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Experimental Study to Implement the Saw-Cut Technique in Post-tensioned Concrete Beams under Laboratory Conditions

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Abstract **-** Post-tensioning is a common procedure used for prestressing a concrete member through reinforcement. The prestressing reinforcement is stressed after concrete casting, and the prestressing force is introduced by anchor heads at the member ends. Main codes provide specifications and requirements for design of post-tensioned concrete members (PCMs), so the designer set the initial prestressing force and must estimate the prestress losses along the service life of the member. Upon service loads. if prestress losses are underestimated in design, excessive deflections and unexpected cracking can occur, whereas inefficient designs are performed if prestress losses are overestimated. Therefore, an accurate determination of the residual prestressing force is essential within the context of the assessment of PCMs. However, conventional construction practice over the years has been carried out without the use of devices to track the evolution of prestress losses from casting, which, in turn, results in an unknown residual prestressing force. Therefore, it is necessary to implement suitable techniques and methods to determining the residual prestressing force in unmonitored PCMs. Hence, this contribution focuses on the development of an experimental study to implement the saw-cut technique to generate notches in post-tensioned concrete beams under laboratory conditions. The rationale of the testing procedure is described, together the main aspects to be considered from a metrological perspective from both electrical and non-electrical extensometry devices. The description of the experimental campaign and the variables considered to produce different stress-strain states, the steps to follow and track the sources of time-dependent prestress losses, and the main results obtained after testing a preliminary series of beams are presented. The advances achieved will serve as basis for a better understanding of the effects of notching by saw cutting and will facilitate further in-situ applications to determine the residual prestressing force in PCMs.

Keywords**:** concrete, prestress, loss, beam, test, notch, saw-cut

1. Introduction

In the case of prestressed concrete through prestressing steel reinforcement, and in post-tensioned concrete members (PCMs) in particular, the prestressing force decreases with time due to both instantaneous and time-dependent sources. The former includes prestress losses due to friction, elastic shortening of the concrete and loss of seat in the anchorage device, whereas the later includes concrete creep and shrinkage and steel relaxation of the reinforcement. As a result, the uniqueness of prestressed concrete structures is particularly relevant, since their tensile-deformational state depends not only on external actions, but also, and notably, on the interaction between the concrete and the active reinforcement responsible for introducing the prestressing force. As Professor Calavera points out with regard to deferred prestress losses, "it is in fact a loss due to a very complex phenomenon of evolution of the reinforcement anchored in a fluid concrete, under a reinforcement tension that in turn decreases with time" [1], and also the Prof. Nawy [2], “An exact determination of the magnitude of these losses –particularly the time-dependent ones– is not feasible, since they depend on a multiplicity of interrelated factors. Empirical methods of estimating losses differ with the different codes of practice …”.

The designer must set the prestressing force and make an estimation of the prestress losses, so that the final value of the prestressing force is equal to or greater than that required for the structure to meet its requirements throughout its service life. Nevertheless, prestress losses are not usually known, and therefore neither is the residual prestressing force, since the usual construction practice to date has not contemplated the incorporation of measuring devices in concrete structures to monitor them over time. So it is noteworthy that there is a great deal of uncertainty when it comes to assessing the extensive stock of existing prestressed concrete structures, as it is increasingly necessary to have information on the condition of the structures: maintenance plans, service life prediction tools, decision-making criteria in the event of extraordinary events, etc., are undoubtedly elements that enhance sustainability in the field of infrastructure management.

Since many existing PCMs were built in the 1960s, the design life will be reached in the near future for a large number of them [3], and a comprehensive assessment from a risk and reliability point of view is required. Recent studies [4-5] carried out on existing prestressed concrete elements report about difficulties in the determination of the prestress losses and the residual prestressing force. Since lots of PCMs have been cast without any kind of instrumentation, the residual prestressing force can only be estimated in an indirect manner. In these cases, additional complexity must be considered in relation to the initial prestress, the materials properties and their evolution and the accounted short- and long-term prestress losses. These difficulties are related to factors including (among others) assumptions about the characteristics of the prestressing system and time-dependent phenomena, as well as the possible development of degradation processes. Uncertainties associated with prestressing have on occasion led several prestressed concrete bridges to structural collapse. Consequently, and as stated in the Strategic Plan 2020-2023 of the World Road Association (PIARC) [6], the scientific method and state-of-the-art knowledge for the assessment of existing structures should be promoted.

