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Analysis of prestressing in old full-scale concrete members

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ABSTRACT

The effective prestressing force is a key parameter that affects the performance of prestressed concrete members (PCM). In fact, the accurate determination of the residual prestressing force is crucial to assess existing PCM since it influences load-carrying capacities, in-service structural properties and remaining service life. The aging of structures, with limited functional capacity, implies a major problem that must be addressed without delay. Progress in the promotion of innovative solutions to extend the service life of structures depends on: (a) the availability of reliable indirect methods, since old PCM were usually no instrumented during casting; (b) the formulation of adequate diagnostics of the residual stress–strain state of structures; and (c) the availability of highly refined predictive tools. The implementation of these elements in the management and maintenance systems of PCM will serve to support decision making associated with structural assessment and to gather information to establish criteria for the design of more resilient PCM.

Among the destructive methods available to empirically assess the actual condition of PCM, it can be found: crack initiation, crack re-opening and tendon cutting. As destructive methods inevitably cause structural damage and are not suitable for application to in-service structures, non-destructive methods or with conditions that only require aesthetic restitution (e.g. exposed tendon deformation, hole-drilling and saw-cuts) appear as an alternative of increasing interest.

As a first step to obtain feed-back from several experimental tests carried out on unmonitored full-scale PCM over the years, this paper examines different techniques and methods used to evaluate the residual prestressing force, and also presents the deviations and uncertainties regarding predictions of short- and long-term prestress losses from main code models used in design. It is concluded that it is interesting to follow a non-destructive indirect testing methodology to be able to keep in service and monitor the current structures. This would make it possible to draw up a maintenance plan based on the condition of the PCM.

1. Introduction and objectives

At present, a large number of prestressed concrete infrastructures in continental Europe and the United States are of advanced age since pouring in the 50–60s and are now approaching the end of their useful life [1]. It is very important to have a good study of the current status of these elements. These prestressed concrete elements (PCMs) were designed according to repealed regulations which did not include certain considerations related to delayed losses occurring in prestressed concrete elements. In addition, different load effects on the bridge and aspects of premature degradation of the elements must be considered. Therefore, due to the severe aging and functional decline of the structure, this is a major problem that needs to be addressed immediately.

Due to the variability of previous design codes, construction methods and tension devices, it is difficult to predict the stress state of this type of structure, so it is necessary to obtain experimental methods to ensure the load capacity of the structure. For all these reasons, the progress that is being made in the promotion of innovative solutions to increase the useful life of structures is interesting, and for this it is important to use reliable indirect methods, since the concrete structures that currently have a useful life are not were instrumented and therefore it is not possible to

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obtain the residual prestressing force from direct methods. Another aspect to consider is the proper diagnosis of the residual stress–strain state of the structure and finally the importance of having highly reliable predictive tools.

2. Experimental methods

Depending on the prestressing obtained, the experimental tests can be divided into two large categories, in a first group, direct methods, where the forces are obtained directly from techniques applied to tendons or concrete elements, and, on the other hand, indirect methods, the prestressing force is obtained from different indirect measurement techniques. Direct methods for the analysis of prestressed concrete beams are mainly used through the implementation of sensors during the design of PCM elements. These sensors are used to measure the actual behaviour of the beam during construction and use. There is a wide variety of direct analysis methods that can be divided into two broad categories, such as:

- Actions on the tendon: this method is based on two main forms of measurement, such as the measurement of tensions in the tendon, using the following elements: strain gauges and fiber optic sensors, and on the other hand, using the force on the anchor head. only for post-tensioned elements through force transducers, elastomagnetic sensors, ultrasound and a large number of other elements.
- Actions in the concrete: these are methods of obtaining efforts, from the displacements observed in the concrete, for this methodology it can be done through obtaining internal efforts, techniques such as VWSG (vibrating wire strain gauge) and VBSG (vibrating beam strain gauges), measurement of existing prestressing force in concrete structures through an embedded vibrating beam strain gauge] or through surface stress measurement elements, within the latter two main types can be differentiated: contact devices, such as strain gauges and through the location of mechanical points, and on the other hand there are non-contact measurements such as photogrammetry, interferometric laser, scanner or stripes.

