

1 Slip distribution model along the anchorage length of prestressing strands

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11

12 **Abstract:**

13 An analytical model to predict strand slips within both transmission and anchorage lengths in
14 pretensioned prestressed concrete members is presented. This model has been derived from an
15 experimental research work by analysing the bond behavior and determining the transmission
16 and anchorage lengths of seven-wire prestressing steel strands in different concrete mixes. A
17 testing technique based on measuring the prestressing strand force in specimens with different
18 embedment lengths has been used. The testing technique allows measurement of free end slip
19 as well as indirect determination of the strand slip at different cross sections of a member
20 without interfering with bond phenomena. The experimental results and the proposed model
21 for strand slip distribution have been compared with theoretical predictions according to
22 different equations in the literature and with experimental results obtained by other
23 researchers.

24 **Keywords:** concrete; strand; bond; prestress; transmission length; anchorage length; slip;
25 model

26

1 **1. Introduction**

2

3 The prestressing force is transferred from the prestressing strands to concrete by bond during
4 the prestress transfer operation. Afterwards, bond mechanisms allow force variations in the
5 prestressing strands ranging from zero at the free end of the member to the full prestressing
6 strand force which is achieved at a distance defined as transmission length [1] –or transfer
7 length [2]–.

8

9 Also, when a pretensioned prestressed concrete member is loaded by external actions, higher
10 forces in the prestressing strands are activated. This increase in prestressing strand force is
11 developed only if bond between concrete and prestressing strands allows it, and a bond length
12 (complementary bond length [3] –or flexural bond length [2]–) beyond the transmission
13 length is required. The sum of the transmission length and this complementary bond length is
14 defined as anchorage length [1] –or development length [2]–. Fig. 1 shows the idealized
15 prestressing strand force profile according to the aforementioned lengths.

16

17 Variation in prestressing strand force along both transmission and anchorage lengths involves
18 bond stresses which are activated by the relative displacement (slips) of the prestressing
19 strand into concrete cross-sections [4, 5]. After prestress transfer, the maximum strand slip
20 occurs at the free ends of the member, and the strand slip will be zero when the full
21 prestressing strand force is achieved and compatibility of strains between the prestressing
22 strand and concrete exists [6]. In addition to the definition of anchorage length in [1], Buckner
23 [7] indicates that the overloading force must be developed without additional strand end slip
24 at the free ends of the member.

25

1 The prestressing strand-to-concrete bond is a function of a large number of factors [8, 9]. A
2 literature review of the factors influencing bond and transmission and anchorage lengths of
3 prestressing reinforcement has been presented in [1]. Several equations to calculate both
4 transmission and anchorage lengths have been proposed [3, 10, 11]. However, knowledge on
5 the slips of prestressing strands is generally limited to free end slip measurements which are
6 used to obtain the transmission length by means of the Guyon's theory [12].

7

8 Consequently, the purpose of this research is to develop an analytical bond model to predict
9 the slip distribution along both the transmission and anchorage lengths of seven-wire 13 mm
10 prestressing steel strands. An experimental program has been carried out to determine the
11 force-slip relationships along the transmission and anchorage lengths for twelve different
12 concrete proportionings by means of the ECADA test method [13].

13

14 **2. Background**

15

16 The measurement of the free strand end slip is a traditional indirect method to determine the
17 transmission length in pretensioned prestressed concrete members. This method has been
18 proposed as a simple non-destructive assurance procedure by which the quality of bond can
19 be monitored within precasting plants [14, 15]. Most experimental standards [16-18] are
20 based on this method along with the analysis of the strains profile on the concrete surface
21 after release, but it provides no information on the anchorage length or on the slips along the
22 transmission length.

23

24 The relationship between the transmission length and the strand end slip can be expressed as
25 [12]:

$$L_t = \alpha \frac{\delta_f}{\varepsilon_{pi}} \quad (1)$$

where L_t is the transmission length, δ_f is the strand end slip at the free end of a pretensioned prestressed concrete member, ε_{pi} is the initial strand strain, and α represents the shape factor of the bond stress distribution ($\alpha = 2$ for uniform bond stress and $\alpha = 3$ for linear descending bond stress distribution). Several experimental and theoretical studies subsequent to Guyon's theoretical analysis have reported α values ranging from 1.5 to 4, as it has been reviewed in [19]. Also a value of $\alpha = 2.44$ for Guyon's equation has been proposed in [19].

A modification of Guyon's expression was proposed by Balazs [4, 20] which takes into account a nonlinear bond stress-slip relationship over the transmission length considering the strand diameter and concrete compressive strength. As a result, the following equations for calculating the transmission length of 13 mm seven-wire prestressing steel strand were developed [4, 20]:

$$L_t = 105d_b \sqrt[4]{\frac{\delta_f^{3/2}}{f_{ci}'}} \quad (2)$$

$$L_t = \frac{111\delta_f^{0.625}}{f_{ci}'^{0.15} \left(\frac{f_{pi}}{E_p} \right)^{0.4}} \quad (3)$$

where d_b is the diameter of prestressing strand, f_{ci} is the concrete compressive strength at the time of prestress transfer, f_{pi} is the strand stress immediately before release and E_p is the modulus of elasticity of the prestressing strand.

An equation to obtain directly the strand slip at the free end as a function of the initial prestress was also proposed by Balazs [4]:

1
$$\delta_f = 1.23 \left(\frac{f_{pi}^2}{E_p \sqrt{f'_{ci}}} \right)^{0.8} \quad (4)$$

2 Another equation that relates the transmission length to the strand free end slip of a
3 pretensioned prestressed concrete member was proposed in [21] ($K = 0.00035 \text{ mm}^{-1}$ for 12.7
4 mm seven-wire strand):

5
$$L_t = \sqrt{\frac{\delta}{K}} \quad (5)$$

6 Regarding the anchorage length, the test methods are based on pull-out tests [22] or full size
7 beams [23]. The former does not reproduce the previous prestress transfer stage, and the latter
8 requires an iterative beam testing process. In this iterative process, there are intrinsic
9 disadvantages due to the size and cost of the members. Other procedures for bond strength
10 determination such as the push-pullout test [24] or the use of cylindrical [25] or prismatic
11 specimens [26] have been used in some cases.

12

13 To measure slips, Mains [27] devised a technique based on determining the reinforcement
14 strain. This technique involves attaching strain gauges inside specially prepared hollow
15 reinforcement. A large diameter is required, and therefore this technique is not applicable to
16 the wires and strands for pretensioned concrete.

17

18 In an experimental study conducted by Ratz et al. [28] on the wire displacements into the
19 concrete along the transmission zones, prestressed concrete specimens were made with holes
20 at various distances at the upper side of specimens. The holes allowed researchers to observe
21 the wires in the specimens. Marks on the wire surface were made. Wire movements relative to
22 concrete at various stages of the prestress transfer were measured using microscopes provided
23 with micrometers eye-glass. The microscopes were attached to the concrete and focused on

1 the holes. From this study, an empirical relationship between the stress in the wire and its
2 displacement within the transmission zone was determined. However, this method has the
3 disadvantage of removing concrete from the surface of the wires by the holes with the
4 consequent destruction of bond.

5

6 An experimental application of air-gage devices to detect small linear movements (slips) of
7 reinforcement in concrete slabs and to convert these slips into changes in air-flow rates was
8 developed by Lewis and Moore [29]. In this procedure, a stainless-steel pin is driven into a
9 hole drilled into the reinforcement. A plastic block is then placed over this pin, and the entire
10 assemblage is cast into the concrete. Consequently, the bond phenomenon and the concrete
11 confinement of the reinforcement are distorted.

12

13 Therefore, the measurement of slips in prestressing reinforcement mothered the application of
14 sophisticated measurement procedures that do not disturb the bond phenomenon.