Therefore, and as a previous step to establish the criteria to be followed in a subsequent experimental program, a preliminary series of post-tensioned concrete beams have been tested with the aim of implement the saw-cut technique as a non-destructive method to obtain representative results to be related with the residual prestressing force. It is intended to set up feasible procedures to materialize the testing technique in experimental laboratory conditions, including systems for stressing and releasing the reinforcement, the steps to follow in order to track the sources of time-dependent prestress losses, the means for inducing the notches by saw-cut, and the possibilities regarding instrumentation devices.

2. Background

Despite the above uncertainties, there are few empirical methods available to assess the actual condition of prestressing systems, and their application in complex conditions is not always feasible. Destructive methods include [5]:

(a) Cracking moment (crack initiation): the element is stressed until the first tensile crack appears, the cracking moment is obtained and with it the residual prestressing force is calculated.

(b) Crack re-opening: a crack caused ex professo is monitored under load; the load that causes the crack to re-open (zero stress in the concrete) is used to calculate the residual prestressing force.

(c) Tendon cutting: the tendon is exposed along a sufficient length to allow strain gauges to measure the strains developed during tendon cutting; the two ends resulting from the cutting are placed at zero tension, which allows the residual prestressing force of the tendon before cutting to be deduced.

Destructive methods inevitably cause structural damage and are therefore unsuitable for application to in-service structures, hence the interest in developing non-destructive methods (or with conditions requiring only aesthetic restitution) such as:

(d) Tendon deformation (exposed tendon) [7]: the tendon is exposed along a span of such length that a tendon deflection check can be performed when subjected to vertical action; from the variation in tendon tension, the residual prestressing force can be determined if calibration data is available.

(e) Hole drilling [2]: a hole is drilled in the concrete and the deformations in the concrete surface are measured by comparison with the pre-hole state, either in the vicinity of the hole (relief technique) or in the core concrete of the hole itself (trepanation technique). The measured deformations are transformed into stresses by means of appropriate calibration constants, and the obtained stresses can be related to the residual prestressing force by means of a model.

(f) Isolated concrete block (saw-cuts) [8]: the residual prestressing force is calculated from the response of a concrete block formed by making surface cuts. These cuts are made perpendicular to the prestressing direction, defining a concrete block between two cuts that is isolated from the effect of the prestressing; the concrete in the block is decompressed. The deformations on the surface of the isolated block are obtained by comparison with the pre-cut state. Once the deformations are known, the stresses are computed and entered into a calculation model to determine the residual prestressing force.

The apparent conceptual simplicity of the Isolated Concrete Block Method (ICBM), together with the low impact on the structure (the cuts only affect the concrete cover and can be resealed), allow to trust in overcoming the limitations associated with the hole drilling technique (low released stress level, difficulty of instrumentation, ...).). Thus, the ICBM has a clear potential to become a non-destructive method of reference -practical, economical and reliable- in the context of the evaluation of PCMs.

3. Testing Prototypes

In the following, based on a series comprised by 3 posttensioned concrete beams (Beam 1, Beam 2a and Beam 2b) tested sequentially as prototypes, the main goals and milestones achieved are described. Fig. 1(left) shows the moulds used for the 3-m-long beams with centred and eccentric prestressing, whereas Fig. 1(right) shows a general view of the casting process. A concrete having 60 MPa of compressive strength and 38400 MPa of concrete modulus of elasticity at 28 days was used. It should be noted that tests were carried out focusing on procedures, tools and means for testing, without considering concrete material properties as a variable.

Fig. 1: General view of moulds (left) and casting process (right).

3.1. Beam 1

The concrete cross-section of this beam was 0.1x0.20 m (wide x height), with a centred 7-wire prestressing strand type Y 1860 S7 13-mm in diameter. The duct was 16-mm in internal diameter. The strand was tensioned at 1400 MPa, which is the maximum (75% of the nominal strength) according to the Eurocode 2 [9]. As shown in Fig. 2, a hollow hydraulic jack with and adjustable mechanical anchorage was used. In this case, a special support was placed between the jack and the beam to allow the location of an intermediate anchorage device. The goal was to have minimal instantaneous prestress losses due anchorage seating given the short length of the beam. Finally, being the prestressing force 140 kN at jacking, the resulting effective prestressing force was 115 kN (18% seating loss).

Fig. 2: Hollow hydraulic jack with and adjustable mechanical anchorage.

Three central zones (A, B, and C) 0.7-m in length were considered independent regarding influences of the corresponding saw cuts. In each zone, a pair of cuts were made with different distance between them: 0.10 m in zone A, 0.14 m in B and 0.12 in C). Fig. 3 shows the layout of the instrumentation devices: force transducers at both ends, strain gauges on the strands near the ends, strain gauges (from two different providers) on the concrete surface and Demec points.

