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Prestress losses evaluation in prestressed concrete prismatic specimens

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Abstract

This paper presents an experimental research work to evaluate prestress losses in pretensioned prestressed concrete. An experimental program including variables such as concrete mix design, specimen cross-section size and concrete age at the prestress transfer was carried out. Several pretensioned prestressed concrete prismatic specimens were made and tested using the ECADA+ test method, based on measuring prestressing reinforcement force. In addition, specimens were instrumented to obtain the longitudinal concrete strains profiles at any time. Measurements from both techniques were taken over one year. Measured prestress losses included elastic shortening losses and time-dependent losses due to concrete shrinkage and creep. A coefficient to account for the relationship between the prestress losses from the measured prestressing forces and the actual prestress losses from concrete compressive strains is proposed. The experimental results were compared with the predicted prestress losses using methods from several codes.

Keywords

Concrete, pretensioned, prestress loss, creep, shrinkage, transfer, strain

1 Introduction

There are two procedures for prestressing a concrete member through reinforcement: post-tensioning and pre-tensioning. In both cases, the initial tensile stress applied in the prestressing reinforcement decreases through several sources. The difference between initial tensile stress and tensile stress in prestressing reinforcement at any time t is defined as total prestress loss (TPL_t). Usually, TPL_t is quantified as a percentage over initial tensile stress.

It is generally accepted that prestress losses have little effect on ultimate design strength and on the capacity of pretensioned concrete members, but that prestress losses can affect service conditions [1]. Upon service loads, overestimating prestress losses can lead to excessive camber and inefficient designs, while underestimating prestress losses can result in excessive deflection and unexpected cracks.

Prestress losses can be determined analytically and experimentally. Methods to estimate prestress losses can be classified into the following levels, listed in ascending order in terms of complexity and accuracy [2-3]: I) lump-sum or approximate methods to estimate *TPL* (oversimplified methods for preliminary design): II) refined or detailed methods to estimate prestress losses separately due to each particular source (commonly used for designs based on elemental information about materials properties and environmental conditions); and III) accurate determination of cumulative losses by time-step methods, which involves knowledge of the loading history on the member (useful in multi-stage bridge constructions at any critical time).

The experimental techniques used to determine prestress losses include several typologies [4-7]: 1) monitoring longitudinal concrete strains over time at the level of the center of gravity of the prestressing reinforcement; 2) load testing to determine crack initiation and/or crack re-opening loads to obtain the available compressive stress in the bottom flange of a member; 3) severing the prestressing reinforcement by cutting it into a representative exposed length after placing strain gauges on the reinforcement; 4) relating the tension in the prestressing reinforcement to the vertical deflection recorded when known weights are suspended from it on a representative exposed length; and 5) determining the side pressure to close the induced crack in a small cylindrical hole drilled in the bottom flange of a member.

All these experimental techniques require a back-calculation of the prestress losses from the test data using theory of mechanics concepts. Method 1 requires the instrumentation of the member during casting, and it can be used to determine prestress losses over time. Methods 2 and 3 are destructive tests and provide information only on the existing prestressing reinforcement stress at testing times (prestress losses are frequently obtained by considering theoretical rather than measured initial prestressing reinforcement stress). Method 4 is a semidestructive test and involves accurately determining the exposed length for calculations. Method 5 is a non-destructive technique which involves an appropriate factor by numerical procedures.

The main objective of this experimental research work is to analyze changes in prestress losses over time in pretensioned prestressed concrete using a testing technique that allows the simultaneous application of the aforementioned Method 1 and the continuous measurement of prestressing reinforcement force. To this end, an experimental program has been set up over a 1-year period with several pretensioned prestressed concrete prismatic specimens varying in terms of concrete mix design, specimen cross-section size, and concrete age at the prestress transfer. The ECADA+ test method [8] has been used to measure the effective prestressing force over time. In addition, specimens have been instrumented to determine the longitudinal concrete surface strain by mechanical gauge points. The experimental results have been compared with predicted prestress losses from existing methods in several codes.

