Determining the Residual Prestressing Force in Unmonitored Full-Scale Prestressed Concrete Members

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Abstract. The accurate determination of the residual prestressing force is essential in the assessment of existing prestressed concrete structures (EPCSs). Since construction practice has not considered the incorporation of measurement devices in the EPCSs for monitoring over time, prestressing losses are usually unknown, and therefore the residual prestressing force. In the case of old prestressed concrete members, additional complexity must be considered in relation to the initial prestress, the materials (prestressing reinforcement and concrete) properties and the short- and long-term prestress losses. From several analyses carried out on EPCSs, it should be pointed out that the residual prestressing force is not always in agreement with the expected value.

In this context, this paper compiles a database of experimental tests carried out on old full-scale prestressed concrete members over the years, which were commonly salvaged from decommissioned bridges, and examines the different techniques and methods used to determine the residual prestressing force. Cases with both destructive and non-destructive approaches are included detailing pros and cons together the uncertainties to be considered in the assessment of EPCSs. The summarized information will serve to a better understanding of the testing techniques and may help to protocolize the assessment of case studies with unknown prestressing force.

Keywords: concrete · prestress · losses · database · test · methods

1 Introduction and Objectives

Much of the current prestressed concrete infrastructure in continental Europe and the United States has aged since it was built in the 1950-1960s and is now nearing the end of its useful life [1]. It is important to study well the current state of these elements. Most of existing prestressed concrete structures (EPCSs) were designed in accordance with repealed codes that did not find certain considerations related to long-term losses that occur in prestressed concrete elements. In addition, different loading effects on and aspects of premature degradation of the EPCSs must be considered. Therefore, due to the rapid aging and functional deterioration of structures, this is a significant problem that must be addressed immediately.

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It is for this reason that the accurate determination of residual prestress is essential for the evaluation of EPCSs since the effect of prestressing has a significant impact on the stress-strain response and capacity of such structures. In mandatory design, the designer must determine the prestress and estimate the loss of prestress for the structure to meet its requirements during its useful life. Since construction practice did not consider the inclusion of measuring devices in the EPCSs to monitor over time, the loss of prestress and therefore the residual prestress are often unknown. There are large uncertainties when evaluating a large fleet of EPCSs that has consumed most of its useful life. Therefore, there is a need to advance scientific methods and cutting-edge knowledge on this topic.

That is why, due to the aging of the infrastructures formed by EPCSs, a new trend arises in terms of the ability to detect, quantify and predict damage by the owners of the EPCSs to allow an evaluation of the effective and safe structural state. Traditionally, the practice of periodic visual inspection dominates maintenance programs around the world [2]. However, it is true that these visual inspections are insufficient to meet current maintenance needs of concrete structures and specially in the case of prestressed concrete structures in which the damage can be hidden on many occasions due to the compression effect caused by the prestressing force [3, 4].

Due to this need for maintenance, these techniques are booming due to the awarness that it is necessary to know the stress-strain state of the EPCSs in order to know what measures are necessary to execute and know the action plan. For this reason, the objective of this paper is the compilation of different methods applied at full scale to carry out an action scheme based on the needs and state of the structure, in order to determine which is the most effective method to obtain the residual prestressing force in EPCSs.

2 Methods for Obtaining Residual Prestressing in EPCSs

The methods used to obtain residual prestressing in External PostTensioned Concrete Structures (EPCSs) can be categorized into two main groups: direct methods and indirect methods.

2.1 Direct Methods

Direct methods focus on either measuring the prestressing tendon or the concrete itself.

Methods focusing on the prestressing tendon involve measuring the tensions or forces in the tendon. This can be done using strain gauges, fiber optic sensors, force transducers, eleastomagnetic sensors, ultrasound, and other measurement techniques.

Methods focusing on the concrete involve measuring internal stress-displacement or strain-displacement. Techniques such as Vibrating Wire Strain Gauges (VWDG) and Vibrating Beam Strain Gauges (VBSG) are used to measure internal stress-displacement. Strain-displacement on the concrete surface can be classified into two groups: those with contact, such as strain gauges and mechanical measurement techniques, and those without contact, such as photogrammetry, laser interferometry, scanners, or stripes.

