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PROPOSED CRITERIA TO DETERMINE EXPERIMENTALLY THE TRANSMISSION LENGTH OF PRESTRESSED REINFORCEMENT

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The relations (force in the reinforcement) vs. (slip of the reinforcement in both extremes of the specimen) during the release on groups of specimens with different embedment lengths have been analyzed. Both sequences of slip values adopt a bilinear form, a descending branch with a growing embedment lengths and a horizontal branch corresponding to the cases of embedment length equal or greater than the transmission length. Therefore, both sequences of slip values permit to establish two new criteria to determine experimentally the transmission length.

Key words: bond, concrete, prestressed reinforcement, transmission length, prestress, slip.

1. INTRODUCTION

The transmission of the prestress force through reinforcement in precast prestressed concrete elements is made by bond. The manufacturing process of this type of elements consists of of the following stages: the reinforcement is tensioned before cast, a concrete block around the prestressing reinforcement is made, and the force introduced is transmitted to the concrete in the transmission operation.

After this, the reinforcement stress varies from zero at the end of the element to a constant value in the central zone (effective stress). Thus, the transmission length is defined as the distance required from the free end of the element to develop the effective stress of the prestressed reinforcement [1].

This length could be experimentally determined, and different methodologies had been proposed [2]. The transmission length determination would be immediate if

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the reinforcement stress variation versus the distance to the free end of the element curve could be known.

Actually it is assumed that the bond performance is essential to an adequate response of pretensioned prestressed concrete applications. The ACI 318-05 [1] indicates that, for bonded applications, quality assurance procedures should be used to confirm that the strand is capable of adequate bond. In spite of the large number of experimental researches carried out, there is not consensus on a standard test method for bond quality.

The application of sophisticated measurement procedures like the radiographic technique [3], the photoelasticity [4], the contact electrical resistivity [5] or ultrasound [6], that do not disturb the bond phenomena have not been developed sufficiently. Thus, it is necessary to appeal to indirect determination of the transmission length.

This paper present a critical analysis of the methods to determine the transmission length and two new criteria from the sequence of slips are proposed.

2. METHODS TO DETERMINE THE TRANSMISSION LENGTH

Traditionally two test methods have been used to determine the transmission length of a prestressed reinforcement [7]:

- Measure of the longitudinal concrete strains, by mean of gluing gauges to the surface of the concrete.
- Measure of the reinforcements end slip of the element.

Recently, the ECADA* test method allows to obtain the transmission length from the measurement of the transmitted prestress force by the reinforcement to the concrete in a series of specimens with different embedment length [2].

2.1. LONGITUDINAL CONCRETE STRAINS METHOD

The method is based in the surface concrete strains versus specimen embedment length curve after the release of the prestressed reinforcement. These strains follows a similar law than the reinforcement stresses. The transmission length is obtained as the distance at which the concrete strain reaches a determinate percentage (α) of the average measure strains (AMS) [8] (Fig. 1). In this way, some consideration can be done:

- In scientific literature, there is not a justification in relation to the value α AMS, lying on the researches criteria the assignation of α (values between 0.85 and 1 are generally assumed).
- There is a subjective delimitation of the section with maximum strains, because the strain curve vary from zero and it could be include or not, points corresponding to the ascend branch in the section.

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

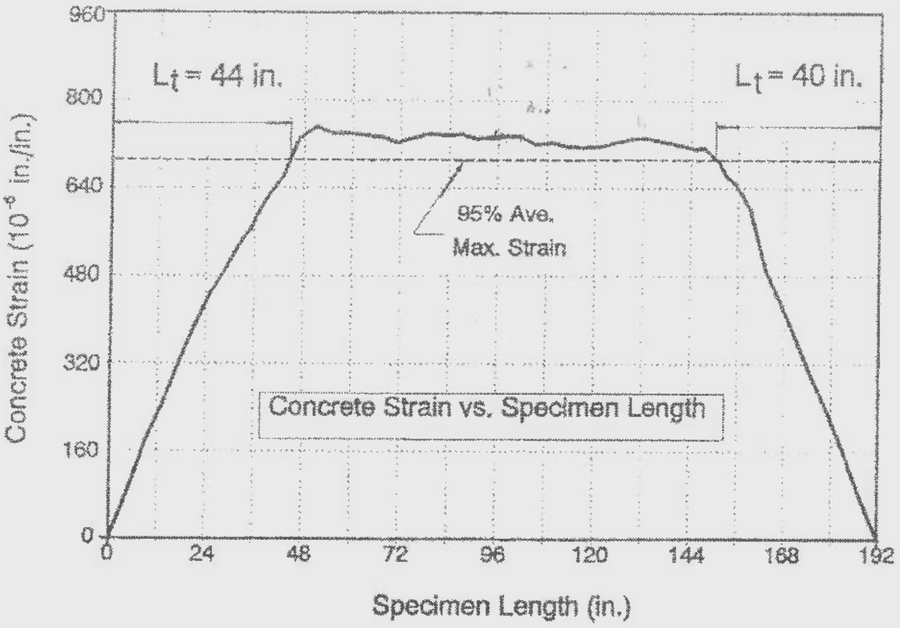

Fig. 1. Transmission length determination [8].
Rys. 1. Ustalenie długości zakotwienia [8]