2 Background

2.1 Sources of prestress losses

For pretensioned prestressed concrete members, the manufacturing process involves the following main stages:

a) First the prestressing reinforcement is tensioned in the casting bed by stretching it between abutments using provisional end anchorages. Instantaneous anchorage seating elastic loss occurs (prestress loss ranging from $f_{p,jack}$ –initial at jacking- to $f_{p,bed}$ –at anchoring-). This prestress loss can be determined from the equipment and fabrication system characteristics, and very often they are fully or partially compensated for by overjacking.

b) Next, while relaxation loss of the prestressing reinforcement occurs, the concrete member is cast around the prestressing reinforcement and additional factors such as temperature by the curing method increases relaxation prestress loss (prestress losses ranging from $f_{p,bed}$ to f_{p0} –just before the prestress transfer-).

c) Finally, when sufficient strength is attained by the concrete, the provisional end anchorages are released and the prestressing reinforcement tends to shorten. The concrete around the prestressing reinforcement shortens as the prestressing force is applied to it, as the prestressing reinforcement that is bonded to the concrete shortens with it. Prestress losses due to the elastic shortening of concrete occur in the central zone of the member (prestress losses ranging from f_{p0} to f_{pi} -initial effective stress, just after the prestress transfer-), and special end zones by varying the prestressing reinforcement stress from zero at the free ends of the member to f_{pi} necessarily exist. The length of these end zones is defined as transfer length [1].

As time passes after the prestress transfer, several time-dependent prestress losses gradually occur by the following sources: concrete shrinkage –volumetric decrease in concrete mass-; concrete creep -increase in compressive strains under sustained stress-; and prestressing reinforcement relaxation -lowered tensile stress under sustained elongation- (as the prestressing reinforcement shortens by concrete shrinkage and creep, a less marked relaxation loss rather than intrinsic relaxation -for constant length and temperature- takes place).

Consecuently, effective stress will change from f_{pi} to a final value f_{pe} after allowing for all the prestress losses. At any time *t*, effective stress will be f_{pt}, and TPL_t can be expressed as follows:

$$TPL_t = \frac{f_{p,jack} - f_{pt}}{f_{p,jack}} \ (in\ \%) \tag{1}$$

Accordingly with [9], TPL_t ranges from 20% to 35%. The contribution of each prestress loss source to TPL_t depends on the structural design, the manufacturing process, materials properties, environmental conditions during service life and the time elapsed.

Eq. (1) is of interest for precasters, but $f_{p,jack}$ never acts on concrete; therefore, other expressions can be used by replacing $f_{p,jack}$ with f_{p0} or f_{pi} in Eq. (1) to obtain expressions of primary interest for designers to account for only the part of *TPL* that is of practical significance. The available tensile stress to be applied to concrete by the prestressing reinforcement is f_{p0}, which is reduced to f_{pi} immediately after the prestress transfer and to f_{pe} after all losses have occurred. Effectiveness ratios can be defined for any time *t,* and particulary in the long term [10]:

$$R_{0t} = \frac{f_{pt}}{f_{p0}} \tag{2}$$

$$R = \frac{f_{pe}}{f_{pi}} \tag{3}$$

$$R_{it} = \frac{f_{pt}}{f_{pi}} \tag{4}$$

2.2 Previous research on prestress losses

Numerous studies have been conducted in the past to measure prestress losses in pretensioned prestressed concrete members and to compare these losses versus design code estimations. Among these studies, there are several laboratory tests of old girders removed from existing bridges and experimental research works including fabrication, testing and field monitoring of pretensioned concrete members under service. Table 1 in [5] and Table 6 in [11] summarize an extensive literature review on references, pretensioned prestressed concrete member identification (type, old time), testing place, experimental technique used, time of study and measured losses. As observed in these tables, measured prestress losses exceed the losses predicted by code specifications in some cases. On the other hand, measured prestress losses that are in line with the values expected by current codes have been obtained in prestressed concrete girders, which exceeded the allowable compressive stress limit [12].

Besides, several studies have been conducted on computational analyses of prestress losses [2,13] and on probabilistic assessments [14,15].

2.3 Methods for estimating prestress losses

Determination of prestress losses usually involves complicated, laborious procedures because time-dependent prestress losses are inter-dependent [16]. Prestressing reinforcement relaxation is continuously altered by changes in stress due to concrete shrinkage and creep. Concrete creep, in turn, constantly alters by changes in prestressing reinforcement stress. Moreover, concrete shrinkage and creep movements are partially restrained by the prestressing reinforcement.

