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

3 Abbreviated title: Measuring in pretensioned concrete

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11

12 **Abstract:**

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

26 **Keywords:**

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

28

29 **1. Introduction**

30

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

39

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

50

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

54

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

62

63 The relative displacements of the prestressing reinforcement into the concrete –slips– are also
64 parameters related with the bond phenomenon [3,10-13]. These slips accumulate at the free
65 end of the member at prestress transfer and can be measured and related to the L_T [14-16], but
66 no condition regarding reinforcement slips is addressed for L_D in the main design codes
67 [9,17,18]. For this reason, anchorage length definition can be based on two modes [19]:
68 anchorage length –without slip– (L_A) and anchorage length with slip (L_S), that is, without and
69 with slips at the free end of the member during the loading stage, respectively.

70

71 On the other hand, L_T depends on the concrete modulus of elasticity –among other factors
72 [20,21]. Prestress loss due to elastic concrete shortening occurs at prestress transfer. Beyond
73 L_T , the prestressing reinforcement force is the effective prestressing force which is determined
74 by strain compatibility between the prestressing reinforcement and concrete.

75

76

77 It is worth noting that, for bonded applications, quality assurance procedures should be used
78 to confirm that the prestressing reinforcement is capable of adequate bond [9]. However there
79 are not minimum requirements for bond performance of prestressing reinforcement in [9]
80 neither in [22,23]. Besides, there is no consensus on a standard test method for bond quality
81 [8]. Methodological aspects are still being studied [24], in addition to the development of new
82 sensors [25] and techniques [26].

83

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

88

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

93

94 The purpose of this paper is to describe the development of a testing technique which allows
95 the simultaneous measurement of the main specific parameters related with the bond
96 phenomena and prestress losses concerning pretensioned concrete members. Particularly as
97 exposed in section 2, the testing technique includes measurement of prestressing
98 reinforcement force, prestressing reinforcement slips, and longitudinal concrete surface
99 strains. Directly or by means a back-calculation from the test results as described in section 3,
100 the tests provide data on prestressing force, transmission length (initial and long-term),

101 anchorage length (without and with slip), bond stresses, prestressing reinforcement slips (free
102 end slip, slips sequences and slips distribution), longitudinal concrete strains, concrete
103 modulus of elasticity at prestress transfer, and prestress losses (instantaneous and time-
104 dependent). By way of example, some experimental results obtained in several studies –
105 conducted at the Institute of Concrete Science and Technology (ICITECH) at Universitat
106 Politècnica de València (Spain)– are shown in section 4.

107

108 **2. Testing technique**

109

110 **2.1. Overview**

111

112 An experimental methodology based exclusively on the measurement of the prestressing
113 reinforcement force was conceived: the ECADA¹ test method [31]. This test method was
114 initially addressed to determine bond lengths [35]. After, a revised version (ECADA+ [36])
115 was developed to measure changes in these lengths through time. Each tested specimen is
116 characterized by means the detensioning (prestress transfer) and the pull-out (loading)
117 operations, which are sequentially performed. The bond lengths are obtained by analyzing
118 series of specimens varying only in embedment length to simulate different cross sections at
119 one end of a pretensioned concrete member. The feasibility of the test method has been
120 verified for a short [37,38] and long-term analyses [39]. The test repeatability has been
121 observed in two modes: (a) when a same effective prestressing force has been measured in
122 specimens with different embedment lengths which are equal to or longer than L_T ; and (b)
123 when identical specimens have been tested.

124

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

125

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

132

133 **2.2. Experimental Set-up**

134

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

138

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

148

149 **2.3. Instrumentation**

150

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

155

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

161

162 The instrumentation devices used in the studies conducted at ICITECH laboratories are:
163 pressure sensor Druck PDCR 4000 350 bar (accuracy $\pm 0.08\%$), force transducers HBM C6A
164 500 kN (sensitivity 2 mV/V, accuracy class 0.5), linear displacement sensors Penny Giles
165 SLS190/50/2K/L/50/01 (typical linearity 0.15%), micrometers Käfer 0-5 mm Ø58 (accuracy
166 $\pm 1 \mu\text{m}$), and mechanical strain gauges (DEMEC points) spaced at 50 mm intervals with an
167 extensometer Mayes Instruments 100 mm base length (accuracy $\pm 5 \mu\text{m}$).

168

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

171

172 **2.4 Specimen test procedure**

173

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

179

180 I) Tensioning

- 181 1. Lining up the prestressing reinforcement in the pretensioning frame with both anchorage
182 devices at their ends (Fig. 3a).
- 183 2. Tensioning of the prestressing reinforcement by using the hydraulic actuator (Fig. 3b).
- 184 3. Acting on the prestressing reinforcement to avoid relaxation losses².
- 185 4. Anchoring provisional of the prestressing reinforcement by unscrewing the end-
186 adjustable anchorage to mechanically block the hydraulic actuator (Fig. 3c).

187

188 II) Casting the concrete specimen

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

193

194 III) Preparing

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

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

198 3. Releasing the provisional anchorage: the hydraulic actuator recovers the actual
199 prestressing reinforcement force (P_0 , just before prestress transfer), and the end-
200 adjustable anchorage is relieved and withdrawn by screwing (Fig. 3e).

201 4. Placing the displacement transducers at both ends of the specimen –at the free end and
202 into the AMA system– (Fig. 3f).

203 5. (LS) Reading the initial set of distances between gauge points.

204

205 IV) Transferring the prestress

206 1. Detensioning: the hydraulic actuator is gradually unloaded and the prestressing
207 reinforcement movement from the free end is produced by push-in. The prestressing force
208 is transferred to the concrete, and the pretensioned concrete specimen is supported by the
209 AMA system (Fig. 3g).

210 2. Stabilization period. The action between the pretensioned concrete specimen and the
211 AMA system requires a stabilization period to guarantee the prestressing force
212 measurement.

213 3. Measuring:

214 i. the prestressing reinforcement force achieved (P_{Ti}) in the AMA system.

215 ii. the prestressing reinforcement slips at both ends.

216 iii. (LS) the actual set of distances between gauge points.