However, these direct methods are typically not available for most EPCSs since continuous monitoring sensors are usually not installed during casting. The main drawback is the need to monitor the prestressing force from the moment of construction.

2.2 Indirect Methods

Indirect methods are employed to obtain the stress state of EPCSs when there is no available information on the evolution of prestressing. These methods have been developed over time based on full-scale tests.

Indirect methods can be classified into two groups based on their effects on the structure:

a). Destructive tests: These tests are commonly used when the structures are not going to be put back into service. They involve deepening the understanding of already dismantled structures. Destructive methods can be further categorized into load tests and actions on the tendon.

Load tests involve applying external loads to obtain residual prestressing. There are two main types of load tests: one for uncracked EPCSs, where external loads are applied to determine the tensile strength of the concrete in the lower fiber, and another for cracked EPCSs, where load increments are introduced to observe crack reopening and subsequent sealing during unloading.

Actions on the tendon include the Strand Cutting technique, where the tendon is instrumented with a strain gauge to measure deformation after cutting the tendon [5].

(b) Non-destructive tests: These methods are specific and used for evaluating EPCSs in service. They are categorized based on actions on the concrete.

Exposed tendon method involves completely exposing the tendon and applying a load solely to the tendon to observe the resulting vertical displacement. From the modulus of elasticity, the tension in the steel at the time of load application can be obtained. However, this technique can cause significant damage and raises questions about its non-destructive nature.

Hole drilling is a technique that consists of drilling holes in the concrete to measure the stress-strains in the adjacent area. Deformations occurring radially to the holes are measured using strain gauges or mechanical measurement points [6].

Saw cut method involves making notches in the concrete to measure stress release through deformation. Strain gauges are used to measure the deformations produced by the notches [7].

These indirect methods provide information about the prestressing state of EPCSs without directly measuring the prestressing elements, but they have their limitations and uncertainties.

Figures 1, 2, 3, and 4 provide schematic representations of the load test method, the strand cutting technique, the exposed tendon method, and the hole drilling and saw cut methods, respectively.

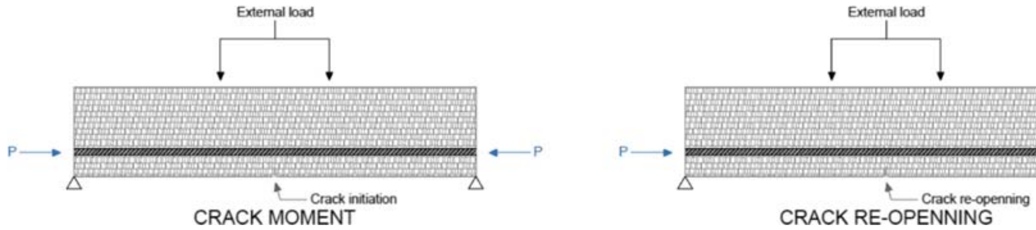

Fig. 1. Scheme method for load test

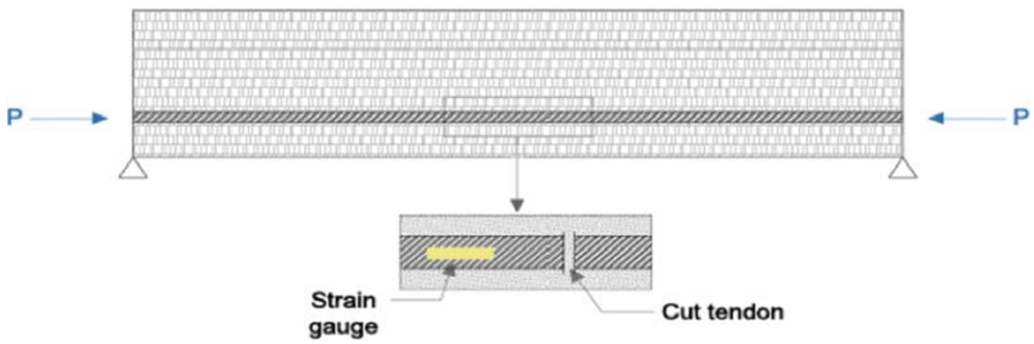

Fig. 2. Scheme method for strand cutting.