15

16 The radiographic strain-measuring technique was applied to measure slips along the
17 transmission length in wires [30]. This technique involves placing small lead markers in slots
18 formed in the reinforcement. The positions of the markers are recorded on an X-ray
19 photograph. Wire slip relative to the concrete may be measured directly as the distance
20 between the portions of a marker embedded in the wire and in the concrete. However, the
21 conditions for obtaining a satisfactory film are critical and this technique has not been
22 developed sufficiently.

23

1 Sophisticated techniques for instrumentation and measurement procedures based on fiber
2 optic sensors are being used in some cases [31], but have not been used for strand-concrete
3 bond.

4
5 Recently, an experimental methodology based on the measurement and the analysis of the
6 force supported by the prestressing strand in specimen series with different embedment lengths
7 has been conceived: the ECADA test method [13, 32]. This test method allows one to
8 determine both transmission and anchorage lengths [33], changes in these lengths with time
9 [34] and prestress losses [35], and the strand slip measurement simultaneously at both ends
10 [36] of a specimen.

11

12 **3. Methodology**

13

14 The ECADA test methodology allows the bond characterization of prestressing reinforcement
15 through the sequential release of the prestress transfer (detensioning) and the pull-out
16 (loading) operation on the same specimen test. This test method is based on measuring and
17 analysing the force supported by the strand in a series of pretensioned prestressed concrete
18 specimens with different embedment lengths. Fig. 2 shows the layout of the test equipment.

19 The equipment consists of a pretensioning frame with an adjustable strand anchorage placed
20 in the frame plate corresponding to the free end and an Anchorage-Measurement-Access
21 (AMA) system placed in the frame plate corresponding to the stressed end of the specimen.

22 The AMA system performs the following functions: it simulates the sectional rigidity of the
23 specimen, serves as anchorage for the prestressing strand, allows the measurement of the
24 force supported by the strand and of the strand slip with respect to the last embedment
25 concrete cross-section of the specimen, and enables access to increase the strand force in the

1 anchorage loading stage. A detailed description of the test method and the AMA system
2 requirements is available in [13, 32].

3

4 **3.1. Testing technique**

5

6 The step-by-step test procedure may be summarized as follows:

7 a) Tensioning stage.

8 a.1) The equipment test is set up with the hydraulic jack connected to the
9 pretensioning frame at the free end.

10 a.2) The prestressing strand is placed in the frame.

11 a.3) Two anchorage devices are put at both ends of the prestressing strand.

12 a.4) The prestressing strand is tensioned.

13 a.5) The prestressing strand is provisionally anchored by means of the adjustable
14 strand anchorage, which is unscrewed.

15 a.6) The hydraulic jack is relieved (and it can be connected to other pretensioning
16 frame for a new operation).

17 b) Casting of the concrete specimen.

18 b.1) Concrete is mixed, poured into the form positioned in the pretensioning frame,
19 and consolidated.

20 b.2) The concrete specimen is cured and remains in the selected conservation
21 conditions to achieve the desired concrete properties.

22 b.3) Prior to testing, the mould is relieved from the pretensioning frame.

23 c) Detensioning stage.

24 c.1) The hydraulic jack is coupled to the pretensioning frame.

1 c.2) When the actual prestressing reinforcement force is recovered by the hydraulic
2 jack, the adjustable strand anchorage device is relieved and withdrawn by
3 screwing.

4 c.3) The strand prestress transfer is produced at a controlled speed through the
5 unloading of the hydraulic jack.

6 c.4) The concrete specimen is supported at the stressed end of the pretensioning
7 frame while the prestressing force is transferred to the concrete.

8 c.5) The hydraulic jack is relieved.

9 d) Loading stage.

10 d.1) The hydraulic jack is anew coupled to the pretensioning frame at the stressed
11 end.

12 d.2) The force in the prestressing strand is increased by loading the hydraulic jack
13 which pulls the AMA system from the pretensioning frame.

15 **3.2. Instrumentation**

16
17 No internal measurement devices are used in order not to distort the strand-concrete bond
18 phenomenon. Following the basis of the ECADA test method, the instrumentation is
19 composed of a force transducer placed at the anchorage device of the prestressing strand at the
20 end of the AMA system, and a hydraulic jack pressure sensor.

21
22 The force transducer allows the prestressing strand force to be measured at all times during
23 testing: tensioning, provisional anchorage, detensioning, and loading. The pressure sensor is
24 used to control the force exerted by the hydraulic jack.

1 Additionally, in this experimental research two displacement transducers have been used: one
2 located at the free end (Fig. 3) to measure the free end slip, and another at the stressed end
3 (Fig. 4) to measure the slip of the strand with respect to the last embedment concrete cross-
4 section of the specimen (stressed end slip).

5

6 **3.3. Criteria to determine transmission and anchorage lengths**

7

8 With the ECADA test method, both the transmission and the anchorage lengths are
9 determined by testing a series of specimens with different embedment lengths. The force in
10 the prestressing strand at the stressed end during both the prestress transfer process and the
11 pull-out operation is measured.

12

13 The transferred prestressing force values (P_t) measured after the c.4 test step are arranged
14 according to the specimen embedment length (Fig. 5). The obtained curves reveal a bilinear
15 law. There is an ascendent initial branch and then a practically horizontal branch
16 corresponding to the maximum possible prestressing force (P_e). This force is determined by
17 the bond performance and the compatibility of strains conditions, and by the properties and
18 characteristics of the prestressing strand and concrete specimen. The transmission length (L_t)
19 corresponds to the shortest specimen embedment length that marks the beginning of the
20 horizontal branch, that is, to the first specimen of the series with $P_t = P_e$.

21

22 For specimen embedment lengths larger than the transmission length, the force in the
23 prestressing strand is increased (d.2 test step). The pull-out force values (P_a) achieved without
24 additional increases of the strand free end slip are arranged according to the specimen
25 embedment lengths (Fig. 5). The obtained curves present an ascending tendency. In these

1 conditions, the anchorage length (L_a) corresponds to the shortest embedment length of the
2 specimens that reach the P_r force –established as a reference to analyze the anchorage
3 behavior– in the prestressing strand, that is, to the first specimen of the series with $P_a \geq P_r$.

4
5 Consequently, in this study the resulting length to reduce the transmission length to the
6 anchorage length ($L_c = L_a - L_t$) has been defined as the complementary bond length (L_c).

7
8 The resolution in the determination of the transmission and anchorage lengths depends on the
9 sequence of specimen lengths tested. Generally, the transmission and the anchorage lengths
10 determination requires testing 6 to 12 specimens with different embedment lengths with a
11 testing increment of 50 mm.

12
13 The characterization of the strand-to-concrete bond behavior can be completed by analysing
14 the force-slip relationships at both ends of the test specimens during the prestress transfer
15 process and the pull-out operation.

16

17 **4. Experimental program**

18

19 In an attempt to experimentally obtain the slip distribution in a seven-wire 13 mm prestressing
20 steel strand along both the transmission and the anchorage lengths, an experimental program
21 has been conducted. The testing equipment consisted of 6 pretensioning frames and 2
22 hydraulic jacks.

23

24 Test specimens had a cross-section of 100 x 100 mm² with a centered single strand. The
25 prestressing strand was low-relaxation, seven-wire steel strand of 13 mm nominal diameter.

1 The strand had a guaranteed ultimate strength 1860 MPa, specified as UNE 36094:97 Y 1860
2 S7 13.0 [37]. The manufacturer provided the following main characteristics: diameter 12.9
3 mm, section 99.69 mm², nominal strength 192.60 kN, yield stress at 0.2% 177.50 kN, and
4 modulus of elasticity 196.70 GPa. The prestressing strand was tested in as-received conditions
5 (free of rust and free of lubricant). A prestress level of 75 percent of the nominal ultimate
6 strand strength (1860 MPa) was applied in all cases, representative of most cases in real
7 applications.