217

218 V) Storing (only for analysis through time)

219 1. Demounting the pretensioned concrete specimen with its coupled AMA system from the
220 pretensioning frame (Fig. 3h).

221 2. Storing the demounted specimen under controlled conservation conditions (Fig. 3i).

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

228

229 VI) Loading

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

239

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

244

245 3. Determination of specific parameters

246

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

252

253 **3.1 Bond lengths**

254

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

259

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

264

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

270

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

273

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

278

279 **3.2 Effective prestressing force**

280

281 The effective prestressing force is directly determined from the P_{Ti} and P_{Tj} values (see section
282 3.1). Besides, it can be obtained according to Eq. (1) from the prestressing reinforcement
283 strain change ($\Delta\varepsilon_p$) beyond L_T accounted for just before prestress transfer until time j . This
284 change is equal to the concrete strain change ($\Delta\varepsilon_c$) obtained at testing steps IV.3.iii (only
285 prestress losses due to elastic concrete shortening are included) or V.4.iii (time-dependent
286 prestress losses are also included). In Eq. (1), E_p and A_p are the modulus of elasticity and the
287 area of the prestressing reinforcement, respectively, and the term $\Delta\varepsilon_p \cdot E_p \cdot A_p$ corresponds to the
288 total prestress losses accounted for until time j .

$$289 \quad P_{Ej} = P_0 - \Delta\varepsilon_p \cdot E_p \cdot A_p \quad (1)$$

290

291 **3.3 Bond stresses**

292

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

296
$$U_x = \frac{P_x}{\Pi_p L_x} \quad (2)$$

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

300

301 **3.4 Prestressing reinforcement slips**

302

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

306

307 a) Free end slip

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

309
$$L_T = \alpha \frac{\delta E_p}{f_{pi}} \quad (3)$$

310 where α represents the shape factor of the bond stress distribution ($\alpha = 2$ for uniform and $\alpha =$
311 3 for linear descending; a 2.8 value is established in several standards [41-43]), E_p is the
312 modulus of elasticity of the prestressing reinforcement and f_{pi} is the prestressing
313 reinforcement stress immediately before release. In is worth noting that Eq. (3) is only
314 applicable if the embedment length is equal to or longer than L_T .

315

316 b) Slips sequences

317 At prestress transfer, and according to the compatibility of strains condition between the
318 prestressing reinforcement and concrete, slips do not occur beyond L_T . In this way, L_T (for
319 both initial and long-term cases) is suitable to be determined from series of specimens by

320 plotting the measured prestressing reinforcement slips –at one end at prestress transfer– vs.
321 specimen embedment length. In these cases, the curves are expected to present a descendent
322 branch followed by a horizontal branch. Again, L_T can be determined as the embedment
323 length of the specimen that marks the beginning of the horizontal branch.

324

325 c) Slips distribution along transmission and anchorage lengths

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

331

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

336

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

340

341 **3.5. Longitudinal concrete strains**

342

343 Longitudinal concrete strains can be obtained from the changes in distances between gauge
344 points before and after prestress transfer (testing steps IV.3.iii or V.4.iii) by dividing them by

345 gauge length. In correspondence with P_{Ti} values, a profile with an ascendent branch, followed
 346 by a practically horizontal branch, is depicted when these strains are plotted according to
 347 embedment length (Fig. 5). Concrete strains increase through time due to concrete creep and
 348 shrinkage, and this causes decreases –time-dependent prestress losses– in prestressing
 349 reinforcement force (P_{Tj} values). An approximate L_T value can be obtained from this profile
 350 directly as the distance from the free end to the beginning of the horizontal branch (Fig. 5) or
 351 by applying some adjustments [3]. In addition, prestress losses can be determined from the
 352 constant strain plateau (see section 3.2).

353

354 **3.6 Concrete modulus of elasticity at prestress transfer**

355

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

361

$$362 \quad E_{ci} = \frac{\frac{P_0}{A_c} - E_p A_p}{\Delta\varepsilon_{ci}} \quad (4)$$

363

364

365 **3.7. Prestress losses**

366

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

370

371 **4. Applications**

372

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

380

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

387

388 **4.1 Analyses from prestressing reinforcement forces**

389

390 Fig. 7 shows the prestressing reinforcement forces for series of specimens A. As it can be
391 observed with increasing embedment length, the prestressing force transferred (P_{Ti}) increases
392 until an effective prestressing force (P_E) of 132.5 kN which is achieved for the transmission
393 length ($L_T = 550$ mm). The P_A forces increase from P_E until the reference force ($P_R = 158$ kN)
394 when the embedment length increases from L_T to the anchorage length ($L_A = 650$ mm). For

395 specimens with embedment length shorter than L_T , P_A coincides with the corresponding P_{Tj}
396 which is in agreement with the Stress Waves Theory [1,44]. As expected, the P_S forces are
397 greater than the P_A forces, and a shorter anchorage length –with slip– results ($L_S = 500$ mm).
398 Generally, determining the bond lengths requires 6 to 12 specimens with different embedment
399 lengths with a testing increment of 50 mm.

400

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

406

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

411

412 Regarding the long-term behavior, Fig. 8 depicts the results for series of specimens B after 6
413 months. The time-dependent behavior shows changes in the effective prestressing force (from
414 $P_E = 132.5$ kN to $P_{Ej} = 119.5$ kN) and also in L_T : the P_{Tj} value is smaller for the first specimen
415 after 6 months, and greater and similar P_{Tj} values are measured in the remaining longer test
416 specimens, that is, there is change in the embedment length that marks the beginning of the
417 horizontal branch. Therefore for this series and time interval, L_T varies from 500 to 550 mm
418 and time-dependent prestress losses about 13 kN are measured. In a general case, this process

419 may be done with other specimens by following the embedment length sequence, and also
420 cases with no changes in L_T through time exist.

421

422 **4.2 Analyses from prestressing reinforcement slips**

423

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

436

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

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

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

446

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

451

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

459

460 **4.3 Analyses from longitudinal concrete strains**

461

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

466

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

470

471 An average concrete strain $\Delta\varepsilon_{ci} = 0.00071$ result in the plateau at prestress transfer. By using
472 Eq. (4), with a specimen gross cross-sectional area (A_g) of $100 \times 100 \text{ mm}^2$ ($A_c = A_g - A_p$), $P_0 =$
473 143 kN and $E_p = 203.35 \text{ GPa}$, the concrete modulus of elasticity at prestress transfer (E_{ci}) is
474 18.23 GPa .