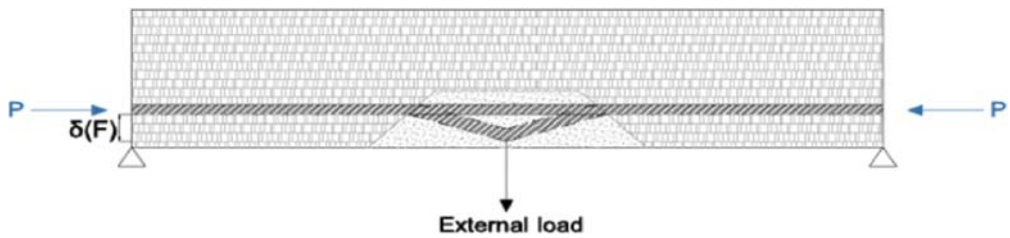

Fig. 3. Scheme method for exposed tendon.

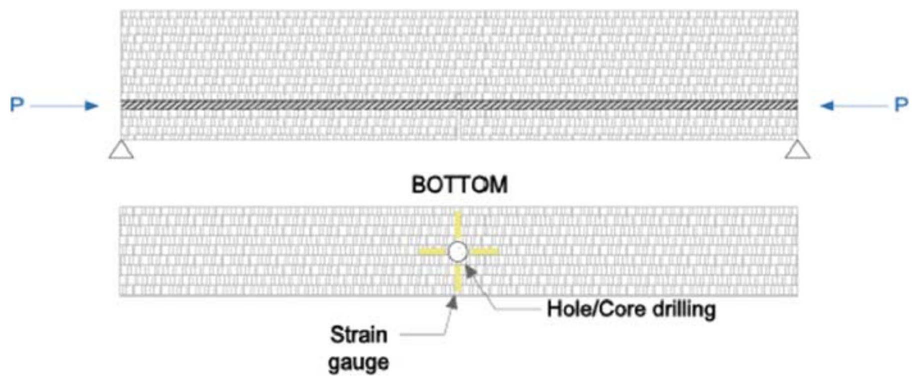

Fig. 4. Scheme method for hole/core drilling.

3 Database of Applications in Old Full-Scale Members

Below is a compilation of indirect methods that have been carried out on full-scale EPCSs. The following table shows important variables such as: age of the tested beam, test method, experimental results, code for obtaining the estimated residual prestressing load and the result obtained, both for the experimental method and for the comparative theoretical method.

Table 1. Compilation of experimental tests.

Source	Year	Cross section	Age	Test Method	Method Results	Code Method	Code Results
[8]	1980	Square	25	Flexural Crack	7,5%	CEB-FIP-1978	15%
[9]	1984	T-Beam	25	Crack Re-openning	10%	ACI and PCI 1975	20%
[10]	1991	Box	27	Crack Re-openning	11%	PCI 1975	21%
[11]	1993	Double T-Beam	34	Flexural Crack	17,5%	Desing project AASHTO 1993	15% 20%
[12]	1996	Double T-Beam	25	Flexural Crack Hole-Drilling	21% 21%	AASTHO	20%
[5]	1996	Double T-Beam	40	Flexural Crack Crack Re-openning Cutting Tendon	20% 20% 20%	AASTHO	27%
[13]	1996	Double T-Beam	28	Flexural crack Crack Re-openning	18%	Bureau of Public Road Lehigh AASHTO	29% 32% 33%
[14]	1997	Box	20	Flexural crack	20%	ACI 818–89	24%
[15]	2006	Double T-Beam	12	Cutting tendon	20%	FIB SIA	20%
[16]	2008	Box	30	Flexural Crack	32,7%	PCI 2004 AASHTO 2006	19% 12%
[17]	2010	Square	42	Crack Re-openning	38%	MC 90 MC 99 ACI 1992 PCI 1975	23% 25% 17% 24%
[18]	2012	Double T-Beam	45	Flexural Crack	25%	AASTHO LRFD (2009)	24,6
[19]	2013	Double T-Beam	61	Flexural Crack	25%	-	-
[20]	2015	Irregular	40	Crack Re-openning	23%	-	-

(continued)

Table 1. (*continued*)