- The shape of the concrete strain curve depends on the measure base of the gauges or the extensometer used, since average strains are presented.
- The concrete strains presents a "delayed" evolution in front of the reinforcement stress curve, reason why the measured transmission length correspond to a slightly superior level than the real transmission length.

2.2. REINFORCEMENT END SLIPS METHOD

GUYON [9] proposed an expression where the transmission length is directly proportional to the reinforcement end slip of a prestressed element and inversely proportional to the initial reinforcement stress:

$$L_t = \alpha \frac{\delta E_p}{\sigma_{p0}}, \tag{2.1}$$

where L_t — transmission length; α — shape of bond stress distribution along the transmission zone: α — 2 constant distribution (Linear variation of the reinforcement stress), α — 3 linear distribution (Parabolic variation of the reinforcement stress);

δ — prestressed reinforcement end slip; E_p — modulus of elasticity of the prestressing reinforcement (MPa); σ_{p0} — reinforcement stress before release (MPa).

Several researches had proposed different values for the bond stress distribution along the transmission zone from experimental results [2] and theoretical studies [10].

The application of this method is simple, whenever the measures of the slips do not be affected by the loss of local bond in the ends. The Equation (2.1) is not applicable to elements that have produced failure of bond. In this case greater slips that would result in wrong larger transmission length are measured.

2.3. Force method

The test method ECADA is based on the measurement and the analysis of the force supported by the reinforcement in a pretensioned concrete element during the sequential development of the transmission and anchorage situations. To this end, part of the element is replaced by a system (called SAM system) that is placed at one end (pull-out end) of a prestressed frame (Fig. 2).

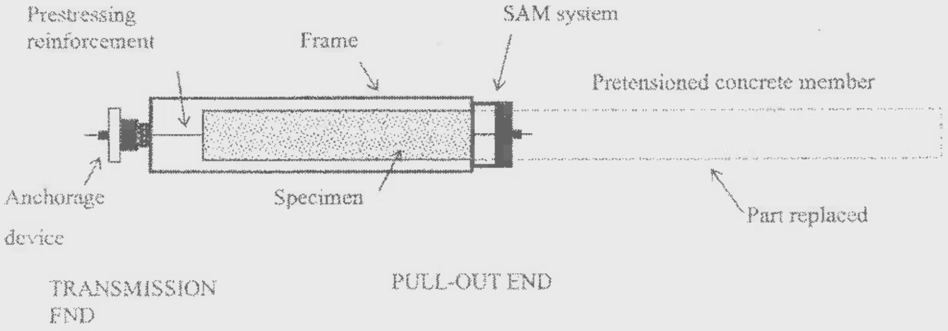

Fig. 2. Test specimen situation in the ECADA test.
Rys. 2. Położenie próbki testowej w badaniu ECADA

The SAM system must carry out the following operations:

- To serve as anchorage for the reinforcement.
- To allow the measurement of the force supported by the reinforcement.
- To enable access to increase the reinforcement stress in the anchorage loading phase.

In addition, for the behaviour of the reinforcement in the SAM system to be the same as it would in the replaced part of the element, the SAM system must fulfil the following conditions:

- To have the same sectional rigidity as the element.
- To disable the confinement effects at the end of the test specimen.

The step-by-step test procedure is as follow (Fig. 3):