As time-dependent prestress losses are performed gradually, a concrete creep at any time t is less than a creep due to the same prestress loss if applied at its full value at the initial time. This phenomenon is frequently accounted for by means of an aging coefficient smaller than unity, which can be included in an age-adjusted effective elasticity modulus of concrete [17,18].

Several methods and empirical equations which use the aging coefficient or are based on simplified analyses are available in the current codes that predict prestress losses.

According to ACI 318 Commentary [1] and PCI DH [19], reasonably accurate prestress losses estimations can be calculated in accordance with the recommendations established by Zia et al. [20]. For unusual design conditions and special structures, a more detailed procedure established by PCI CPL [21] can be considered.

More recently, AASHTO LRFD [22] adopted new methods (approximate and refined-detailed methods based on [3,11]) in 2007 to estimate prestress losses since the current prestress losss methods led to unrealistic applications with high-strength concrete. However, AASHTO Standard [23] specifications for prestress losses estimation remain in accordance with 2004 AASHTO LRFD [24]. PCI BDM [25] includes both the AASHTO Standard [23] and the LRFD [24] methods.

The Spanish Code specifications of structural concrete [26] for prestress losses estimations account for the aging coefficient, and they coincide with the specifications established in both Eurocode-2 [27] and Model Code 2010 [18].

3 Testing technique

The ECADA+ test method [8] has been used. ECADA+ is a revised, improved version of the original ECADA[1] test method [28], and it determines transfer length and development length [29,30]. Its feasibility has been verified for short-term [31,32] and long-term [33] analyses.

In this work, only specimens with an embedment length longer than the transfer length have been included in the experimental program. Hence in this case, the ECADA+ test method [8] has been used to measure effective prestressing force over time and, complementarily, specimens have been instrumented to determine longitudinal concrete surface strains.

3.1 Test basis, equipment and instrumentation

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

The ECADA+ test method is based on measuring and analysing the force supported by the prestressing reinforcement in a series of pretensioned prestressed concrete specimens with different embedment lengths over time. Specimens were made and tested using pretensioning frames, as shown in Fig. 1. In this way, each specimen has only one special end zone with the corresponding transfer length.

A hollow hydraulic actuator with an end-adjustable anchorage device was placed at one end of the pretensioning frame (see Fig. 1) to carry out operations of tensioning, provisional anchorage, and detensioning of prestressing reinforcement. At the opposite end, an Anchorage-Measurement-Access (AMA) system was placed to simulate specimens' sectional rigidity.

The strictly necessary instrumentation devices for the ECADA+ test method include a pressure transducer to control the hydraulic actuator, and a hollow force transducer placed in the AMA system to measure prestressing reinforcement forces at all times during the test (tensioning, provisional anchorage, detensioning, and analysis with time). A hollow force transducer HBM C6A was used in each specimen test.

Additionally, detachable mechanical strain gauges (DEMEC points) were used to obtain the longitudinal concrete surface strains at the prestressing reinforcement level. An extensometer was used to measure the distance between gauge points with a 100 mm gauge length. Gauge points were spaced at 50 mm intervals.

No internal measuring devices were used in the tested specimens to not distort the bond phenomenon.

3.2 Specimen preparation and fabrication

Specimen preparation and fabrication followed these phases:

- Lining up the prestressing reinforcement in the pretensioning frame with both anchorage devices at their ends.
- Prestressing reinforcement tensioning using the hydraulic actuator (Fig. 2a).
- Acting on the prestressing reinforcement to avoid relaxation losses[2].
- Provisional prestressing reinforcement anchorage by unscrewing the end-adjustable anchorage to mechanically block the hydraulic actuator (Fig. 2b).
- Specimen concreting into the integrated mould, mounted in the pretensioning frame, around the prestressing reinforcement.
- Maintaining the selected conservation conditions to achieve the desired concrete properties.
- Demounting the mould from the pretensioning frame.
- Attaching gauge points by epoxy glue along both lateral sides of the specimen at the prestressing reinforcement level (Fig. 2c).

3.3 Test procedure

The different test procedure phases were the following:

a) Prestress transfer release:

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[2] By following the manufacturer's recommendations, the prestressing reinforcement was overtensioned at 82% of the nominal ultimate reinforcement strength over a 10-minute period prior to anchoring.