8
9 Twelve concrete mixes with water/cement ratios ranging from 0.3 to 0.5, cement contents
10 between 350 and 500 kg/m³, and compressive strength at the time of testing f'_{ci} from 24 to 55
11 MPa were tested. Concrete components were: cement CEM I 52.5 R [38], crushed limestone
12 aggregate 7/12, washed rolled limestone sand 0/4, and a polycarboxylic ether high range
13 water reducer. All concretes mixes were designed with a constant gravel/sand ratio of 1.14.
14 Concrete proportionings, concrete compressive strength values at the time of testing and the
15 embedment lengths in the specimens tested (see Section 3) are shown in Table 1.

16
17 All specimens were subjected to the same consolidation and curing conditions. The prestress
18 transfer was gradually performed 24 hours after casting (b.1 test step), and a 2-hour
19 stabilization period after the prestress transfer (c.4 test step) was considered before
20 determining the transferred prestressing force values (P_t).

21
22 The loading stage (d.2 test step) was also gradually performed after the stabilization period.
23 For the anchorage analysis, a reference force (P_r) of 158 kN was established as representative
24 of the force that can be applied to the strand before failure in this experimental study. The

1 pull-out operation was performed to achieve this reference force (P_r) without strand slip at the
2 free end of the test specimen during this operation.

3

4 During the detensioning stage, and also in the loading stage, visible splitting cracks have not
5 appeared in any of the tested specimens.

6

7 **5. Results and discussion**

8

9 The transmission and anchorage lengths were determined for each concrete mix from series of
10 specimens with different embedment lengths. As an example, Fig. 6 shows the results of
11 prestressing force (P_t) transferred to concrete and of attained pull-out forces (P_a) versus the
12 embedment length for specimens of concrete M-350/0.50. The results of transmission and
13 anchorage lengths for all concrete concrete mixes are summarized in Table 2.

14

15 **5.1 Slips resulting from prestress transfer operation**

16

17 The characterization of bond behavior during the prestress transfer can be analyzed from the
18 curves obtained [prestressing force transferred – strand end slip]. Fig. 7 shows these curves at
19 both ends of the specimens (their embedment lengths are shown) for concrete mix M-
20 500/0.30. In the case of the test specimens with embedment length shorter than the
21 transmission length (400 mm), it can be observed a bilinear response with an ascendent initial
22 branch and a practically horizontal branch after a certain slip value (peak-slip). The peak-slip
23 value at the free end ($\delta_{f,peak}$) and at the stressed end ($\delta_{s,peak}$) correspond to the same level of
24 prestressing force transferred, resulting in the beginning of the generalized slippage of the
25 prestressing strand. The horizontal branch is longer when embedment length is shorter, and

1 the prestressing force transferred to concrete increases when the embedment length increases
2 until it corresponds to the transmission length.

3

4 In Fig. 7 it can also be observed that the obtained curves are similar for test specimens with
5 embedment length equal to or longer than the transmission length. Slip values at both ends
6 increase progressively while the prestressing force is transferred to the concrete. In these
7 cases, a final slip value is obtained, and no peak-slip value appears.

8

9 As previously mentioned, the maximum strand slip after prestress transfer occurs at the free
10 end of a specimen. The strand slip will be zero beyond the transmission length where
11 prestressing strand force does not vary with the specimen length and compatibility of strains
12 between the prestressing strand and concrete exists. Therefore, strand slips at the stressed end
13 should not occur in specimens with embedment lengths equal to or longer than the
14 transmission length. However, the movements of the AMA system compounds from strand
15 tensioning stage to detensioning (from step test procedure a.4 to c.4) imply a residual slip of
16 the strand which takes place at the stressed end. Consequently, even if the specimen
17 embedment length is greater than the transmission length, a small slip of the strand at the
18 stressed end is registered (see Fig. 7b).

19

20 Analysing the bond behavior from Fig.7a, the $\delta_{f,peak}$ values are arranged according to the
21 specimen embedment length (shorter or equal to the corresponding transmission length) as it
22 is shown the Fig. 8 in this particular manner: the $\delta_{f,peak}$ registered in a test specimen with
23 embedment length l corresponds to the strand slip in a cross section placed at a distance l
24 from the end of the transmission length (which is known) towards the free end of the
25 specimen. In this way for each embedment length l , it has been considered that the prestress

1 transfer response is achieved when the bond capacity is exceeded. The strand slip value at a
2 distance from free end equal to 0 (also $l = 400$ mm –for M-500/0.30–) corresponds to the
3 strand free end slip for the specimen embedment length equal to transmission length. This
4 distribution of $\delta_{f,peak}$ values results in an attempt to indirectly determine the strand slip at
5 different cross sections along the transmission length of a pretensioned prestressed concrete
6 member without distorting the bond phenomenon.

7

8 Fig. 9 shows a comparison of the strand slip distribution along the transmission length for
9 concrete mixes M-400/0.40 and M-500/0.30. As observed, strand slips are lesser for the case
10 of M-500/0.30. This fact is consistent with the higher concrete compressive strength of this
11 mix with respect to M-400/0.40, which presents greater strand slips and longer transmission
12 length.

13

14 **5.2 Equation for slip-length relationship along transmission length**

15

16 Based on the experimental results from the twelve concrete mixes including 52 specimens
17 with embedment length shorter or equal to the corresponding transmission length, a good
18 adjustment to the strand slip values along the transmission length has been obtained. As a
19 result, Eq. (6) gives the strand slip distribution at every location within the transmission
20 length.

$$21 \quad \delta_{f,x} = 8.7 \frac{(L_t - x)^2}{L_t^2 \sqrt{f_{ci}}} \quad (6)$$

22 where $\delta_{f,x}$ is the strand slip at the located section x after detensioning (mm), x is the distance
23 of a cross section from the free end (mm), and f_{ci} is the concrete compressive strength at the
24 time of prestress transfer (MPa).

1

2 Fig. 10 shows the correlation between the predicted strand slip by applying Eq. (6) and the
3 obtained experimental results (measured $\delta_{f,peak}$ values). A high coefficient of correlation R^2 of
4 0.965 has been obtained.

5

6 **5.3 Comparison with other test results and equations**

7

8 The obtained experimental results in this work and the proposed strand slip distribution model
9 by Eq. (6) have been compared with the theoretical predictions according to several equations
10 from the literature (Eq. (1) to Eq. (5)). Also, test results reported by other researchers –on 13
11 mm prestressing steel strands including simultaneously transmission length determination and
12 measurement of the strand free end slip (δ_f)– have been included for comparison purposes.

13

14 The theoretical values of the strand free end slip by applying Eq. (1) to Eq. (6) to the
15 corresponding measured transmission length value have been obtained. In the case of the Eq.
16 (1), the following values for the shape factor $\alpha = 2$, $\alpha = 2.44$, and $\alpha = 3$ have been considered.

17

18 Fig. 11 shows the obtained ratios [δ_f predicted / δ_f measured] –by using the proposed Eq. (6)–
19 versus the δ_f measured. The average value and the standard deviation of the resulting ratios
20 and δ_f measured are also plotted in Fig. 11. As it can be observed, a general trend of a
21 decreasing [δ_f predicted / δ_f measured] ratio when the δ_f measured increases exists for all the
22 authors. As shown in Fig. 12, this trend is also observed when the strand free end slip
23 predictions are made by Eq. (4). For the others equations, the comparisons result in an
24 appearance as observed in Fig. 13 for Eq. (1) by substituting $\alpha = 2.44$. In these cases, the

1 aforementioned trend by applying Eq. (6) or Eq. (4) has not been observed, and also a greater
2 range of the [δ_f predicted / δ_f measured] ratios for a single δ_f measured value appears.
3
4 Table 3 summarizes the main results of the analyzed comparisons. The average value and the
5 standard deviation of the obtained ratios [δ_f predicted / δ_f measured], and the percentage of
6 points that fall in the rectangle formed by the intersection of the four standard deviation lines
7 (see Figs. 11 to 13) are reported. As observed, predictions from the different equations can
8 underestimate or overestimate of experimental data. The average ratios for all results range
9 from 0.59 to 1.19, and the standard deviation from 0.20 to 0.32. The proposed Eq. (6)
10 performs well with a 0.98 average ratio and the highest percentage of points falling into the
11 aforementioned rectangle (71.2%).