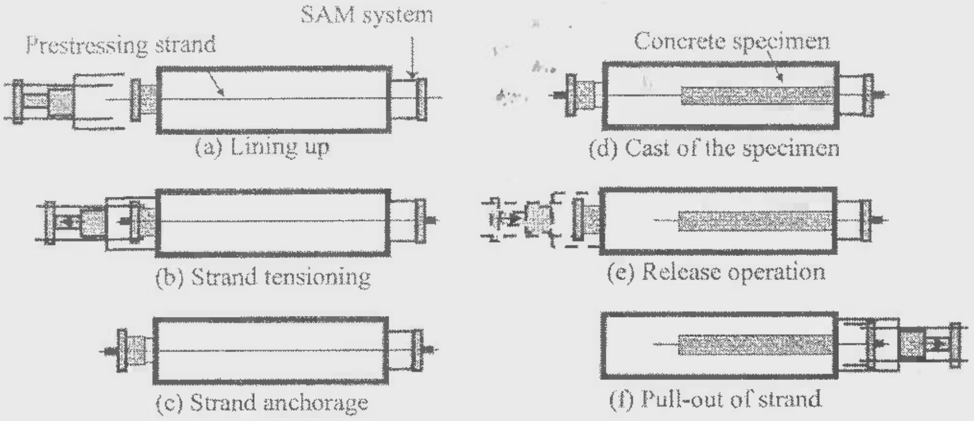

Fig. 3. Test phases diagram.
Rys. 3. Wykres faz eksperymentu

- Lining up: the reinforcement is placed in the frame.
- Tensioning of the reinforcement: the hydraulic jack pulls the anchorage plate separating it from the mechanical device.
- Anchorage of the reinforcement: the mechanical approximation device is unscrewed until it makes contact with the anchorage plate and records the force supported by the reinforcement. The hydraulic jack is relieved.
- Concreting of the test specimens.
- Release: the hydraulic jack recovers the force supported by the mechanical device. The mechanical device is relieved and withdrawn by screwing. The reinforcement release is produced by means of the hydraulic jack relief at controlled speed.
- Stabilisation period.
- Reinforcement pull-out operation: the hydraulic jack is placed at the pull-out end of the frame and increases the tension in the reinforcement by hauling on the anchorage plate (which separates from the frame) until the slippage or breakage of the reinforcement or failure of the concrete by splitting. This operation of pull-out is made with the purpose of determining the anchorage length of the prestressed reinforcement.

No internal measuring device is used in the test specimens to do not distort the bond phenomenon. The instrumentation is reduced to: a force transducer to measure the force supported by the reinforcement at all times during the test; a hydraulic jack pressure sensor to control the tensioning, release and pull-out operations. Additionally, for this work two linear variable differential transducer for measuring reinforcement end slip of the prestressing reinforcement at both ends had been used.

For this method the transmission length is determined from the results of series with different embedment length specimens. The transmission length corresponds to the embedment length of the shortest specimen for which the transmitted force reaches the maximum force of the series [2, 11].

For smaller embedment lengths, the transmitted force is smaller; for embedment lengths greater than the transmission length, the transmitted force is the effective prestressing force.

The main inconvenient of this test rest on the need to adjust the answer of the simulation system to the sectional stiffness of the cross-section and the concrete modulus of deformation of the concrete specimen.

The resolution in the determination of the transmission length will depend on the sequence of lengths of the specimens tested.

3. EXPERIMENTAL PROGRAM

A group of specimens with different embedment lengths to determine experimentally the transmission length had been tested. The ECADA test method was used.

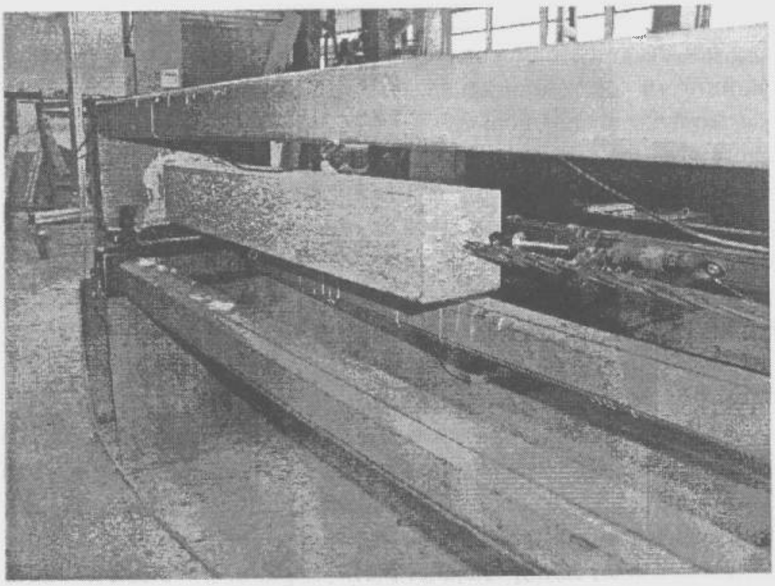

Fig. 4. LVDT in the free end of the specimen.
Rys. 4. LVDT na swobodnym końcu próbki

To measure the reinforcement end slip and the force transmitted in the specimen, linear variable differential transducer (LVDT), one at each end of the specimen (Fig. 4

and Fig. 5) to measure the slips steel-concrete, and a load cell in the SAM system were mounted. Neither the load cell nor the LVDT affected the bond phenomena.