On the other hand, there are indirect residual prestressing measurement methods, which can be classified in the same way as the previous ones depending on the methodology used, such as:

- Load tests in flexure, to produce crack initiation when the PCM is not cracked, and to produce crack reopening when cracks exist.
- Tests by actions on the tendons, consisting of techniques acting mainly on the tendon in which we find the tendon cutting technique, which consists of making a cut in the cable and measuring the deformation released in the tendon after the cut or the method of exposure of the tendon, which consists of leaving the tendon visible by removing part of the concrete and applying a force perpendicular to the axis of the cable and observing the deformation that has occurred in it and from this being able to obtain the tension at which it was subjected to said tendon.
- Actions on the concrete, the latter consist of carrying out different tests only affecting the concrete part, within which there are two main types, the first of which is the drilling techniques of the concrete core, these depending on the type of drilling carried out can be by means of a drilling bit or by means of drilling with a circular crown, the other experimental technique that can be carried out is the saw-cut technique, which consists of applying cuts in the PCM so that the tension release that can be obtained can be obtained. This occurs in the different notches or groups of these.

There are also other types of indirect methods on concrete which are based on sophisticated techniques such as ultrasonic waves, impact-echo either transversal or longitudinal, LC oscillation, induced magnetism and identification systems.

Within the previous techniques discussed above and focused on the objective the research project of the authors, the interesting ones for elements already executed and put into service the application techniques are those of indirect methods, and between them, those that do not correspond to sophisticated techniques. These methods, depending on the degree of damage caused to the PCM, can be classified as destructive and non-destructive tests.

Depending on the corresponding needs for each of the application cases, the most frequent case that we are going to find today for the analysis of prestressing losses are PCMs that have not been instrumented during execution to be able to monitor of the prestressing losses. Therefore, the direct methods are ruled out for this case. On the other hand, depending on the existing needs and if the PCM presents the need to continue being in service, it is necessary to opt for non-destructive methods. However, if its return to service is not required, destructive methods can be applied for its study.

3. Old full-scale PCM

There are currently a large number of methods that have been advancing, one of the first methods used for the analysis of the effective prestressing force in bridges dates back to 1980 [2] in which two prestressed concrete beams were tested in Belgium, called Flexural Crack. It consists of an indirect test method corresponding to a destructive method, since after this test the element cannot be put back into service. The test carried out consisted of subjecting the PCM element to bending with two concentrated loads by means of a hydraulic jack. Once the load increments were applied, the deflections, deformations and cracks were measured, as conclusions were obtained. from this test that the losses obtained were 15% with respect to the initial design, while applying the CEB-FIP Model Code of 1978 design regulations, the values were quite approximate, on the contrary, applying the regulations used for the design, they were estimated at 7.5% well below the results obtained, all this applied to the Desmet at Ghent in 1949, with a useful life of 30 years.

In 1991, Shenoy et al. [3] carried out a test using the crack reopening technique for 27-year-old beams. These beams had the main characteristic that when they were subjected to the bending test they were already cracked, therefore a bending test by applying two point loads in the center of the beam and taking a measurement with strain gauges, it was possible to observe how after applying the load the crack closed again, assuming that at the instant in which the reopening of the crack occurred crack stress in the lower fiber was zero. During this indirect destructive test, it was concluded that the losses were around 11% of prestressing losses, while applying the predictive method of the PCI 1975, the estimated losses were 21%, so it was concluded that the structure presented a level of residual prestress more than acceptable.

Another application of the previously commented test model is that it was used to analyse 34-year-old beams that was carried out in 1993 [4] test with similar characteristics to the one previously commented, in this last test it was concluded that the measurement of real losses was 17.5% while the estimates in the project were 15%, so the loss of strength was actually greater than that initially estimated. In addition, the authors made a calculation of estimated losses with the regulations in force in 1993 at AASHTO and obtained that the estimated losses with current regulations were 20%.