475

476 Regarding prestress losses, they can be obtained as $\Delta\varepsilon_p \cdot E_p \cdot A_p$ (see Eq. (1)). For instantaneous
477 prestress losses, $\Delta\varepsilon_p = \Delta\varepsilon_{ci} = 0.00071$ and it results 14.9 kN . Time-dependent losses and total
478 prestress losses can be obtained from subsequent profiles. For a 12 months interval, time-
479 dependent prestress losses are obtained from $\Delta\varepsilon_p = \Delta\varepsilon_{c,12} - \Delta\varepsilon_{ci}$, resulting in 25.4 kN ($\Delta\varepsilon_{c,12}$
480 $= 0.00192$); and total prestress losses are obtained from $\Delta\varepsilon_p = \Delta\varepsilon_{c,12}$, resulting in 40.3 kN
481 (also as $14.9 + 25.4 = 40.3 \text{ kN}$).

482

483 **5. Conclusions**

484

485 In this study, a testing technique to measure simultaneously prestressing reinforcement forces
486 and slips and concrete strains in pretensioned concrete specimens has been developed. The
487 testing technique reproduces sequentially the prestress transfer and loading stages and
488 simulates the behavior at one end of a member. From the test results, directly or by means
489 back-calculations using theory of mechanics concepts, several specific parameters concerning
490 pretensioned concrete members can be determined. This testing technique allows obtain
491 additional knowledge about bond behavior of prestressing reinforcement and prestress losses

492 for a better determination of transmission and anchorage lengths and the available
493 prestressing force at different cross-sections of a pretensioned concrete member. Regarding
494 both initial and long-term behavior, the testing technique shows satisfactory experimental
495 results. In this way, the testing technique possess good qualities for application to the precast
496 concrete industry: pretensioned concrete members can be characterized for design, production
497 process and quality control.