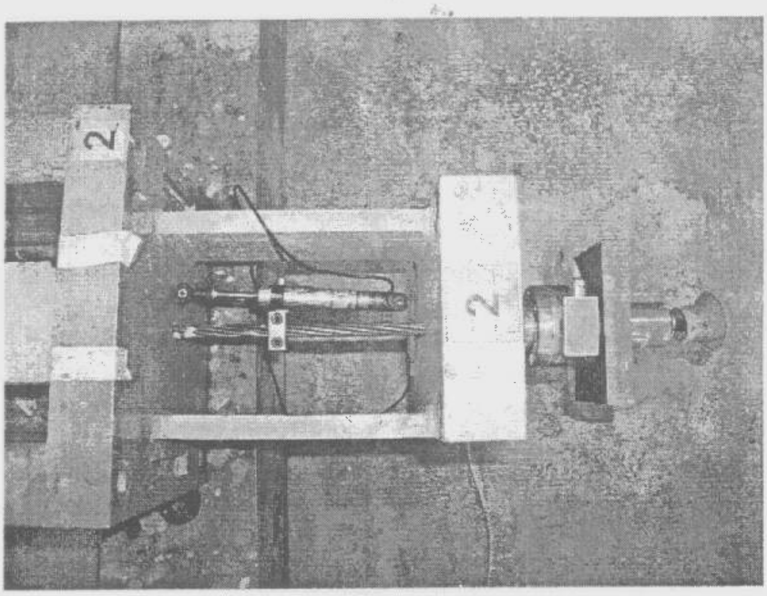

Fig. 5. LVDT in the end of the frame where the SAM system in placed.
Rys. 5. LVDT na końcu ramownicy, w miejscu usytuowania systemu SAM

Twelve different concretes with a range of water/cement ratios (W/C) from 0.3 to 0.5, cement quantity (C) from 350 kg/m^3 to 500 kg/m^3 and a compressive strength from 30 to 70 MPa at 24 hours had been fabricated.

The concrete components were: Cement CEM I 52.5 R, crushed limestone aggregate 5/10, washed rolled limestone sand 0/4 and ISOCRON FM-211 as superplasticizer additive. The different tested concretes are shown in Table 1.

All the 10×10 cm^2 cross-section specimens have one concentric seven wire strand (UNE 36094:97 Y 1860 S7 13.0) at a prestress level of 75% the nominal ultimate tensile strength. The main characteristic where 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 kPa.

The specimens were subjected to the same consolidation and curing conditions. The release was gradual at 24 hours from the casting and the stabilization period was of 2 hours from release.

Table 1

Test program concretes mix design.
Skład mieszanki betonu w programie doświadczalnym

Cement [kg/m^3]	w/c ratio	f_c (24 hours) [MPa]
350	0.50	33.2
	0.45	45.0
	0.40	56.0
400	0.50	30.5
	0.45	35.5
	0.40	48.3
	0.35	61.0
500	0.35	58.3
	0.30	69.9

4. RESULTS

From the ECADA test, the transmission length for every concrete studied were obtained. The relations force in the slip versus the slip slip at both ends after the release had been analyzed. Figure 6 presents the result of the serie of specimens tested made with concrete of 500 kg/m^3 in cement quantity and a water/cement ratio of 0.30.

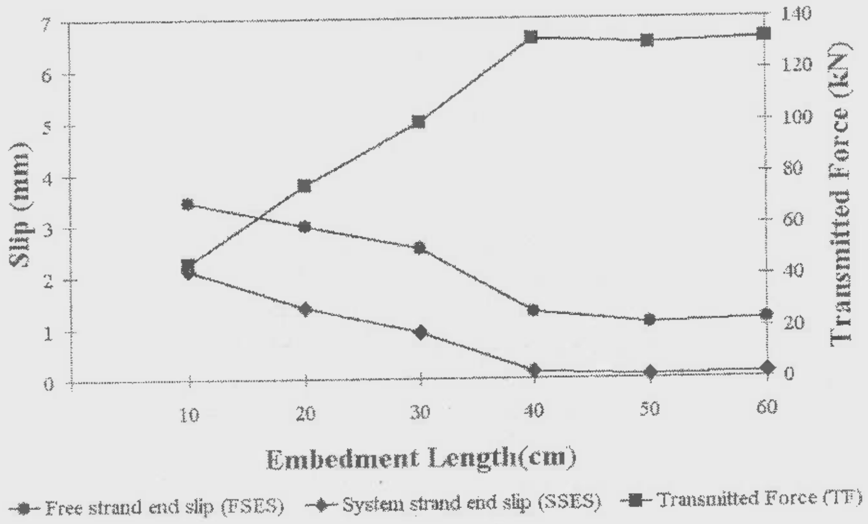

Fig. 6. Experimental results for concrete C 500 kg/m^3 and w/c 0.30
Rys. 6. Wyniki doświadczenia dla betonu C 500kg/m^3 i w/c 0.30