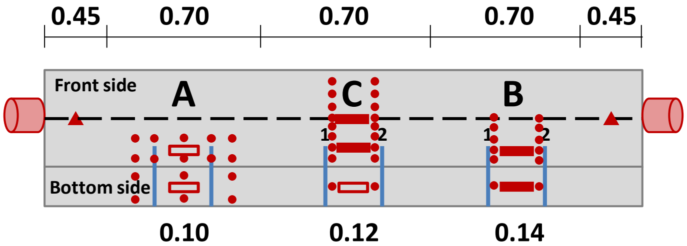

Fig. 3: Instrumentation layout of Beam 1.

Saw cuts were made with a disk saw available in the laboratory. To facilitate tasks and to perform saw cuts at the requested locations and with the desired depths, a specific timber support was designed, as shown in Fig. 4. Several cuts having depths from 10 to 50 mm were made. As expected, the relief of concrete compressive stresses were different as the distance between cuts was different in each testing zone.

Fig. 4: Performing a saw cut in Beam 1.

The problems to perform the tests were the main sources to improve procedures for the next prototype. They consisted of: (a) the duct dimensions were insufficient to allow the strain gauges on the strand along the jacking process, so the gauges were broken; (b) the system of the disk saw to regulate the cut depth was not stable enough along the cut; (c) the timber support only allowed one position for cutting, and had to be removed after each cut to measure; and (d) the intermediate anchorage was not effective regarding the detensioning phase, which was necessary to recover the force transducer, and this was due to the role of the adjustable mechanical anchorage and different distances between the involved anchorage devices in each stressing phase: both end devices at tensioning, intermediate and beam-end devices at anchoring, jack-end and intermediate device at recovering and again both end devices at detensioning.

3.2. Beam 2a

On this occasion, the concrete cross-section was 0.1x0.30 m (wide x height), with a 7-wire prestressing strand type Y 1860 S7 13-mm placed with an eccentricity 0.05m. The duct was 21-mm in internal diameter. As in Beam 1, the strand was tensioned at 1400 MPa. As shown in Fig. 5, a mono-strand jack with interlocking was used, and the resulting effective prestressing force was 110 kN (21% seating loss).

Fig. 5: Mono-strand jack for 13-mm strand diameter.

Three central zones (A, B, and C) 0.7-m in length were considered to perform pairs of cuts at distances of 0.12 m, as shown in Fig. 6, which depicts the instrumentation layout. With respect to Beam 1, an additional sequence of Demec points between zones A and C was placed to determine the distance of influence of the saw cuts towards the adjacent zone, and only one force transducer was used.

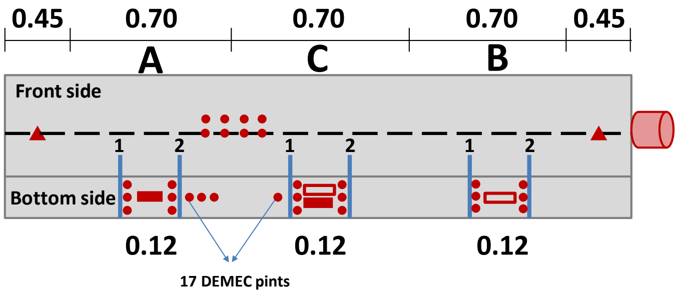

Fig. 6: Instrumentation layout of Beam 2a.

Saw cuts were made with a new disk saw with a locking position at every 5 mm allowing depths ranging from 5 to 60 mm. To facilitate tasks and to perform saw cuts at the requested locations and with the desired depths, a new specific timber support was designed, as shown in Fig. 7. On this occasion, the timber support included two improvements: (a) the two required saw cuts can be performed for the same position of the support; and (b) measurements can be taken without removing the timber support. So all the process including subsequent cuts with progressive depths and the corresponding measurements after each depth is performed without removing the timber support from its location which, in turn, results in a better performed saw cut. Fig 8 illustrates the location of the timber support in zone A, before cutting (Fig. 8(left)) and after cutting (Fig. 8(right)). It should be noted that the analyses of measurement data were strongly influenced by the measurement base length considered: 60 mm for the case of strain gauges and 100 mm for Demec points.

Fig. 7: Performing a saw cut in Beam 2a.

Fig. 8: Location and instrumentation of a pair of cuts, before cutting (left) and after cutting (right).