498

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500

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508

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510

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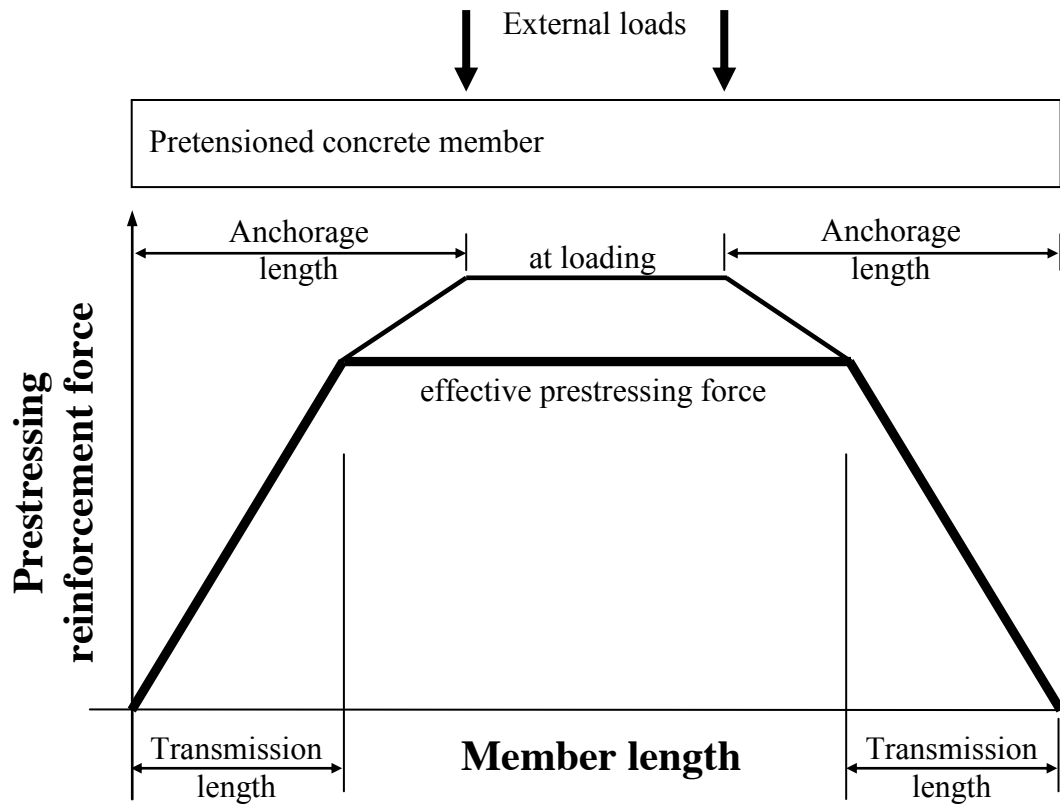
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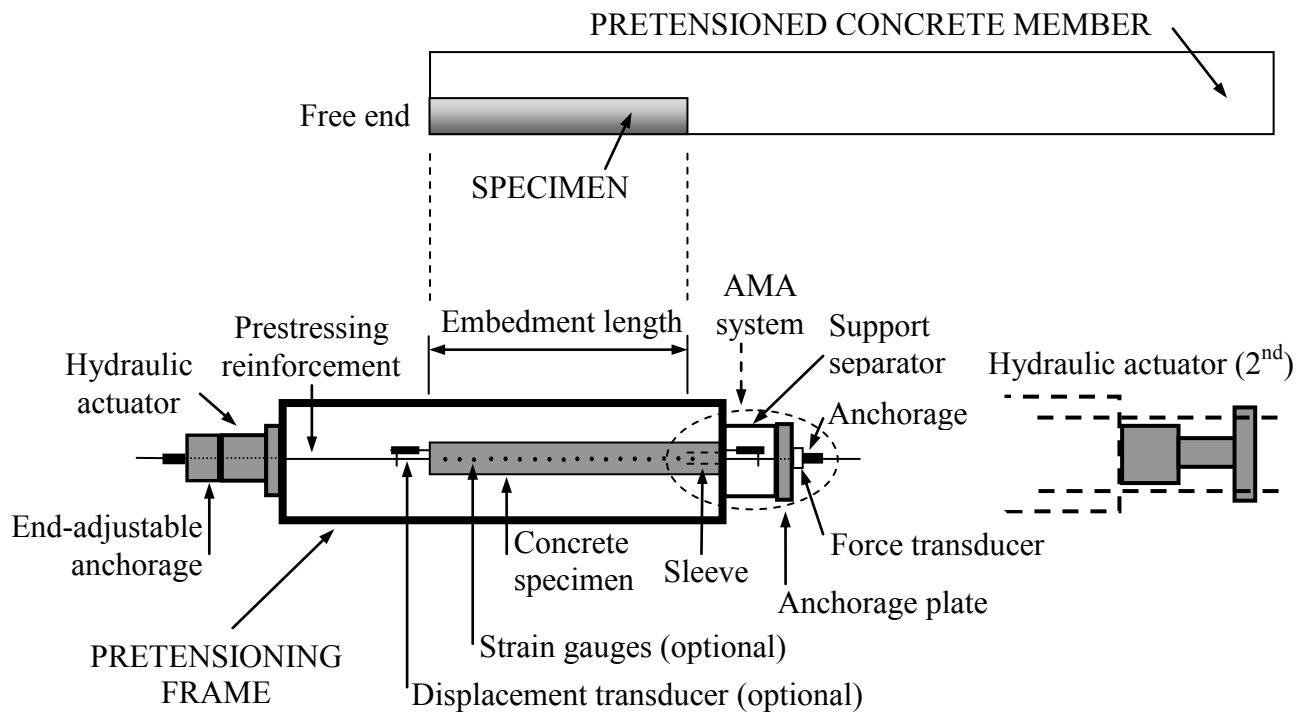