12

13 **5.4 Slips resulting from pull-out operation**

14

15 The characterization of bond behavior during the loading operation can be analyzed from the
16 obtained curves [prestressing strand force achieved – strand end slip]. Fig. 14 shows these
17 curves at both ends of specimens (their embedment lengths are shown) for concrete mix M-
18 500/0.30. As observed for the specimen embedment lengths shorter than the transmission
19 length (400 mm), strand end slips start when the pull-out force exerted by the hydraulic jack
20 is of the order –they are slightly lower and not equal because of force losses between testing
21 stages– of the actual prestressing strand force after detensioning (see Fig. 7). In agreement
22 with the Stress Waves Theory [5, 42] and as shown in Fig. 14, strand end slips begin when the
23 pull-out force exerted by the hydraulic jack is equal to the actual prestressing strand force for
24 the specimen with an embedment length equal to the transmission length. Also, only
25 specimens with embedment length greater than the transmission length allow the prestressing

1 strand force to increase without strand end slip. In these cases, a higher pull-out force without
2 strand end slip is achieved for a greater specimen embedment length. Finally, the specimens
3 with embedment length equal to or greater than 350 mm attain the P_r force, and the strand
4 slips developed at both ends in these cases are lesser when the embedment length is greater.
5 As the specimen with 600 mm embedment length reaches the P_r force without free end strand
6 slip at this test stage, 600 mm is the anchorage length for mix M-500/0.30 [7].

7
8 Fig. 15 illustrates the measured stressed end slip (δ_s) along the complementary bond length
9 for concrete mixes M-400/0.40 and M-500/0.30. These strand slips correspond to the
10 maximum stressed end slip just before free end slip at loading begins. The specimens have
11 embedment lengths ranging from the transmission length to the anchorage length. Only the
12 complementary bond length beyond the transmission length has been illustrated (i.e. 100 mm
13 in length corresponds to embedment length equal to 550+100 mm for M-400/0.40 and
14 400+100 mm for M-500/0.30). As observed, strand slips are lesser for the case of M-
15 500/0.30. This fact is consistent with the higher concrete compressive strength for this mix
16 with respect to M-400/0.40. In this way, the obtained curves represent the strand slip at
17 different cross sections along the complementary bond length of a pretensioned prestressed
18 concrete member without distorting the bond phenomenon.

19

20 **5.5 Equation for slip-length relationship along complementary bond length**

21

22 Based on the experimental results from nine of the twelve concrete mixes (data from M-
23 450/0.4, M-500/0.35 and M-500/0.40 were unavailable for this purpose) including 35
24 specimens (9 with embedment length equal to transmission length and 26 with embedment
25 length ranging from transmission length to anchorage length), a good adjustment to the

1 stressed end slip values along the complementary bond length has been obtained. As a result,
2 Eq. (7) gives the strand slip distribution at every location within the complementary bond
3 length.

$$4 \quad \delta_{s,x} = 9 \cdot 10^{-5} \frac{(x - L_t)^2}{\sqrt{f_{ci}}} \quad (7)$$

5 where $\delta_{s,x}$ is the strand slip at the located section x at loading (mm), x is the distance of a
6 cross section –ranging from transmission length to anchorage length– from the free end (mm),
7 and f_{ci} is the concrete compressive strength at testing time (MPa).

8

9 Fig. 16 shows the correlation between the predicted strand slip by applying Eq. (7) and the
10 experimental results (measured δ_s values). A coefficient of correlation R^2 of 0.839 has been
11 obtained.

12

13 Results for strand slip along the complementary bond length are not available in the literature.
14 Therefore, it is not possible to make comparisons. Numerical simulations based on pull-out test
15 specimens with short embedment length [6] provided a theoretical strand slip-length
16 distribution which is qualitatively similar to the obtained in this experimental research work.

17

18 **5.6 Equation for slip-length relationship along the anchorage length**

19

20 Since the anchorage length is composed of the transmission length plus the complementary
21 bond length, the strand slip distribution at every location within the anchorage length can be
22 obtained by assembling the two models obtained. Fig. 17 illustrates the complete curves for
23 concrete mixes M-400/0.40 and M-500/0.30.

24

1 **6. Conclusions**

2

3 An experimental program to analyze bond behavior based on force-slip relationships and to
4 determine transmission and anchorage lengths of 13 mm prestressing steel strand has been
5 conducted by means of the ECADA test method. The following conclusions may be drawn
6 from this experimental research:

7 •Based on strand force-slip behavior as a function of the embedment length, a test
8 methodology to measure indirectly the strand slip at different cross sections of a
9 pretensioned prestressed concrete member without distorting the bond phenomenon has
10 been developed.

11 •The influence of concrete compressive strength on the strand slips has been analyzed: strand
12 slips are lesser for the case of higher concrete compressive strength, both at the prestress
13 transfer and pull-out (loading) stages.

14 •The following equation is proposed to predict the slip-length relationship within
15 transmission length of 13 mm prestressing steel strand (see notation in 5.2):

$$16 \quad \delta_{f,x} = 8.7 \frac{(L_t - x)^2}{L_t^2 \sqrt{f_{ci}}}$$

17 •The following equation is proposed to predict the slip-length relationship within the
18 complementary bond length of 13 mm prestressing steel strand (see notation in 5.5):

$$19 \quad \delta_{s,x} = 9 \cdot 10^{-5} \frac{(x - L_t)^2}{\sqrt{f_{ci}}}$$

20 •These equations have been experimentally verified. A high coefficient of correlation R^2 of
21 0.965 has been obtained between predicted and measured slips for transmission length, and
22 0.839 for complementary bond length.

- 1 •Regarding transmission length and free end slip of 13 mm prestressing steel strand, the
2 obtained experimental results and the proposed equation have been compared with pre-
3 existing equations in the literature and with test results reported by others researchers:
- 4 •Predictions give in some cases a general trend to decrease the prediction value when the
5 measured value increases.
 - 6 •A greater range of the predicted values for a single measured value appears when the
7 equations based on Guyon’s model are used.
 - 8 •A good prediction for all results has been found by using the proposed model in this
9 work.
- 10 •An analytical bond model to predict the slip distribution of the prestressing strand at every
11 location within the anchorage length is available by the sequential assembly of both
12 previously proposed slip-length models.