- Reading the initial set of distances between gauge points (before the prestress transfer).
- Releasing the provisional anchorage: the hydraulic actuator recovered the actual prestressing reinforcement force (P_0), and the end-adjustable anchorage was relieved and withdrawn by screwing (Fig. 2d).
- Detensioning: the hydraulic actuator was unloaded in a controlled manner, and the prestressing reinforcement movement from the free end was produced by push-in. When the prestressing reinforcement had been completely released, the prestressed specimen was supported by the AMA system.
- Stabilization period.
- Measuring the prestressing reinforcement force achieved (P_{t1}) in the AMA system.
- Re-reading the set of distances between gauge points (after the prestress transfer).

b) Prestressed specimen storage:

- Demounting the pretensioned prestressed concrete specimen joined to the AMA system from the pretensioning frame (Fig. 2f).
- Storing the demounted specimen under controlled conservation conditions.
- Subsequent measurement of the prestressing reinforcement force (P_t) in the AMA system and reading the set of distances between gauge points at a given time was done periodically.

3.4 Results

An approximate transfer length determination can be obtained from the longitudinal concrete surface strains [34]. These strains can be obtained from the changes of distances between gauge points before and after the prestress transfer. The strain change for each 100 gauge length is assigned to its center point sequentially from the free end. A bilinear profile with an ascendent initial branch and a practically horizontal branch at which the concrete surface strains became somewhat uniform was observed when these longitudinal concrete strains were plotted according to specimen embedment length. Transfer length can be estimated as the length of the first region; that is, as the distance from the free end marking the beginning of the horizontal branch (Fig. 3).

Beyond transfer length, the constant strain plateau corresponds to the region of the specimen where compatibility of strains between the prestressing reinforcement and the concrete exists. Prestress losses can be determined in this region, and transfer length remains as a special end region where prestress losses occur in addition to the bond phenomenon.

The effective prestressing force at any time *t* can be measured from the AMA system and can be also obtained from the concrete compressive strains in the region plateau of the specimens according to Eq. (6) based on strains compatibility between concrete and the prestressing reinforcement ($\Delta\varepsilon_c = \Delta\varepsilon_p$):

$$P_{t,s} = P_0 - TPL_{t,s} = P_0 - \Delta\varepsilon_p(t) \cdot E_p \cdot A_p \tag{6}$$

where:

$P_{t,s}$ is the effective prestressing reinforcement force at time *t* from specimen strains

P_0 is the prestressing reinforcement force just before the prestress transfer

$TPL_{t,s}$ is the total prestress loss accounted for until time *t* ($TPL_{t,s} = \Delta\varepsilon_p(t) \cdot E_p \cdot A_p$)

$\Delta\varepsilon_p(t)$ is the prestressing reinforcement strain change beyond transfer length, accounted for from just before the prestress transfer until time *t*

E_p is the elasticity modulus of the prestressing reinforcement

A_p is the prestressing reinforcement area

From the initial longitudinal concrete strains profile (ε_{t1}), the initial effective prestressing force ($P_{t1,s}$), including prestress losses due to the elastic shortening of concrete, can be obtained. From subsequent profiles (ε_t) at any time t, $P_{t,s}$ and accumulated prestress losses can be obtained.

Furthermore, the ideal AMA system must have the same sectional rigidity as the specimen and must display the same time-dependent behavior [8,28]. Sectional rigidity depends on the concrete properties and the specimen's cross-section. For different test conditions, various AMA system designs should be devised. However, it is not really feasible to design a system for each specific test condition. For this reason, the rigidity of the AMA system design is greater than the specimens' sectional rigidity (it must never be lower), and the prestressing reinforcement force measured in the AMA system after release is greater than the effective prestressing force in the specimen, resulting in an end-discontinuity effect (Fig. 4).

4 Experimental program

To study the prestress losses changes over a 1-year period on several pretensioned concrete prismatic specimens, an experimental program was carried out by varying the concrete mix design, specimen cross-section size and concrete age at the prestress transfer.

4.1 Materials

Three different concrete mix designs applicable for the precast prestressed concrete members industry with different compressive strengths at the time of testing (f'_{ci}) ranging from 24 to 58 MPa were tested. For all the concretes, the components were: cement CEM I 52.5 R [35], crushed limestone aggregate (7-12 mm), washed rolled limestone sand (0-4 mm), and a superplasticizer additive. The mix design and concrete compressive strength of the tested concretes are shown in Table 1.