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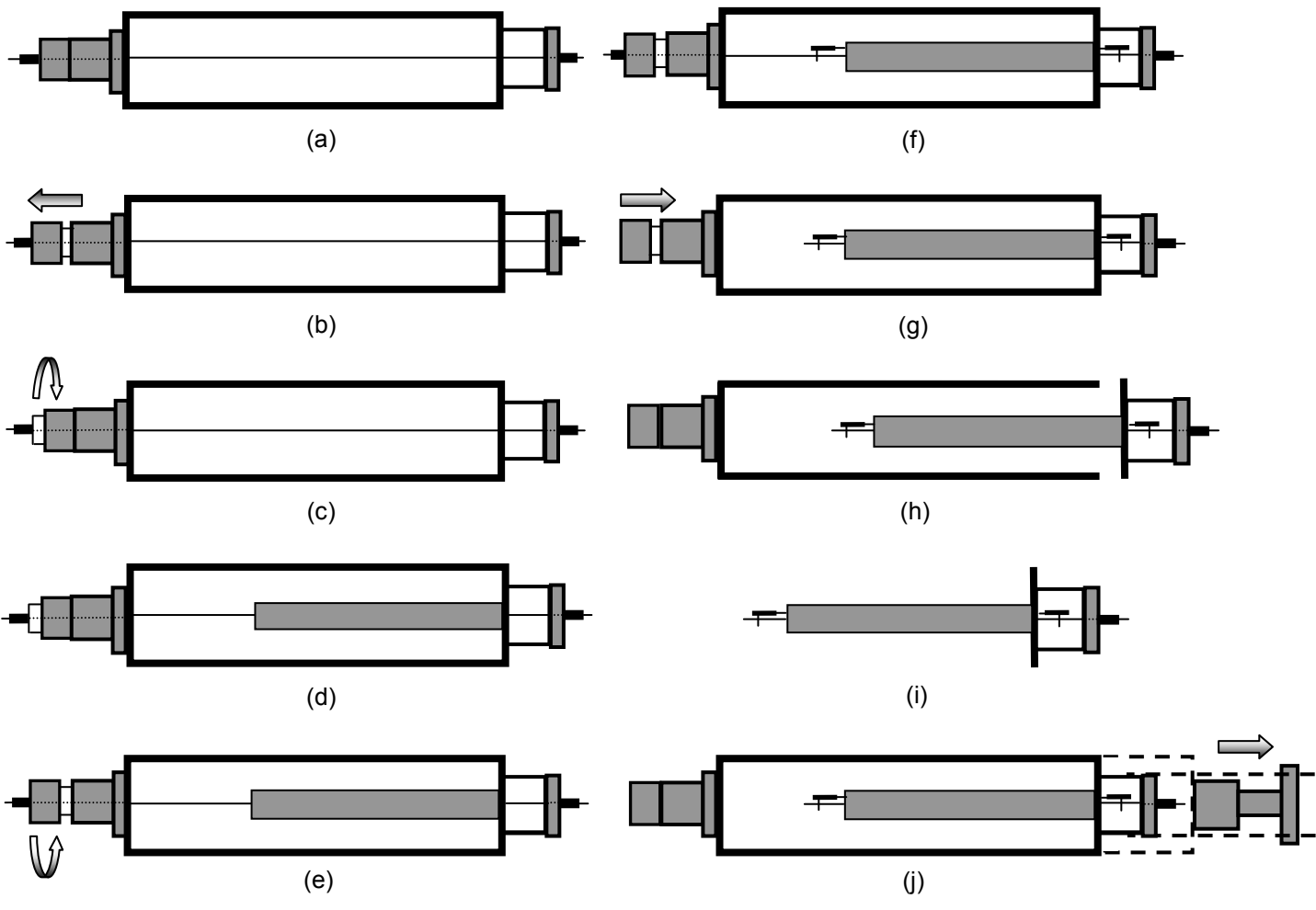
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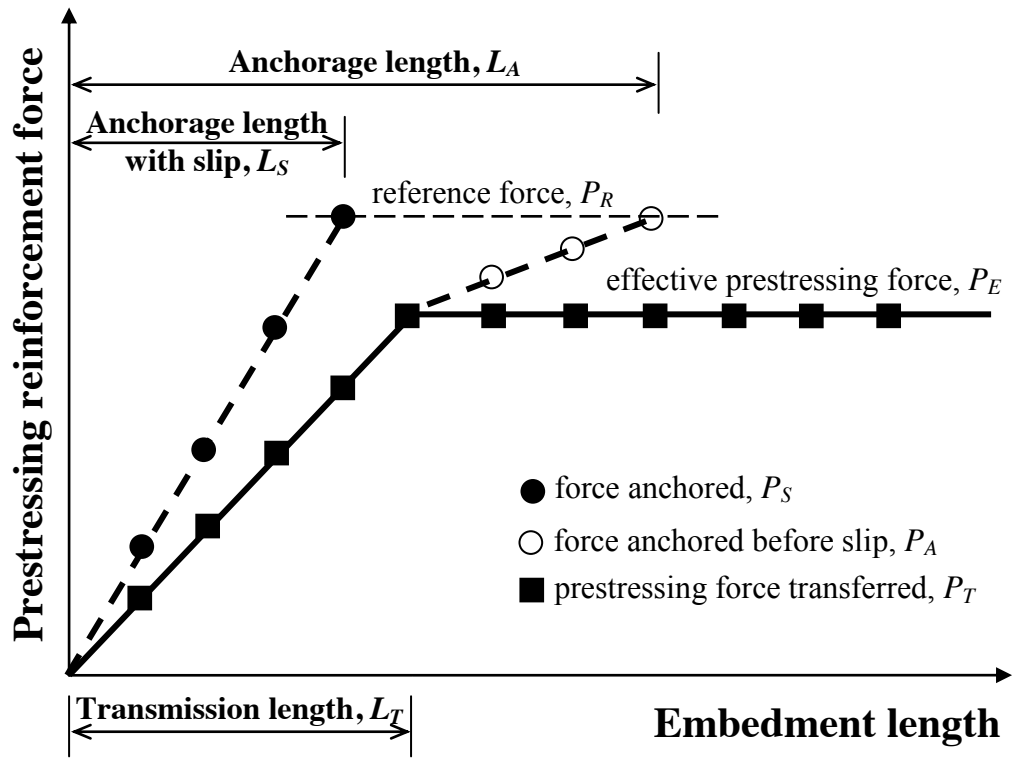
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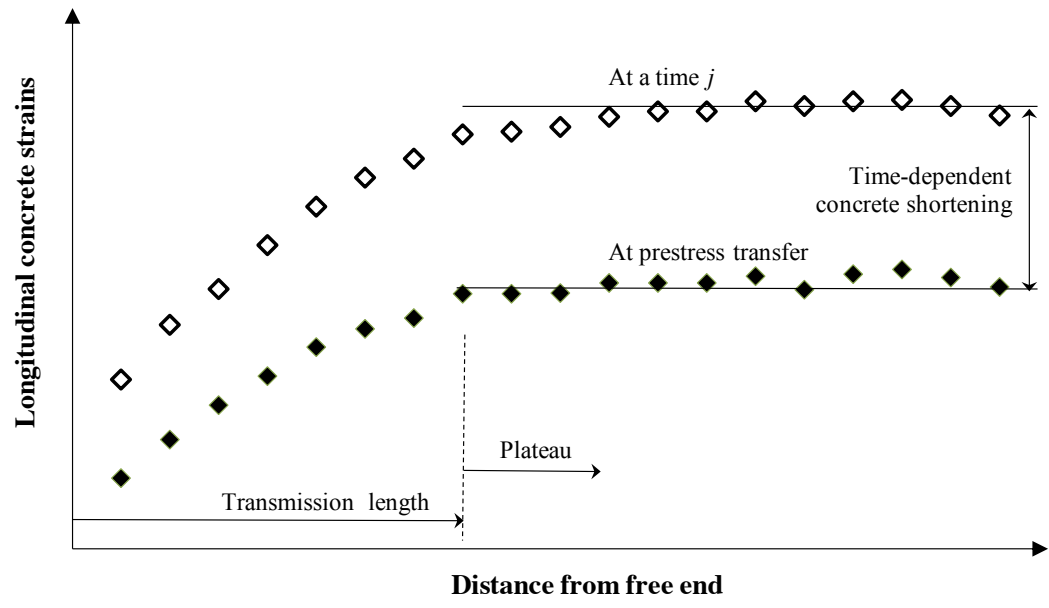
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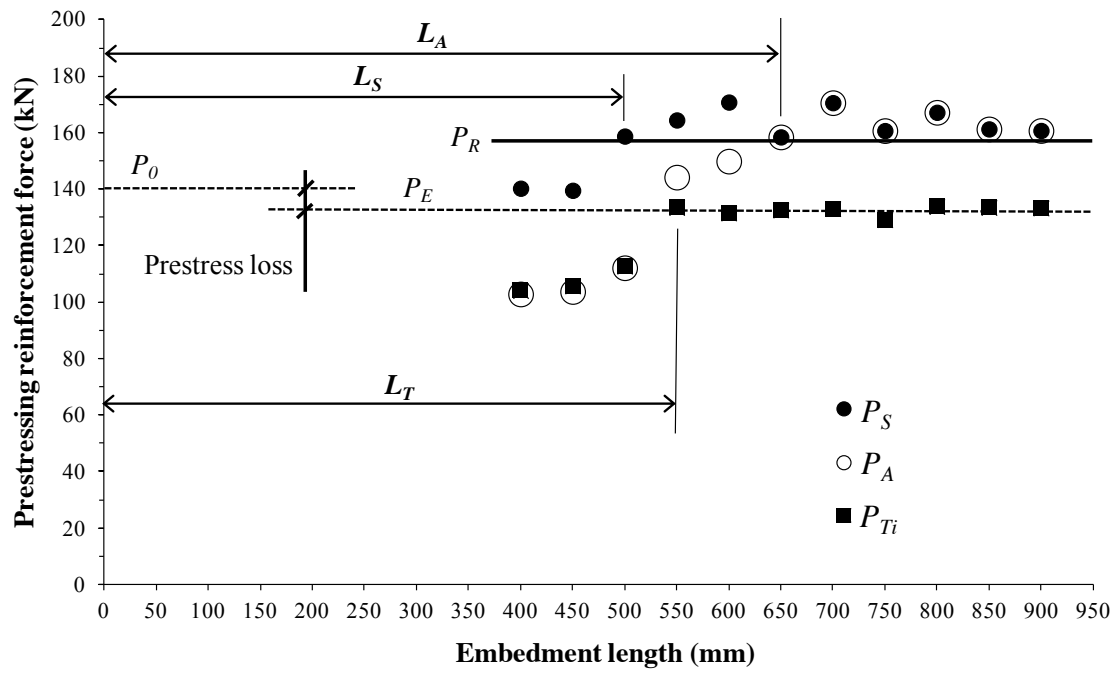