In 1996, Azizinamini et al. [5] carried out an analysis of the residual prestressing for 25-year-old prestressed concrete beams. This analysis represented an important advance in terms of the projection of new non-destructive techniques, since a flexural crack test was carried out and the results were compared with the implementation of a new non-destructive method called hole-drilling [5]. In this study, the beam was initially subjected to a bending test in order to obtain the residual prestressing. This method, as has been mentioned, turns out to be a destructive method, so the beam cannot be put back into service. The procedure consisted of applying a moment in the tested beam, and by placing two strain gauges in the bottom side, it was possible to obtain the start of decompression in the central beam. From this, it was possible to obtain the prestressing force that was acting at that moment ensuring that in the lower fiber of the beam the stress was the tensile strength of the concrete. Parallel to this test, the non-destructive method was carried out, which consisted of drilling the concrete core by means of an auger until decompression was obtained on the underside of the beam. In this case, the instrumentation consisted of placing strain gauges in the bottom part of the beam, in the concrete drilling area near the central area of the span.

This method was carried out in parallel by means of a finite element design, based on the expression:

$$S = (\gamma * Q)/\beta = K * Q \quad (1)$$

where K is the stress ratio factor, S, and Q is the application of load until the crack closes. The methodology used by these authors in the trial was as follows:

- Drilling a hole in the bottom flange of prestressed girders.
- Pre-cracking the hole, so that the crack would start at coordinates (a, 00, 0) and run parallel to the girder span. It should be noted that the size of this crack is small, approximately 1in. (25 mm) in diameter.
- Increasing the side pressure, Q, over a limited width, W
- Determining the side pressure, Q, at which the crack just completely closes
- Using an appropriate K factor obtained from analysis and the side pressure, Q, corresponding to the crack closure, Eq. (1) will then give S, the available stress at the extreme fiber of the bottom flange of the prestressed girder.

Comparing the results obtained with the different methods, it was concluded that for the flexural crack method, the percentage of losses obtained was around 21%, while the hole-drilling technique provided similar results and the great potential that may come to have this method of obtaining the residual prestressing.

Another indirect method used for the analysis of prestressed bridge beams was carried out by a research group at the University of Zilina (Slovakia) [6], in which the stress state of the beams recovered from a 62-year-old bridge, in this case an indirect method called saw-cut was used. This technique consists of measuring the stress release of an isolated block from a pair of notches in which it can be obtained from the deformations produced by the concrete between notches. It is a non-destructive method and therefore very useful today. In the research [6], a finite element model of the structure was carried out in order to make comparisons of the stress state of the bridge. The methodology used for the test consisted of making a pair of notches with a depth of 30 mm spaced 120 mm apart. To measure the released strain produced by the notches, a strain gauge was used. The values obtained were associated with a residual prestressing in the structure of 3480 kN while the one elaborated by the numerical analysis led to a value of 3550 kN, which supposes an error of 2%, which is attributed to measurement errors or characterization of the materials.

4. Methodology to choose the appropriate method

Having discussed all of the above, it is important to follow a scheme like the one shown in Fig. 1, in which it is interesting to address different scenarios in order to obtain the most appropriate test method to obtain the stress state of the PCM. In the first place, it is important to take into account whether the structure during its casting has been monitored and therefore reliable and continuous starting data is available over the years.

From here, two possible scenarios are considered: In the event that would have been monitored during execution (1), and therefore direct methods would be applicable to obtain the stress state, or otherwise no measurement elements had been provided when (2) was executed, which in this option is the which happens in most cases and therefore can only be applied by indirect methods, it should be noted that the indirect method is always applicable in these cases, since detection will always be possible.

Therefore, non-destructive indirect methods are techniques that can be used for all the cases in which they have been previously discussed, and above all they can be used for structures that need to be kept in service.