The prestressing reinforcement was a low-relaxation seven-wire steel strand specified as UNE 36094:97 Y 1860 S7 13.0 [36] with a guaranteed ultimate strength of 1860 MPa. The main characteristics were adopted from the manufacturer: 13 mm diameter, a cross-sectional area of 100 mm^2, ultimate strength of 200.3 kN, yield stress at 0.2% 189.9 kN, and an elasticity modulus of 203.35 GPa. The prestressing strand was used under the as-received condition. Strands were rust- and lubricant-free, without any special treatment.

4.2 Specified parameters

All the specimens were prestressed by means of a concentrically located single strand at the prestress level before releasing 75% of the nominal ultimate strand strength. Specimen embedment length was always[3] 1350 mm, and three different cross-sections were used: 100x100 mm^2, 80x80 mm^2, and 60x60 mm^2. All the specimens were subjected to the same consolidation and curing conditions.

The prestress transfer release time was specified for each specimen. The prestress transfer was gradually performed at a controlled speed of 0.80 kN/s. A stabilization period of 2 hours from the release was established for the initial analysis of the test results.

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[3] Based on previous studies by the authors [29-33] and on analytical predictions from equations in the literature [37,38], 1350 mm is longer than the transfer length for the specified parameters.

Specimens were stored inside a chamber where temperature and humidity were controlled: temperature, 20-22ºC; relative humidity, 50-60%. Fig. 5 shows some instrumented specimens with the corresponding AMA system in the chamber. After storage, subsequent sets of gauge points readings and prestressing reinforcement force measurements were taken at 1, 2, 3, 7, 14, and 28 days, and then monthly.

4.3 Program

The three different cross-sections used were combined with the three concrete mix designs. Besides, several ages of prestress transfer release were established. Table 2 summarizes the test program established. It was not possible to test all the combinations because of the controlled storage chamber size.

A specimen designation is: M-D-T, where M is the concrete mix type (A, B, or C), D is the side (in mm) of the specimen cross-section (100, 80 or 60 mm), and T is age in hours (h) at the prestress transfer (12, 24 or 48 h).

In addition, non-pretensioned concrete specimens were made for each concrete mix design to measure concrete shrinkage in specimens with and without untensioned prestressing reinforcement. These specimens were instrumented with DEMEC points and were stored under the same conditions in the chamber. Fig. 6 offers a view of some specimens for the shrinkage measurements.

5 Test results and discussion

5.1 Experimental measurements

For this work, the prestress losses accounted for between jacking and the prestress transfer release were excluded. As the hollow force transducer was placed in the AMA system in contact with the anchorage device, the prestressing reinforcement force just before the prestress transfer release (P_0) was known. Furthermore, prestress losses due to prestressing reinforcement relaxation were ruled out by applying a temporary overstressing (see Section 3.2).

By way of example, Fig. 7 shows the longitudinal concrete strains profiles at several ages for specimen A-100-24. The results were obtained by averaging the readings from two opposite specimen faces. The three zones observed were: transfer length, plateau, and end-discontinuity. Greater concrete compressive strains resulted from early concrete age at the prestress transfer. Transfer length was 400 mm. The initial end-discontinuity zone was approximately 200 mm in length given the sequence of readings from the DEMEC points: there was a 120-mm sleeve beyond the 1350-mm specimen embedment length, and the first affected readings were the 100-mm gauge length corresponding to the 1250-1350 mm embedment length, whose values were assigned to its center point -1300 mm-. As time passed, end-discontinuity became more pronounced because of the different time-dependent behaviors displayed by the AMA system in relation to the specimen.

Table 3 summarizes the main test results just after the prestress transfer and after one year, including the measured prestressing reinforcement forces in the AMA system (P_0, P_{t1}, P_t), the average concrete strains for the plateau zone (ε_{t1}, ε_t) and the corresponding effective prestressing forces ($P_{t1,s}$, $P_{t,s}$) according to Eq. (6). Specimens were ordered according to concrete mix design by increasing both cross-section size and concrete age at the prestress transfer.