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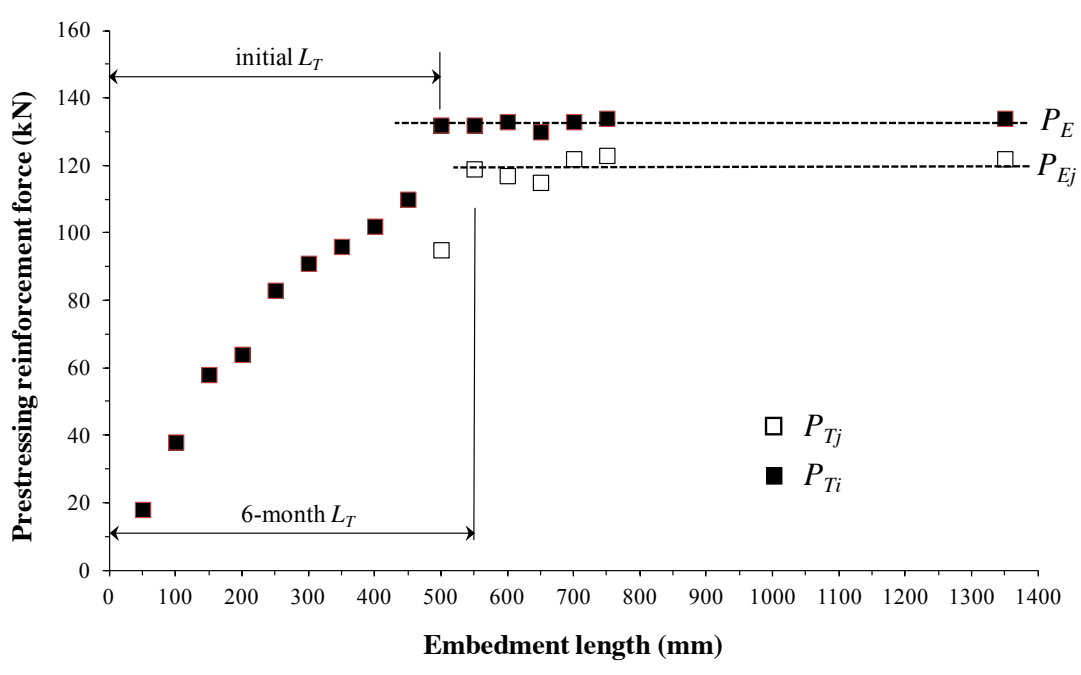