13

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15

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24

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Table 1

Concrete mixture designs and specimen embedment lengths tested

Designation	cement (kg/m ³)	water/cement ratio	f_{ci} (MPa)	$f_{c,28}$ (MPa)	specimen embedment length (mm)
C-350-0.50	350	0.50	26.1	50.7	400/450/500/550/600/650/ /700/750/800/850/900
C-350-0.45		0.45	37.3	61.5	450/500/550/600/650/700
C-350-0.40		0.40	46.7	69.2	450/500/550/600/650/700
C-400-0.50	400	0.50	24.2	42.8	500/550/600/650/700/750/ /800/850/900/950/1000/1050
C-400-0.45		0.45	28.3	50.2	450/500/550/600/650/700
C-400-0.40		0.40	41.4	66	250/350/400/450/500/550/600/ /700/850/1350
C-400-0.35		0.35	45.3	75.3	350/400/450/500/550/600/ /650/700/750/800/850/900
C-450-0.40	450	0.40	36.3	65.2	350/400/450/500/550/600/ /650/700/750/800/850/900
C-450-0.35		0.35	46.6	73.6	350/400/450/500/550/600/ /650/700/750/800/850/900
C-500-0.40	500	0.40	30.8	59.2	350/450/500/550/600/650/ /700/750/800/900/1000
C-500-0.35		0.35	46.6	N.A.	350/400/450/500/550/600
C-500-0.30		0.30	54.8	N.A.	50/100/150/200/250/300 /350/400/450/500/550/600

Table 2

Transmission and anchorage length results

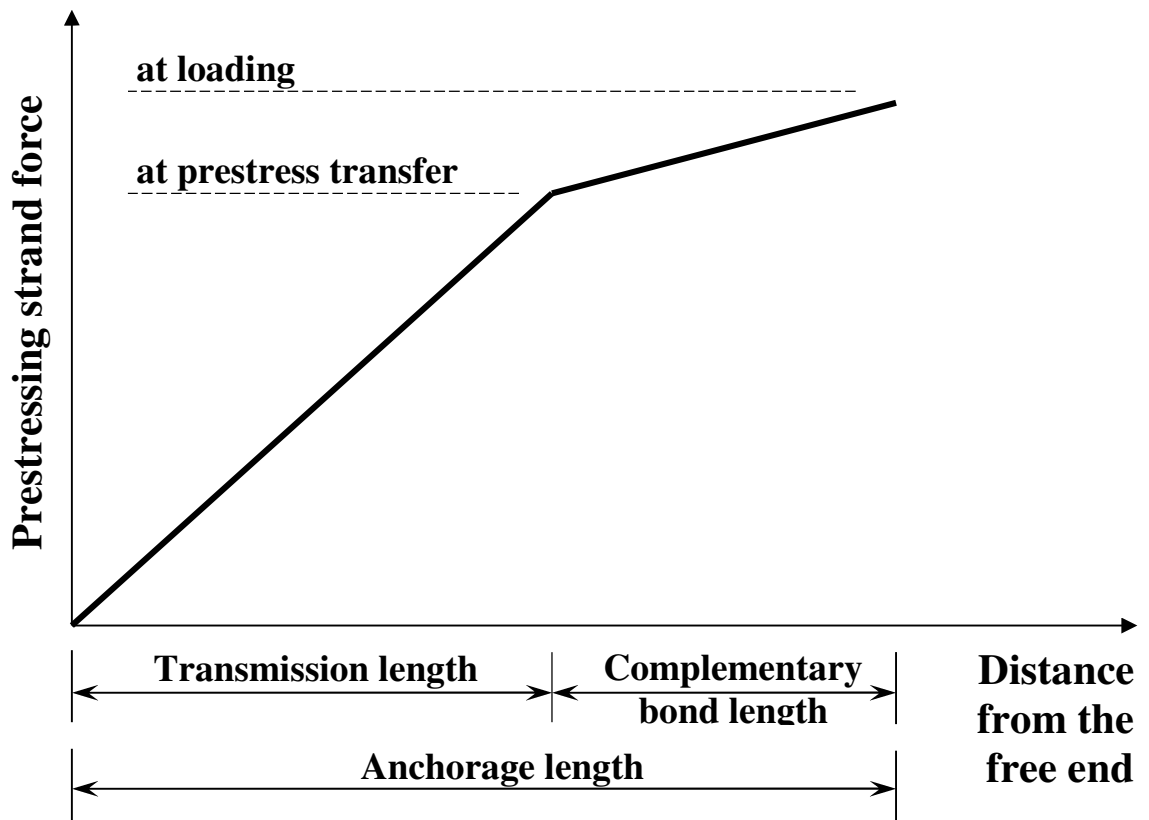
Designation	Transmission length (mm)	Anchorage length (mm)	Complementary bond length (mm)
C-350-0.50	550	650	100
C-350-0.45	550	700	150
C-350-0.40	550	700	150
C-400-0.50	650	850	200
C-400-0.45	550	700	150
C-400-0.40	550	700	150
C-400-0.35	500	600	100
C-450-0.40	550	700	150
C-450-0.35	500	650	150
C-500-0.40	600	800	200
C-500-0.35	450	600	150
C-500-0.30	400	600	200

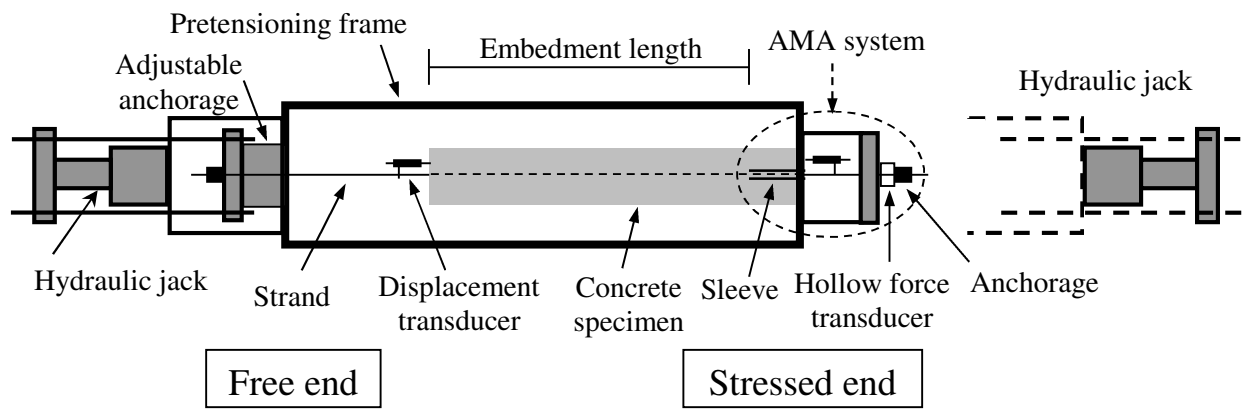
Table 3

Summary of predicted/measured ratios from comparisons of test results and equations