As observed in Table 3, an overestimation of the prestressing reinforcement force was obtained when measuring prestressing forces was considered: P_{t1} and P_t were always greater than $P_{t1,s}$ and $P_{t,s}$, respectively. This was caused by the end-discontinuity effect and, consequently, the actual prestress losses were underestimated from measuring prestressing forces. In order to determine appropriate coefficients to account for prestress losses underestimation, several adjustments based on specimen cross-section sizes were made for both the instantaneous and time-dependent responses of the AMA system; see Fig. 8. Therefore, the following equation is proposed:

$$\Delta P = \kappa \cdot \Delta P_{AMA} \tag{7}$$

where:

ΔP is the actual prestress losses (from the specimen strains)

κ is a coefficent to account for the end-discontinuity effect

for the instantaneous response:

2.2 (for 100x100 mm^2 specimen cross-section), 2.4 (80x80 mm^2), and 2.8 (60x60 mm^2)

for the time-dependent response:

2.8 (for 100x100 mm^2 specimen cross-section), 2.6 (80x80 mm^2), and 2.4 (60x60 mm^2)

ΔP_{AMA} is the prestress losses from the measured prestressing forces

Fig. 9 depicts both the instantaneous and time-dependent prestress losses for all the specimens tested, including the prestress losses from specimen strains, the prestress losses from the measured prestressing forces, and the adjusted values of the prestress losses according to Eq. (7). As observed, the actual prestress losses can be estimated from the measured prestressing forces by applying the obtained κ coefficient. The tendencies according to concrete mix design, specimen cross-section size, and concrete age at the prestress transfer were maintained with the estimation, and only a few values offered a relatively poor estimation.

In order to separately obtain time-dependent losses by concrete creep and shrinkage, Fig. 10 depicts the average concrete strains for the plateau zone with the time for specimen A-100-24 by way of example. The upper curve, obtained from the longitudinal concrete strains profiles at each time, accounts for the total concrete strains (instantaneous –just after prestress transfer, time 0– and time-dependent). Besides, the lower curve, obtained from the longitudinal concrete strains measured in non-pretensioned concrete specimens with untensioned prestressing reinforcement to determine concrete shrinkage, was included. By substracting measured shrinkage strains from measured total strains, the concrete strains under loading at each time are obtained. Now, by substracting measured instantaneous strains from concrete strains under loading, strains due to concrete creep at each time can be determited. Therefore, the prestress losses due to concrete creep can be accounted for separately by the other sources.

Fig. 11 shows the prestress losses obtained experimentally by the three sources (elastic shortening, creep and shrinkage) for all the specimens tested. As this figure illustrates, prestress losses decrease in a same concrete mix design when the specimen cross-section increases and the concrete age at the prestress transfer increases. For equal specimen cross-section size and concrete age at the prestress transfer, the prestress losses in specimens made with concrete C are greater than those in specimens made with concrete B which, in turn, are greater than the prestress losses in specimens made with concrete A: C-100-48/B-100-48; C-100-24/B-100-24/A-100-24; C-80-48/B-80-48; B-80-24/A-80-24; B-60-48/A-60-48. Larger differences between specimens correspond to the prestress losses due to concrete elastic shortening, whose values ranged from 10% for the specimens with greater cross-sections, 15-20% for specimens with intermediate cross-sections, and 25-30% for specimens with smaller cross-sections. The total measured prestress losses values ranged from 25-60% (25-40% for specimens with greater cross-sections, 40-50% for specimens with intermediate cross-sections, and 50-60% for those with smaller cross-sections), exceeding the percentages detailed for design according to [9], except for those specimens with greater cross-sections. This fact can be explained by the different concrete stress levels and the deformability behavior relating to specimen cross-sections.

5.2 Comparison with predicted prestress losses

Theoretical values of prestress losses were estimated by measuring parameters using several prestress loss methods for comparison purposes: PCI DH [19], PCI CPL [21], AASHTO STD [23], AASHTO LRFD [22] (Approximate and Refined methods), and MC [18] - EC [27] - EHE [26]. By way of example, Fig. 12 depicts the measured and predicted prestress losses for specimen A-100-24.

As observed in Fig. 12, prestress losses due to elastic shortening practically did not differ among the various methods. The best prediction for total prestress losses corresponded to the AASHTO LRFD Refined, in spite of an overestimation of prestress losses due to concrete creep and an underestimation of prestress losses due to concrete shrinkage. The MC/EC2/EHE method well predicted prestress losses due to concrete creep, and it also gave the greater prestress loss prediction due to concrete shrinkage. The most simplified methods

(PCI DH, AASHTO STD, AASHTO LRFD Approximate) gave similar prestress losses due to concrete shrinkage, but differed in their predictions of prestress losses due to concrete creep.

