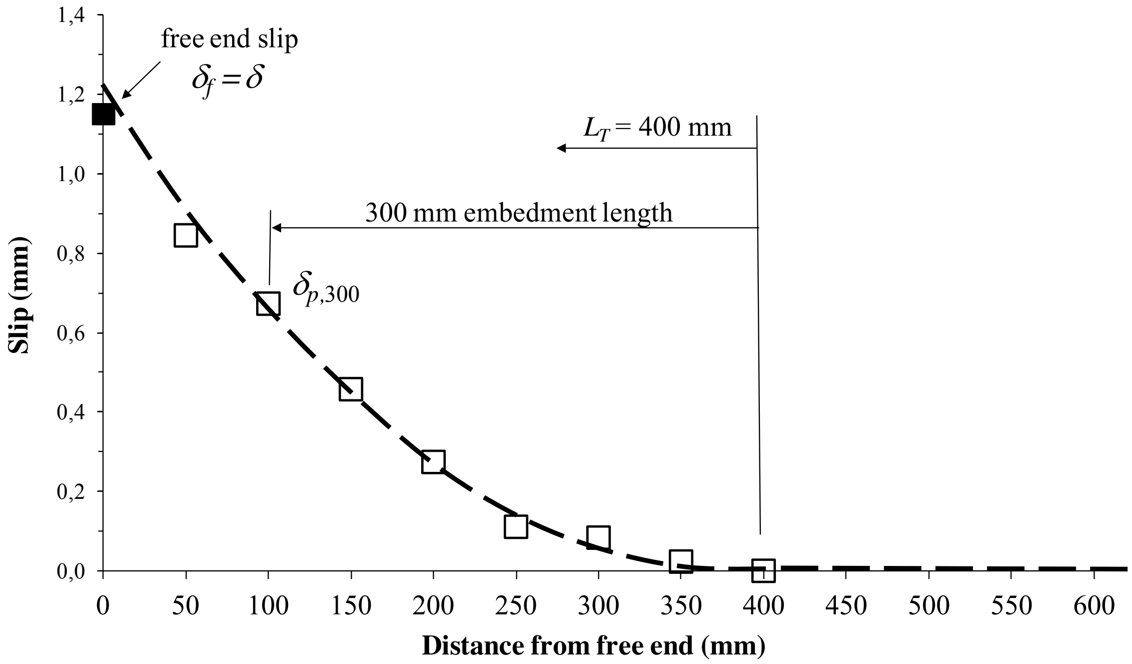
140
120
100
80
60
40
20
0
Prestressing force transferred (kN)
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5
4,0
Free end slip (mm)
600
550
450
400
500
350
300
250
200
150
100
50
Final slip, δ_f
Peak-slip, δ_p
Emdebment
length (mm)

Figure(s)



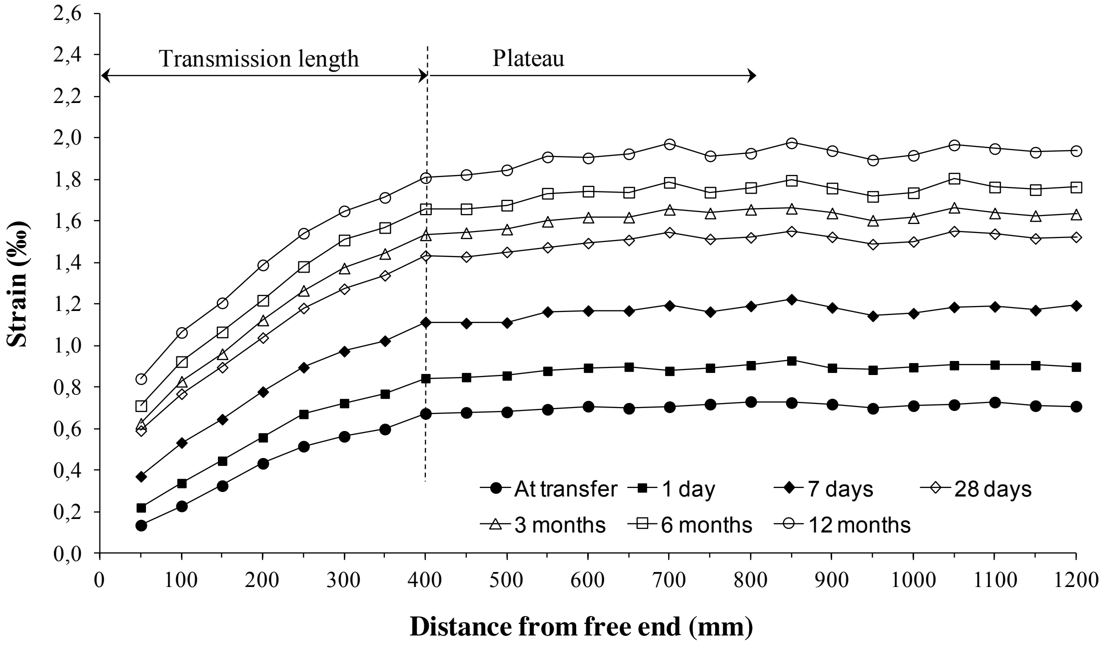
5,0
4,5
4,0
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
Slip (mm)
L_T
δ_f
δ
0
50
100
150
200
250
300
350
400
450
500
550
600
Embedment length (mm)

Figure(s)



free end slip
$\delta_f = \delta$
L_T = 400 mm
300 mm embedment length
$\delta_{p,300}$
1,4
1,2
1,0
0,8
0,6
0,4
0,2
0,0
Slip (mm)
0
50
100
150
200
250
300
350
400
450
500
550
600
Distance from free end (mm)

Figure(s)



2,6
2,4
2,2
2,0
1,8
1,6
1,4
1,2
1,0
0,8
0,6
0,4
0,2
0,0
Strain (‰)
Transmission length
Plateau
At transfer
1 day
7 days
28 days
3 months
6 months
12 months
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
Distance from free end (mm)

Table(s)

Table 1

Specimens used for example data sets

Identification	f_{ci} * (MPa)	Specimen cross-section	Age at prestress transfer	Tested embedment lengths (mm) (testing increment of 50 mm)
Series A	26.1	100x100 mm^2	24 h	From 400 to 900
Series B	52.0	80x80 mm^2	24 h	from 50 to 750, and 1350 (initial analysis) from 500 to 750, and 1350 (long term analysis)
Series C	54.8	100x100 mm^2	24 h	from 50 to 600
Specimen D	52.0	100x100 mm^2	24 h	1200

* f_{ci} is the concrete compressive strength at prestress transfer