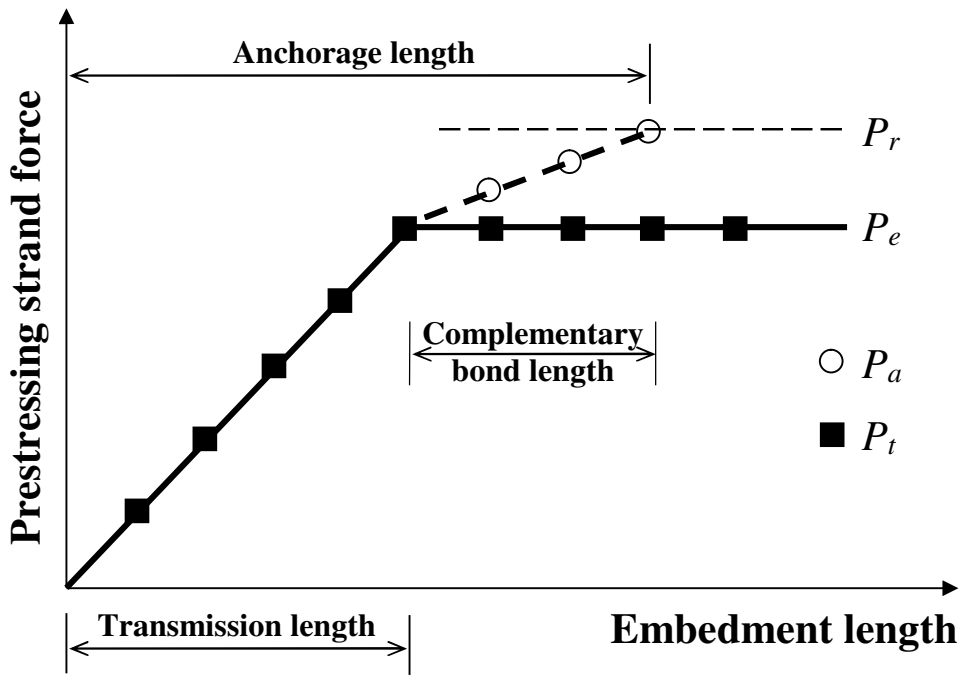
Equation source		Experimental data source								All data		% points into the defined rectangles
		Russell and Burns (1996) [41]		Rose and Russell (1997) [42]		Oh and Kim (2000) [43]		Test results				
		Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.			
Eq. (1) [12]	$\alpha = 2$	2.41	0.33	1.25	0.16	1.97	0.14	1.92	0.25	1.18	0.30	63.7
	$\alpha = 2.44$	1.98	0.27	1.02	0.13	1.62	0.11	1.57	0.21	0.96	0.25	63.7
	$\alpha = 3$	1.61	0.22	0.83	0.11	1.31	0.09	1.28	0.17	0.78	0.20	63.7
Eq. (2) [4]		2.01	0.35	0.31	0.09	1.35	0.23	0.96	0.15	0.59	0.26	69.8
Eq. (3) [20]		1.87	0.25	0.63	0.11	1.44	0.14	1.26	0.17	0.76	0.24	65.1
Eq. (4) [4]		1.84	0.34	1.90	0.29	1.59	0.12	1.82	0.25	1.19	0.32	68.4
Eq. (5) [21]		1.83	0.27	0.48	0.11	1.27	0.17	1.05	0.16	0.64	0.22	71.2
Eq. (6) proposed		1.56	0.29	1.63	0.25	1.39	0.10	0.98	0.19	0.98	0.26	71.2