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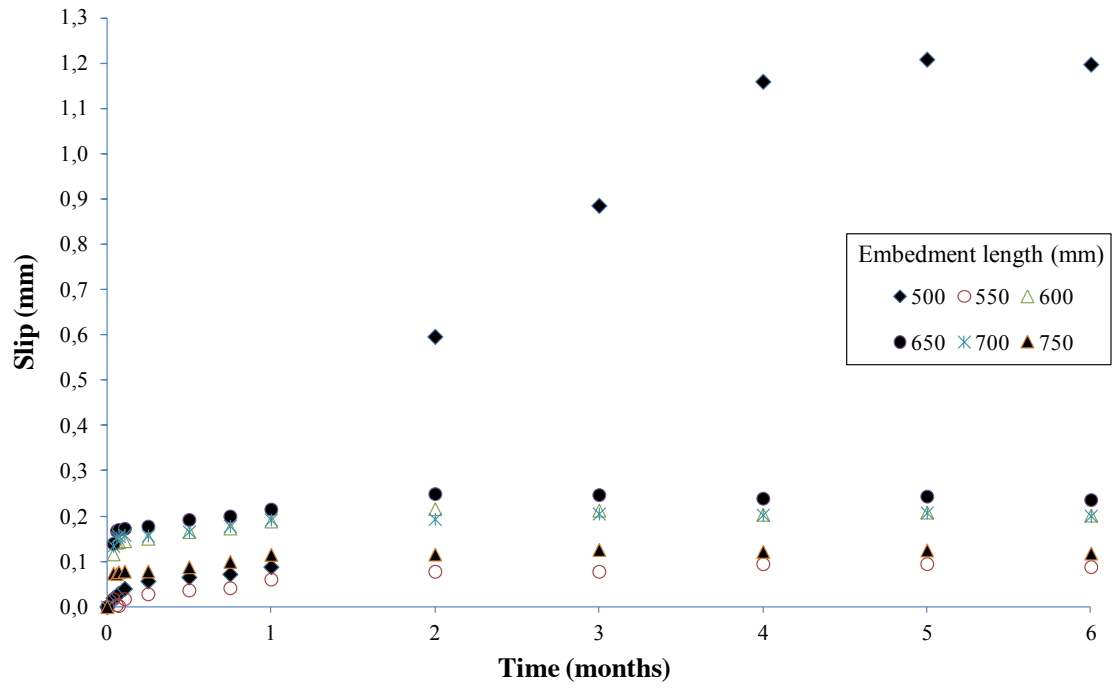
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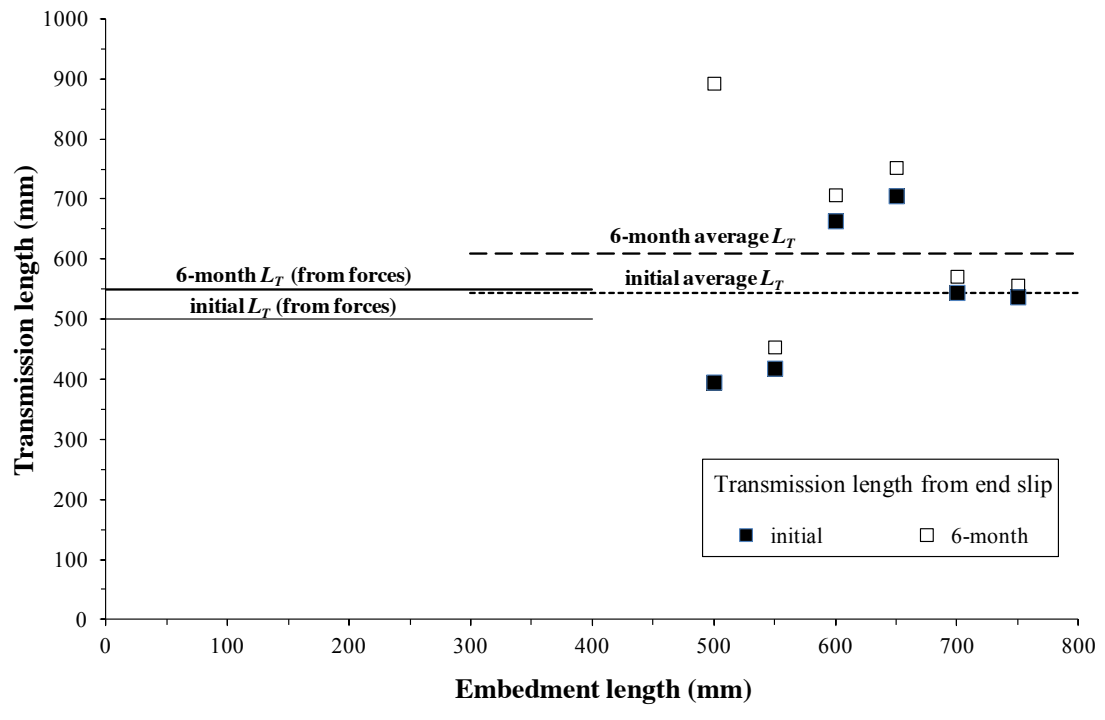
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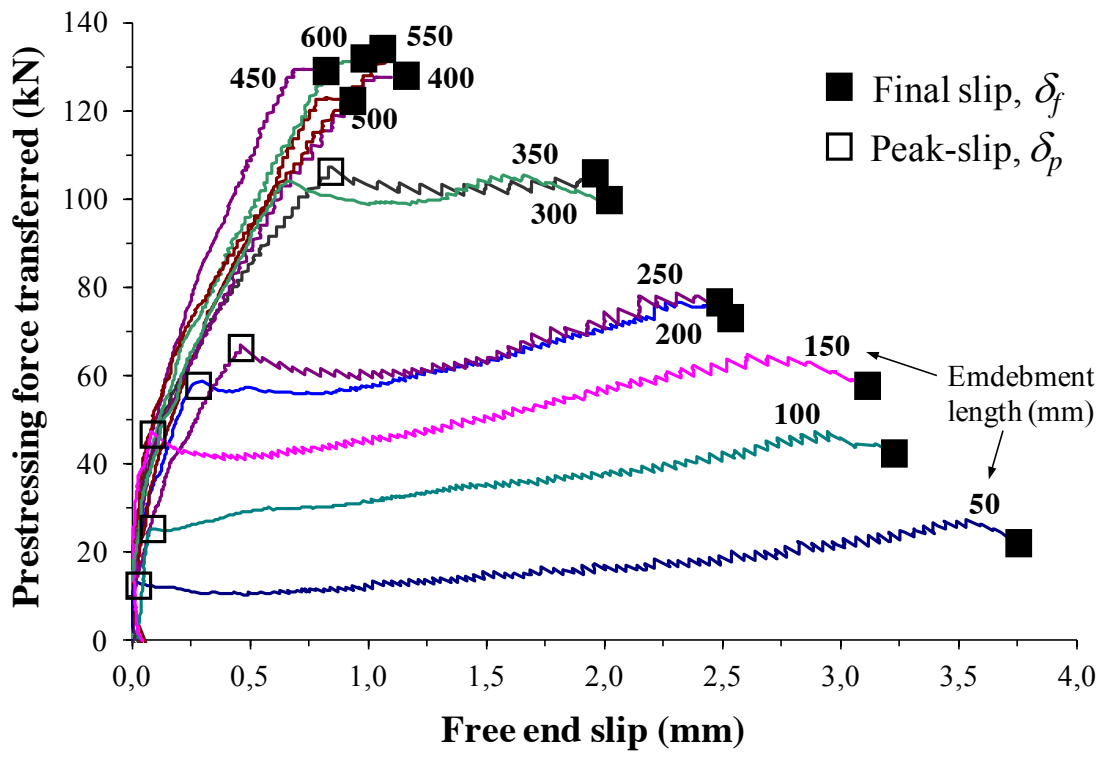
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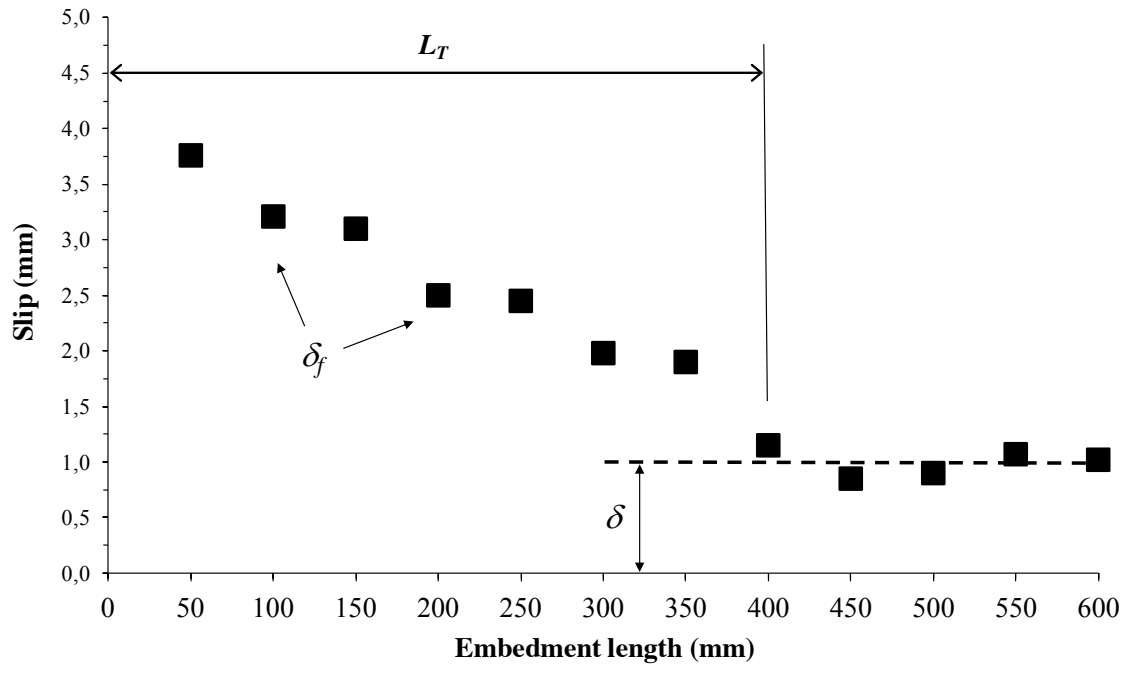