The prestress losses predicted by all the aforementioned methods for all the specimens were computed and are summarized in Table 4. The comparisons made of the predicted prestress losses with measured prestress losses are included in Figs. 13, 14 and 15, which depict the total prestress losses after one year, the predicted/measured ratios, and the effectiveness ratios according to Eq. (4), respectively.

As observed in Fig. 13, the tendencies of the measured prestress losses according to the variables concrete mix design, specimen cross-section size and concrete age at the prestress transfer are followed by the predicted prestress losses by all the methods: for all the methods, total prestress losses lowered within the same concrete mix design when the specimen cross-section increased and the concrete age at the prestress transfer increased, and predicted prestress losses in those specimens made with concrete C were greater than the prestress losses in those made with concrete B, and they were also greater than prestress losses in specimens made with concrete A.

As Fig. 14 illustrates, the AASHTO LRFD Refined and the MC/EC2/EHE methods show the best predictions. Some slow trends to underestimate both the prestress losses for concrete mix design C from the AASHTO LRFD Refined method and the prestress losses for concrete mix design A from the MC/EC2/EHE method are depicted. PCI DH, PCI CPL, and the AASHTO STD methods gave similar predictions, with slow trends to a greater underestimation of prestress losses when concrete compressive strength decreases (within the same concrete mix design, and for different concrete mix designs maintaining specimen cross-section and concrete age at the prestress transfer). The AASHTO LRFD Approximate method shows the best agreement with the AASHTO LRFD Refined method when concrete compressive strength decreased.

Finally, Fig. 15 shows the effectiveness ratios obtained by Eq. (4) from the measured values and by all the methods. After one year, the tensile stress available in the prestressing reinforcement ranged with values from 0.55 to 0.80 times the prestressing reinforcement stress immediately after the prestress transfer. For the different variables considered in the test program, higher ratios were recorded for those cases with greater concrete compressive strength, larger specimen cross-section size, and higher concrete age at the prestress transfer. In Fig. 15, the global trends depending on prediction methods are depicted consistently with the trends observed in Figs. 13 and 14.

6 Conclusions

Changes in prestress losses over one year in pretensioned prestressed concrete specimens have been analyzed by simultaneously using two measurement techniques: prestressing reinforcement force measurement through the ECADA+ test method; longitudinal concrete strains measurement at the level of the center of gravity of the prestressing reinforcement. The main conclusions drawn from this experimental study are:

- A prestress losses underestimation has been obtained from the measured prestressing reinforcement forces. Based on specimen cross-section size, appropriate coefficients related to the effective prestressing forces from specimen strains to account for prestress losses underestimation have been established for both the instantaneous and time-dependent responses of the equipment test.

- The different concrete stress level and deformability behavior related to the specimens' cross-section influences prestress losses: prestress losses decrease in the same concrete mix design when the specimen cross-section increases and concrete age at the prestress transfer increases; for equal cross-sections and concrete age at the prestress transfer, prestress losses decrease when the specimen's concrete compressive strength increases.
- The larger differences between specimens correspond to prestress losses due to elastic shortening of concrete, whose values range from 10% for specimens with greater cross-sections, 15-20% for specimens with intermediate cross-sections, and 25-30% for specimens with smaller cross-sections.
- The total measured prestress losses values range from 25-60%: 25-40% for specimens with greater cross-sections, 40-50% for specimens with intermediate cross-sections, and 50-60% for specimens with smaller cross-sections.
- The prestress losses predicted by several methods based on codes follow the tendencies seen for measured prestress losses: total prestress losses decrease with greater concrete compressive strength, greater specimen cross-section, and higher concrete age at the prestress transfer.
- The AASHTO LRFD Refined and the MC/EC2/EHE methods offer the best predictions. The PCI DH, PCI CPL, and AASHTO STD methods provide similar predictions, with a slow trend towards a more marked prestress losses underestimation when concrete compressive strength decreases. The AASHTO LRFD Approximate method agrees the most with the AASHTO LRFD Refined method when concrete compressive strength decreases.
- The prestressing effectiveness ratios range from 0.55 to 0.80 of prestressing reinforcement stress immediately after the prestress transfer. Higher ratios were recorded for cases with greater concrete compressive strength, greater specimen cross-section size and higher concrete age at the prestress transfer.

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