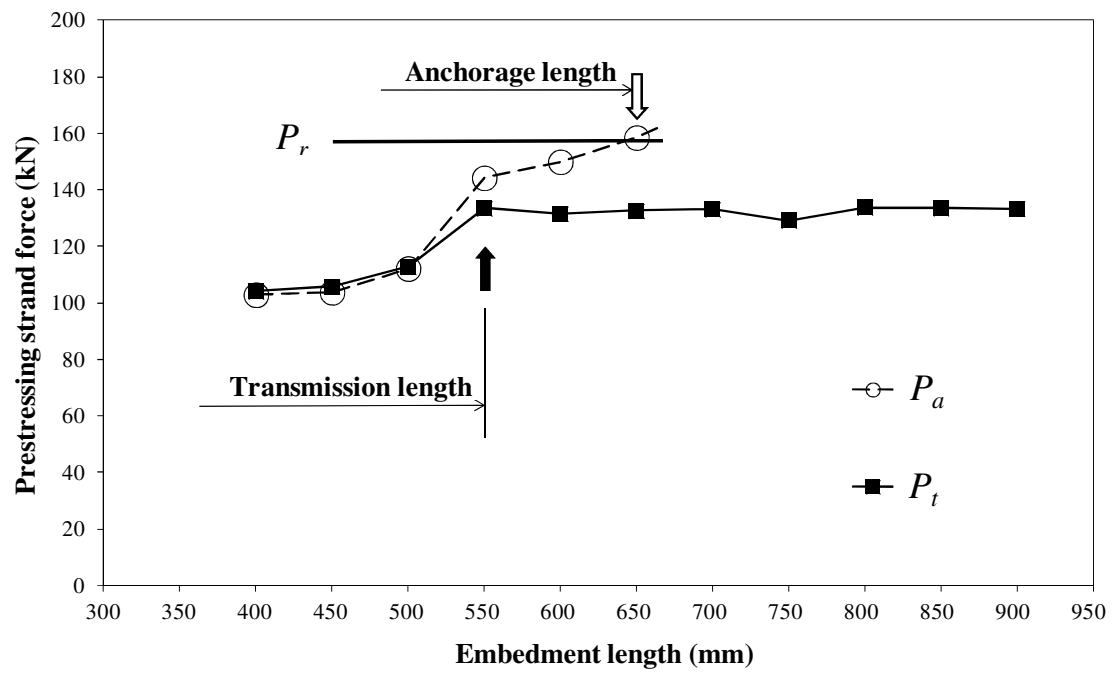
Note: S.D. is standard deviation

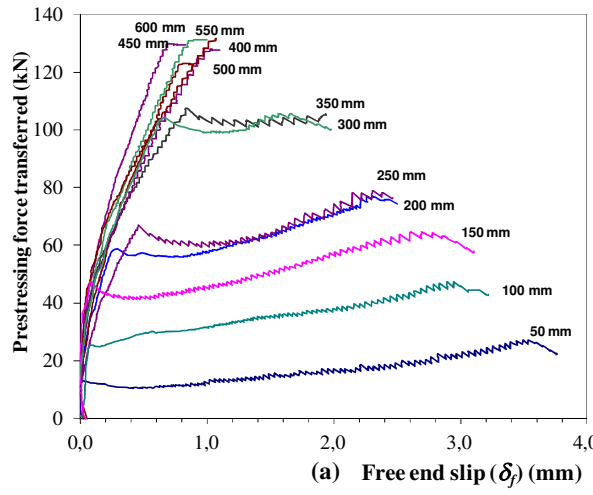




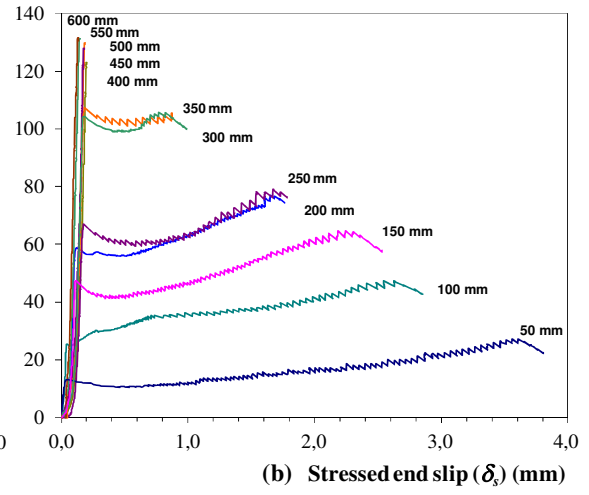




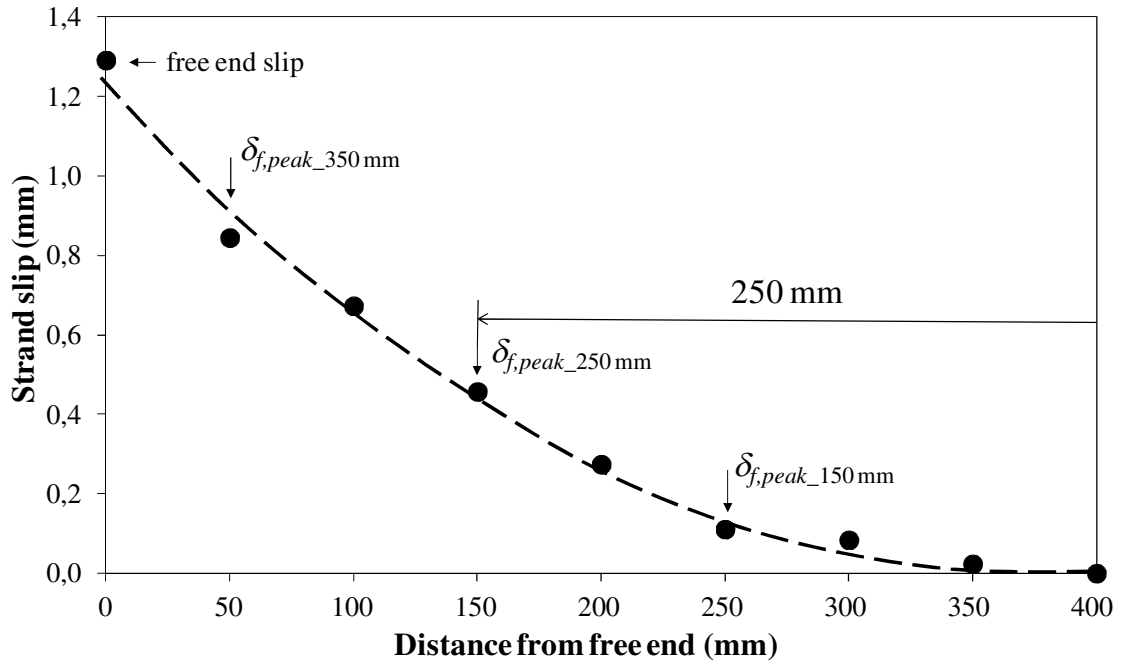


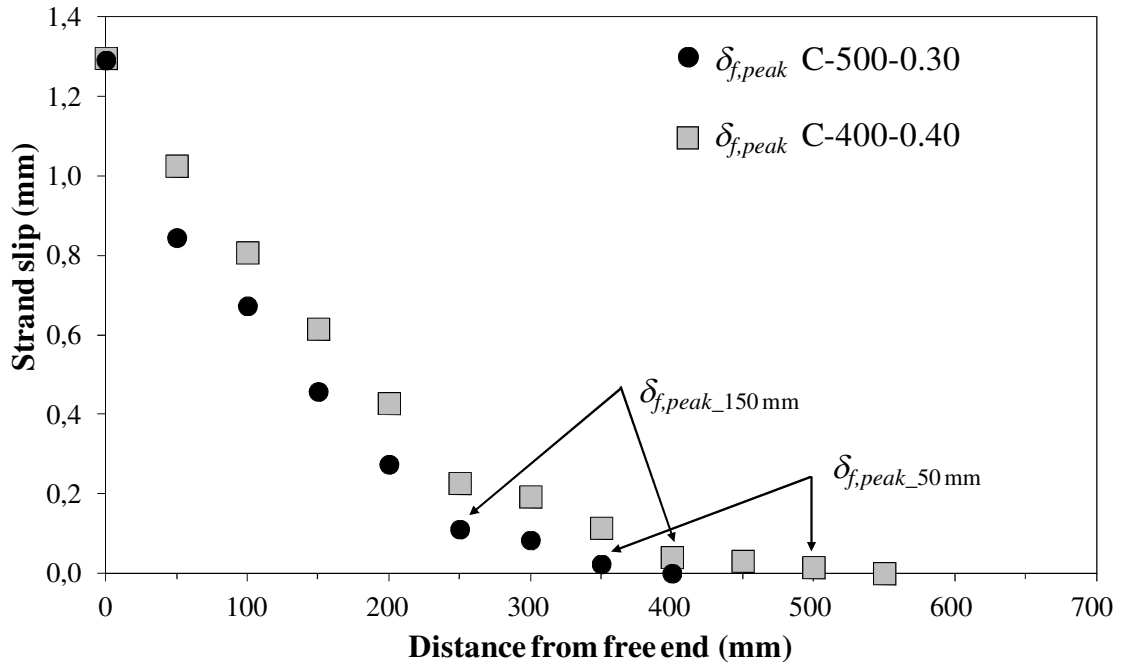


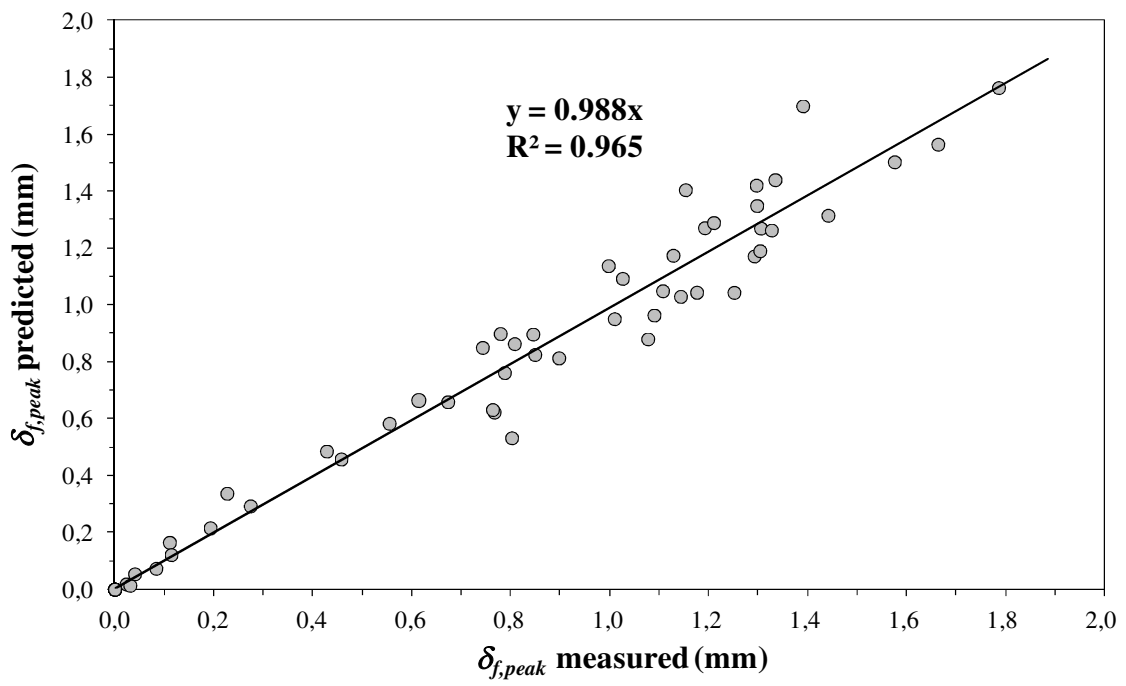
(a) Free end slip (δ_f) (mm)