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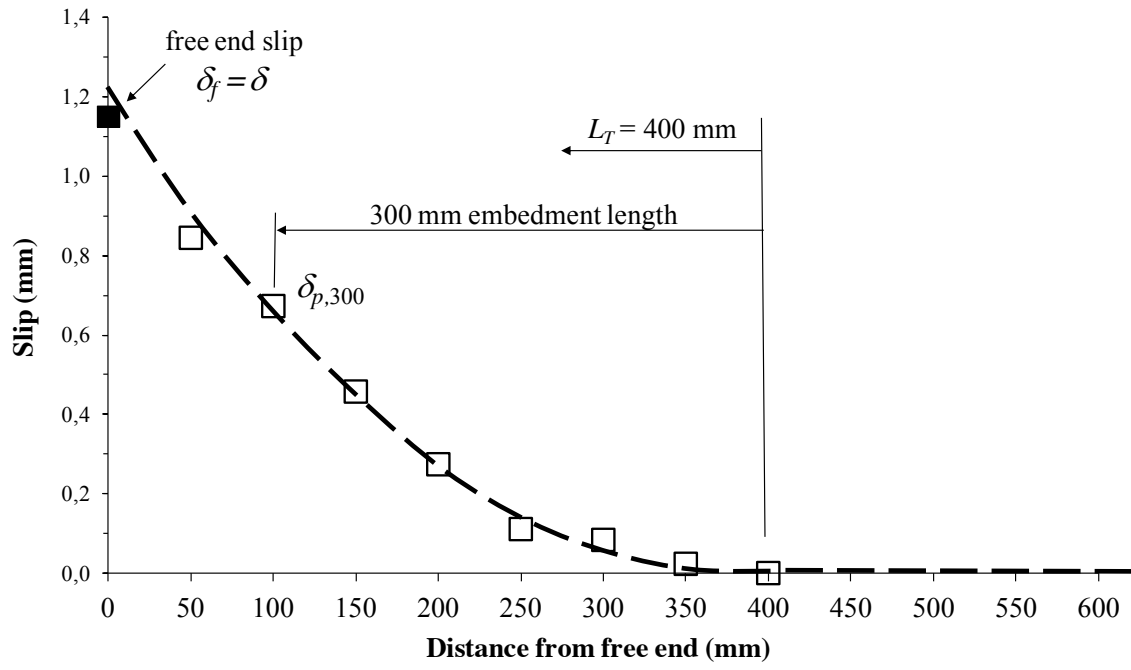
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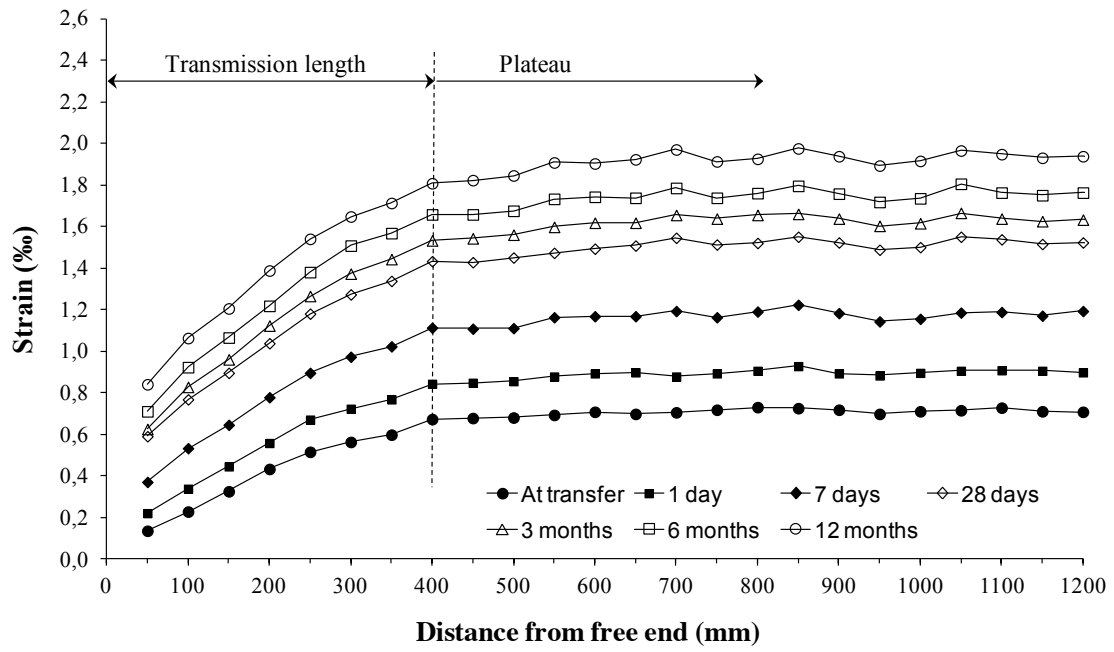


Table 1

Specimens used for example data sets

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

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