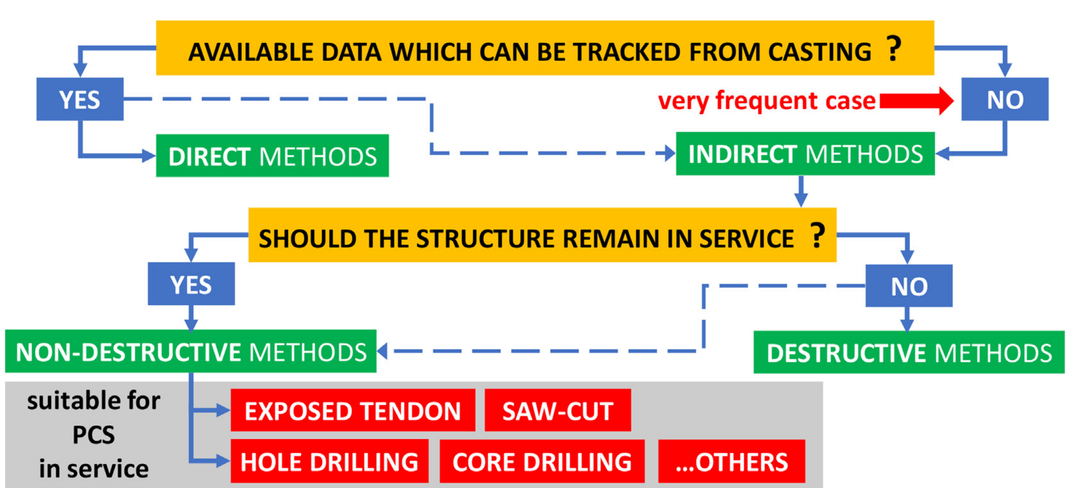

Fig. 1. Diagram of the methodology to follow to choose the appropriate method.

Fig. 2. General view of part of a beam with saw-cuts and holes-drilled (left) and part of a beam with cores-drilled (right).

In the event that the structure does not want to continue to be kept in service, there is the possibility of applying destructive tests, otherwise, in which the PCM is going to be a functional element, the only possible way is to use methods to obtain the prestressing non-destructive residual and minimally affect the tested element. Therefore, non-destructive indirect methods are techniques that can be used for all the cases in which they have been discussed above, and above all they can be used for structures that want to be kept in service, which is the trend that is taking place. Therefore, there is great evidence of improvement in these last methods and therefore it is interesting to deepen and improve non-destructive techniques such as: exposed tendon, saw-cut, hole-drilling and core-drilling.

For this reason, an experimental program is being conducted by the authors at the ICITECH (Institute of Concrete Science and Technology, Universitat Politècnica de València, Spain). The program includes series of prestressed concrete beams to implement the saw-cut and the hole-drilling/core-drilling techniques, with the aim of testing the effectiveness and limitations of these techniques on a comparative basis. Fig. 2 shows parts of two beams, one with saw-cuts and holes-drilled (left) and the other with cores-drilled (right). Since concrete properties vary through time, different stress/strains scenarios can be tested by combining ages of prestress and testing. The prestressed concrete beams are instrumented with mechanical gauges and with a force transducer that allows control of the entire process. In this way, analytical and numerical approaches based on the experimental results can be formulated as a suitable manner to check the residual prestressing force. The idea is to advance in a model to be able to estimate the residual prestressing force in unmonitored conditions, as occurs in most of the existing PCM in service.

5. Conclusions

In this article, a series of methods have been presented to be able to monitor the residual prestressing force for prestressed concrete elements. It has been possible to verify how the methods that have been used at present are and the deviations that they have had with the calculation codes used depending on the age of these elements. Therefore, the conclusions obtained are:

- Direct methods can be used if they have been implemented during manufacture and it has been possible to obtain a history of prestressing losses.
- When the residual prestressing force has been experimentally determined, there has been stated in some cases that the prestressing losses have been lower than the predictions made by the codes, but this aspect should not be trusted since it may happen that the deterioration of the tendons is greater than expected.
- The trend over the years is to introduce indirect methods that allow obtaining the stress state of the element and to be able to know the residual prestress in the PCM.
- Due to the current age of the structures, it seems interesting to follow a non-destructive indirect testing methodology to be able to keep in service and monitor the current structures. This would make it possible to draw up a maintenance plan based on the condition of the PCM.
- The saw-cut and hole-drilling/core-drilling methods have a wide scope for improvement and seem interesting methods to obtain the residual prestressing force of the PCMs.

Data availability

No data was used for the research described in the article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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