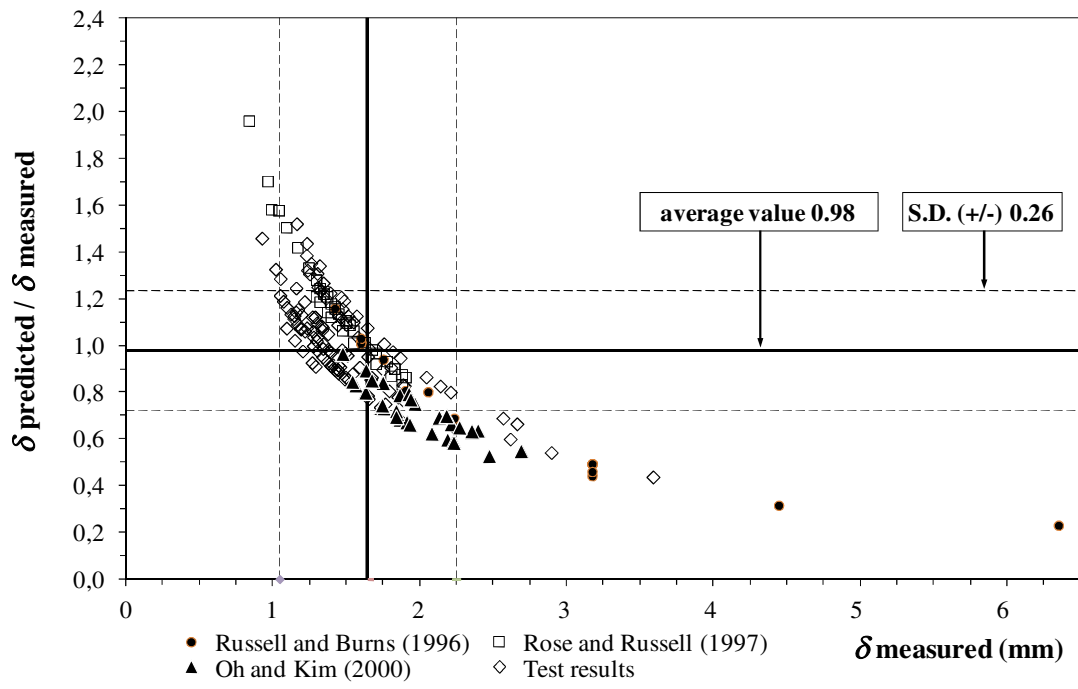


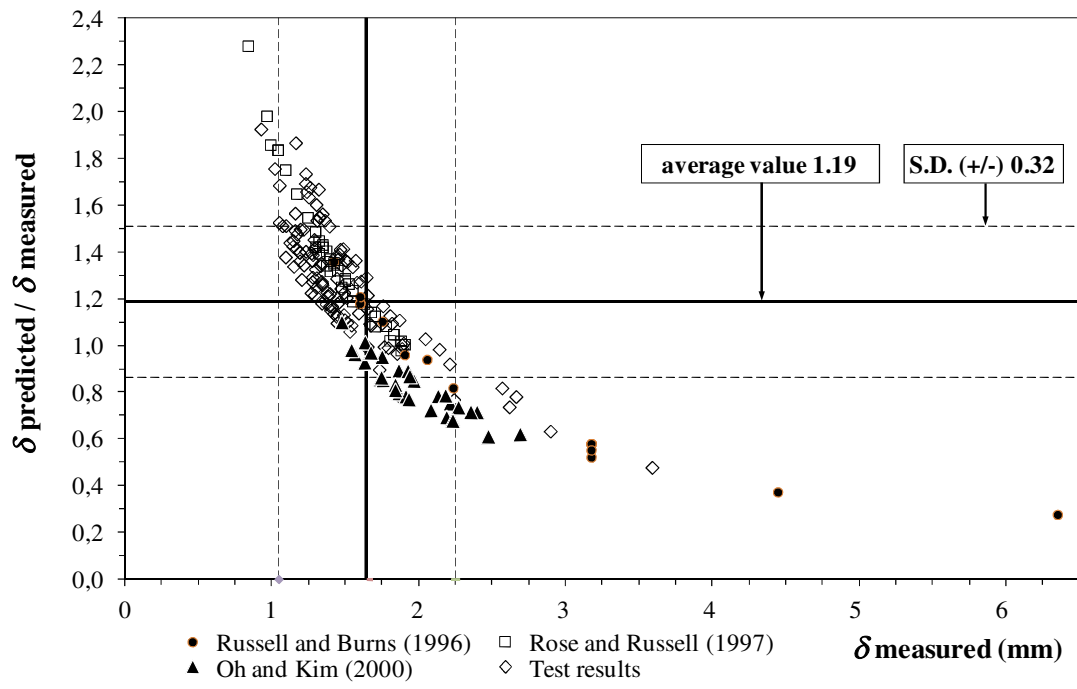
(b) Stressed end slip (δ_s) (mm)

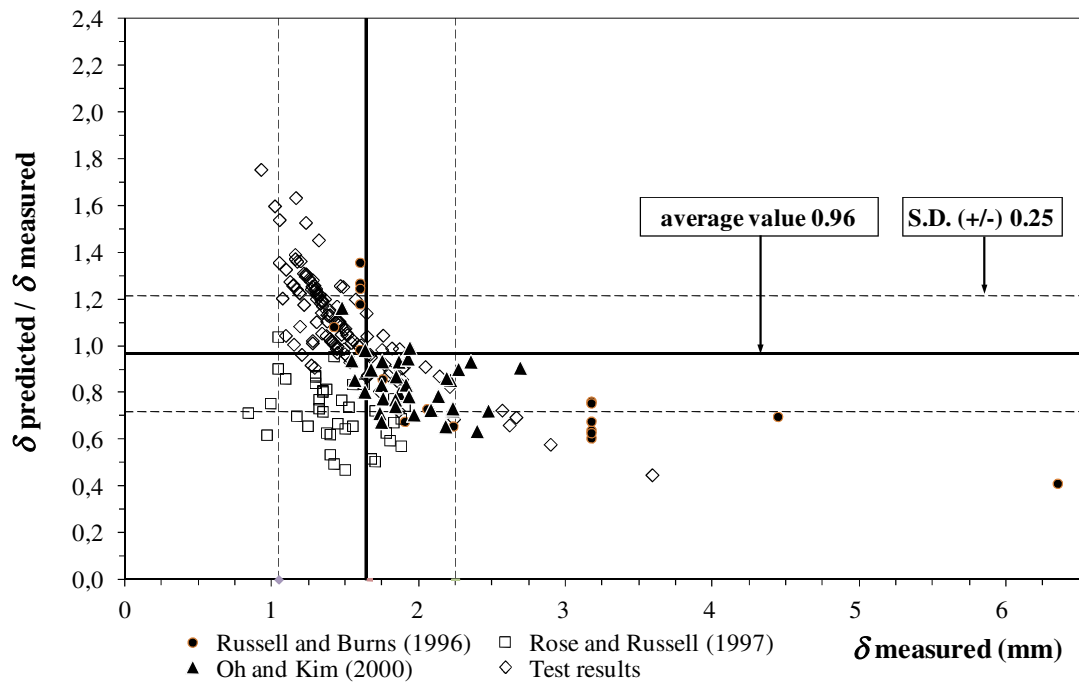


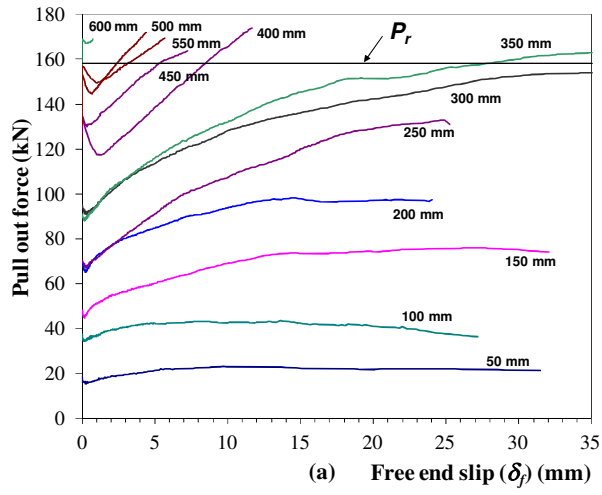




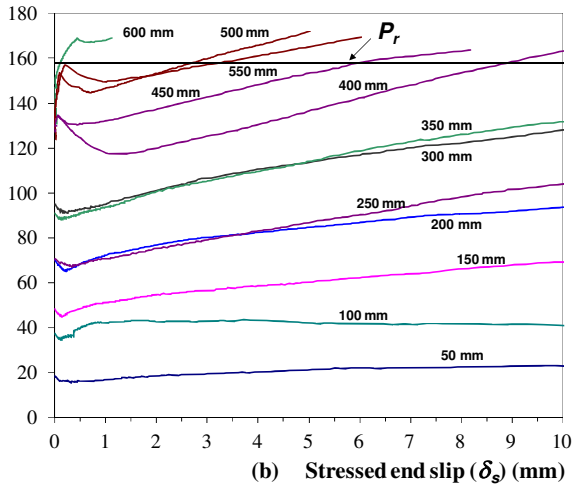








(a) Free end slip (δ_f) (mm)



(b) Stressed end slip (δ_s) (mm)