The main lessons learned from this prototype were: (a) the duct dimensions were sufficient to allow the complete role of the strain gauges on the strand along the jacking process; (b) the system of the new disk saw with locked positions for each cut depth was stable along the cut; (c) the timber support should include a better guidance for the disk saw; (d) the saw cuts did not influence at a distance of 0.35 m; and (e) the force in the strand could be monitored with only a force transducer at one end.

3.3. Beam 2b

This prototype was a reply of Beam 2a, with a change regarding the prestressing strand and the stressing jack: the strand diameter was 15.2 mm, and the mono-strand jack (Fig. 9) had not an interlocking system. As in Beam 1 and Beam 2a, the strand was tensioned at 1400 MPa, which corresponded to 196 kN. However, the final effective prestressing force at anchoring was only 112 kN (43% seating loss).

Fig. 9: Mono-strand jack for 15.2-mm strand diameter.

Regarding the timber support, a complementary platform was added in the central part, as shown in Fig. 10. The advantage was to allow a better guidance and action of the disk saw. However, a main disadvantage was the impossibility of a direct measurement from the Demec points without removing the timber support after each desired depth of a pair of saw cuts was performed.

Fig. 10: Performing a saw cut in Beam 2b.

4. Experimental study

In this section, the main aspects to be considered to establish a tentative experimental study under laboratory conditions are exposed.

4.1. Parameters involved

The parameters involved can be classified into three groups: (a) Related to the member: dimensions (length and cross-section), concrete materials (e.g., maximum aggregate size), location of the tendons, existence of reinforcing bars and/or stirrups, concrete properties (e.g. compressive strength and elastic modulus),…; (b) Related to the prestress: prestress level, age of prestress, age of testing, prestress losses (instantaneous and time-dependent), ratio of concrete compressive stress over concrete strength,…; and (c) Related to the saw cut technique: distance between the both cuts of a pair, distance between pairs of cuts, depth of cuts, measurement base length considered, …

4.2. Program proposal

A program proposal should offer the possibility to materialize different stress/strain scenarios to be tested with a simplified conception and cost and, at the same time, the possibilities and limitations of the laboratory should be taken into account for a realistic development. In this sense, the facilities at ICITECH can host members until 4-m length, which is due to the dimensions of the freight elevator that must be used to access to the basement were conditions of temperature and humidity are more easy controlled for storage purposes and prestress losses monitoring.

Table 1 summarizes a campaign including 22 specimens for a given concrete member as a reference. By combining ages of prestress and testing, different stress/strains scenarios result since concrete properties vary through time. In addition, other parameters (see 4.1) can be varied. In particular, the authors are working with this idea and with three different cross sections: 0.10x0.25 m, with prestressing eccentricity of 0.035 m (1 strand), 0.08x0.25 m, with prestressing eccentricity of 0.035 m (1 strand), and 0.10x0.55 m, with prestressing eccentricity of 0.085 m (3 strands), which respectively require a 3-day concrete compressive strength for prestress anchoring of 20, 24 and 26.8 MPa due to the concrete compressive stress limit of 60% of concrete compressive strength required by Eurocode 2 [9].

Table 1: Campaign proposal for a given concrete member as a reference.

#BEAMS	AGE [days] OF TESTING (SAW CUT)						
AGE [days] PRESTRESS	3	7	14	28	56	120	240
3	1	2	3	4	5	6	7
7	--	8	9	10	11	12	13
14	--	--	14	15	16	17	18
28	--	--	--	19	20	21	22

In addition, complementary series of beams to analyze deformability conditions based on elastic concrete modulus of the tested beams are required, in two ways: (a) beams to be prestressed and tested under flexural loading at ages of 3, 7, 14 and 28 days, and unstressed at 28 days; and (b) beams to be prestressed, tested under flexural loading and unstressed at ages of 3, 7, 14, 28, 56, 120 and 240.

5. Conclusions

The following conclusions can be drawn from this study:

The relief of concrete compressive stresses was different as the distance between cuts was different in each testing zone. The distance of 0.12 m between cuts seems the more appropriate to combine different measurement base lengths from both electronic and mechanical extensometric devices.

The mono-strand jack with interlocking of the anchorage device for 13-mm strands showed a good balance regarding ease and speed of use and level of prestressing.

The performance of the disk saw, together with a specific support to facilitate its location and guidance, are crucial to ensure that an accurate cut is made with the desired depth and width. An improved support should be designed with a complementary platform easy to remove to allow measuring between cuts without removing the whole support from its location.

Based on a few concrete members as a reference, different stress/strains scenarios to be tested can be carried out by combining ages of prestress and testing, since concrete properties vary through time.

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