For every embedment length the transmitted force in the ECADA test and the slips at both ends are shown. For a 40 cm embedment length, corresponding to the transmission length according to the transmitted force curve (see Subsec. 2.3), it is observed a clear change in the curves, tend that allows to determine the transmission length from any of the three observed curves.

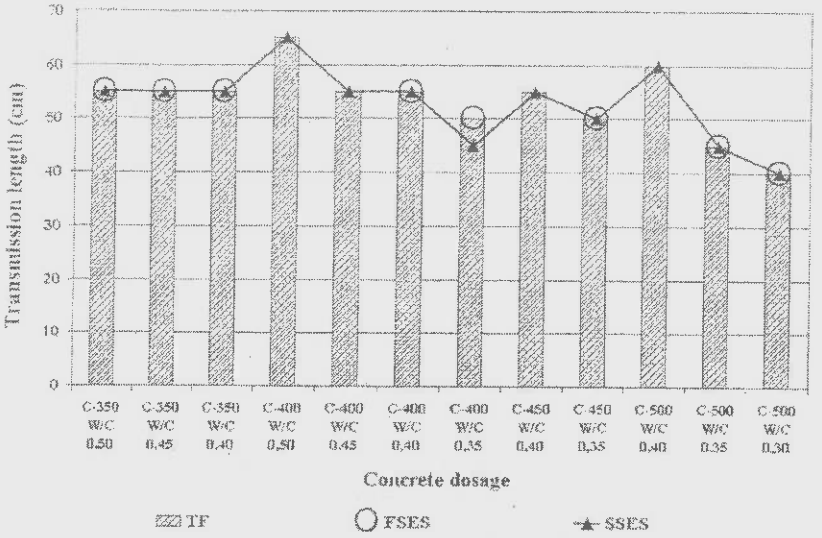

Fig. 7. Experimental transmission lengths.
Rys. 7. Doświadczalna długość odcinka zakotwienia

Figure 7 shows a comparison of the transmission lengths obtained in the different concrete tested from the three curves. For some series of specimens with the same concrete dosage it has not been possible to determine the transmission length from the free slip end slip curve (FSES) because it does not present a clear change of slope (4 of the 12 concretes dosages tested).

A correspondence (11 of the 12 concrete dosages tested) between the results from the transmitted force (TF) and the results obtained from the system slip end slip (SSES) is observed. Also there is a total correspondence (8 concrete dosages) between the transmission lengths obtained from the transmitted force and the obtained from the FSES for the cases where it has been able to be determined.

5. CONSLUSIONS

From the results obtained, the following conclusions can be drawn:

- The sequence of slips values (at both ends) as a function of the embedment length adopts a bilinear form, a descending branch with growing embedment lengths and a horizontal branch that correspond to the cases of embedment length higher or equal to the transmission length.

- Both slip sequences FSES and SSES are two new criteria to determine experimentally the transmission length.
- The transmission length results are obtained by direct observation of the curves, thus, an adjustment or estimation of the expecting values is not required.
- The reliability of the obtained results from the sequence of slips is contrasted by the clear correspondence with the results from the method of forces.
- The sequences of slip values from the free slip end slip (FSES) in some cases do not present a clear change in slope that allows to determine the transmission length.

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PROPONOWANE KRYTERIA EKSPERYMENTALNEGO OKREŚLANIA DŁUGOŚCI ODCINKA PRZEKAZYWANIA SIŁY ZBROJENIA SPRĘŻAJĄCEGO

Streszczenie

Badano relacje pomiędzy siłą w zbrojeniu a poślizgiem zbrojenia na obu krańcach próbki podczas zwalniania siły, w grupach próbek o różnej długości zakotwienia. Obie sekwencje wartości poślizgu przyjmują formę nieliniową, krzywa jest opadająca wraz ze wzrostem długości zakotwienia oraz pozioma, odpowiadająca przypadkom, kiedy odcinek przekazywania siły sprężającej jest równy lub większy niż długość zakotwienia. Tak więc obie sekwencje wartości poślizgu pozwalają utworzyć dwa nowe kryteria doświadczalnego ustalania długości zakotwienia.

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