Source	Year	Cross section	Age	Test Method	Method Results	Code Method	Code Results
[21]	2016	Square	40	Crack Re-openning	20,9% 24,5% 26,3%	-	-
[22]	2021	Double T-Beam	81	Flexural Crack	20%	Bayesian	30%
		Slab	62	Saw-cut	24%	FEM	22%

4 Analysis of Database

Table 1 shows that many experiments have yielded unexpected results, indicating that current experimental codes may not be adequate in certain situations. This discrepancy can be attributed to deferred effects in concrete and steel, which were not accurately considered in previous codes. Aggressive environments and unforeseen actions in design contribute to unanticipated stress states, potentially requiring repairs.

Furthermore, the tests in Table 1 demonstrate a shift from destructive indirect methods to non-destructive tests over time, indicating an increasing trend in studying the stress state of structures. To enhance the reliability of techniques for obtaining residual prestressing, Fig. 5 proposes a selection process for determining the appropriate method to evaluate the structure's state, aiming to standardize the assessment of practical cases with unknown prestressing force.

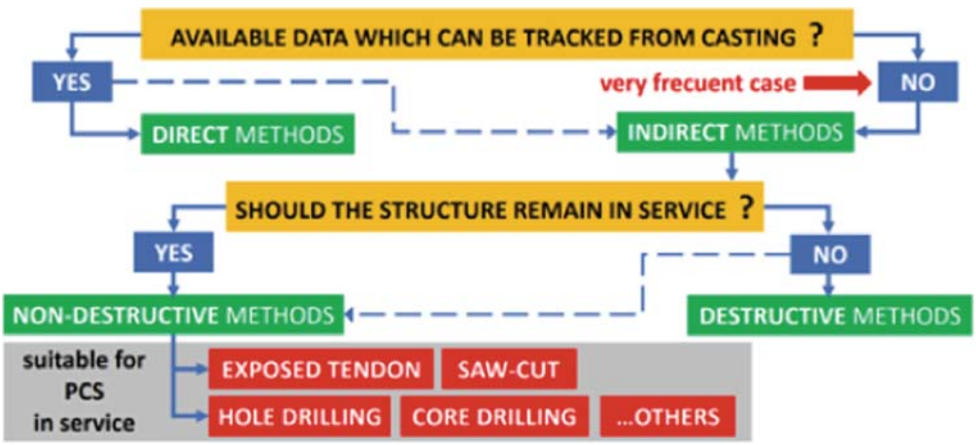

Fig. 5. Diagram of the methodology to follow to choose the appropriate method.

Figure 5 outlines the process for selecting the suitable method to obtain residual prestress in EPCSs. The first consideration is whether the structure is monitored during construction, providing reliable and continuous data over the years. Two scenarios are then distinguished: if monitoring is in place, a direct method is employed to obtain the stress state, while in cases where no measurement element is available, only an indirect method can be applied. Notably, the indirect method is always applicable as prestress detection is always possible.

Non-destructive indirect methods can be used in all the aforementioned cases, particularly in structures that need to remain functional. When a structure is slated for replacement, destructive methods can be employed; otherwise, non-destructive methods, which cause minimal damage and are repairable, are the only viable option. The key advantage of non-destructive indirect methods is their applicability in various scenarios, including structures intended for continued use, aligning with current trends. All of this shows substantial evidence supporting the continued improvement of non-destructive techniques such as exposed tendon, saw cutting, hole drilling, and core drilling.

5 Conclusions

In this paper, a series of tests have been presented to be able to determine the residual prestressing force for the case of EPCSs. It has been stated how the methods that have been used in recent years are feasible and reliable and it has been observed the deviations that they have had with the calculation codes used depending on the age of these elements. Therefore, the conclusions obtained are:

- A number of tests have been carried out for a long time to obtain the residual prestress, with a lot of cases in which the prestress losses have been lower than the predictions made by the codes, but this aspect should not be relied upon as it can 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 know the residual presstress in EPCSs.
- 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, so with this it will be possible to develop a maintenance plan based on the state of EPCSs.
- The methods of sawing and drilling/coring holes have a lot of room for improvement and seem interesting methods to obtain the residual prestressing force in EPCSs.

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