Available Tests to evaluate Residual Prestressing Forces in Concrete Bridges

Angélica Agredo Chávez, Jaime Gonzalez-Libreros, Gabriel Sas, Lennart Elfgren

Luleå University of Technology, Luleå, Sweden

Silvia Bianchi, Fabio Biondini

Politecnico di Milano, Milan, Italy

Brian Kukay

Montana Technological University, Montana, United States

Contact: angelica.agredo@ltu.se

Abstract

The reduction of the structural capacity and eventual collapse of existing concrete bridges is often related to the loss of the initial prestressing forces. This loss can be associated to immediate or time dependent factors such as elastic shortening, creep, relaxation, loading, and cracking, among others. In addition, environmental factors can lead to corrosion of the strands with the subsequent reduction of their area, loss of bond with the concrete and additional cracking which in turn will influence the value of the residual prestress force and the bridge capacity. Therefore, the evaluation of such losses is critical in the decision-making process of defining a financial and environmental cost optimized intervention strategies (e.g., strengthening or replacement). In this paper, a detailed literature review regarding destructive and non-destructive methods for measuring the residual force in prestressed concrete bridges is carried out and used to develop a database of existing experimental tests.

Keywords: concrete bridges, residual prestressing forces, prestressing losses, evaluation prestressing force, methods residual stress, in situ tests, assessment of PC bridges, flexural bearing capacity.

1 Introduction

European road traffic has greatly increased during the past years due to several reasons such as the requirement of supplying for a larger population, reduction of transportation costs, and an urge of decreasing polluting emissions [1]. This issue has been being formally acknowledged by 96/53/EC directive (The Council of the European Union, 1996), which allows the circulation of Long and Heavy Vehicles (LHVS) [1] within European member union states, on an equal and not discriminatory basis. As consequence, there is a pressing need of not only ensuring structural reliability but also, reducing the maintenance and repairing costs of the existing road infrastructure.

One of the most critical issues regarding the assessment of the structural capacity of existing concrete bridges is related to the evaluation of the loss of the initial prestressing forces. This loss can lead to a significant reduction of the bridges' structural capacity and their eventual collapse [2]. Among the factors that are associated to a decrease in the initial prestressing force, it is possible to find time-dependent factors such as elastic shortening, creep, relaxation, loading, and cracking, among others [3]. In addition, environmental factors can lead to corrosion of the strands with the subsequent reduction of their area, and loss of bond with the concrete [4].

It is then clear that an evaluation of such losses is critical in the process of defining the intervention strategy on such structures (e.g., maintenance, bridge load ratings, demolition, etc.). These interventions should be designed to improve or maintain the structure's capacity or, depending on the case, plan its replacement, guarantying a financial and environmental cost optimized solution [5]. Although an important effort has been carried out in previous years on the development of reliable and accurate experimental and analytical methods for the measurement of residual prestressing forces [6], there is not yet a well-established process and research on the topic it is kept ongoing.

The aim of this paper is to summarize the work made regarding the methods to measure residual prestressing forces. With this goal, a detailed literature review of available research papers was carried out and the main findings of this process are presented here. It is expected that this paper will help researchers to plan future experimental tests that focus on variables with scarce data, serving as a reference point for the development of future research.

2 Available methods for measuring the prestressing force

Figure 1 shows how research (expressed here as number of published papers on indexed journals found in Google Scholar research tool) on the loss of residual prestressing forces has grown steadily during the previous decade. Papers included in Figure 1 are those found using combination of the following keywords: "evaluation prestressing force", "prestressing losses", "method residual stress", "in situ tests", "assessment of PC bridges", "flexural bearing capacity".

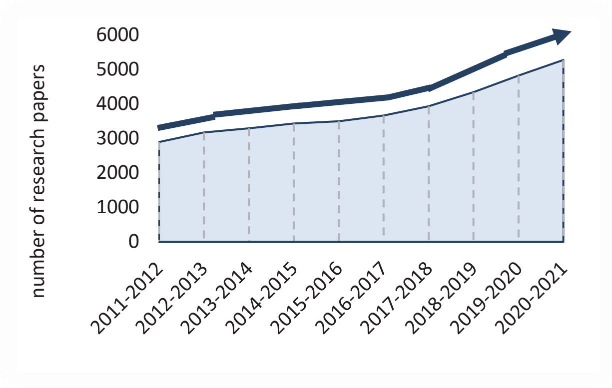

Figure 1. Number of research papers/year

A significant amount of the papers deals with methods to evaluate residual prestressing forces. As shown in Figure 2, authors mainly classify the methods as destructive and non-destructive. Non-destructive methods do not compromise the bearing capacity of the structure, regardless of minor interventions that could be performed during and/or after the test. Meanwhile, destructive methods may affect the structural behaviour of the bridge.

For the case of non-destructive methods, in addition to testing methods (see section 3), hybrid methodologies of data-based monitoring (i.e., structural health monitoring) have been developed in the last years to overcome main drawbacks of a specific method. Further research is still necessary to validate its application for both equipment and data processing to promote their practical implementation in industry [7,8].

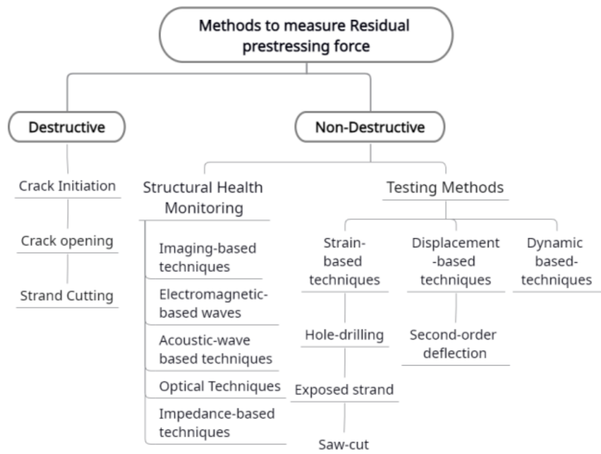

Figure 2. Methods to measure residual prestressing force.

3 Testing Methods

As shown in Figure 2, non-destructive testing methods can be divided in strain-based, displacement-based, and dynamic-based techniques. Among these, testing methods that used strain as the main parameter, are the most popular. This is also the case for destructive methods, also shown in Figure 3, that are based the measurement of the strain in the tendons.

Emerging techniques based on vertical deflections (i.e., displacement-based) take accurately and instantaneously into account the changes of structural geometry due to prestressing losses. These techniques also consider the combined effects of tendon relaxation, concrete creep and shrinkage, and parameters of the real environment as, e.g., temperature and relative humidity [9].

Dynamic-based techniques are still open to debate as several authors, e.g. [10,11], have agreed that changes in natural frequency due to prestress losses are negligible. In addition, these methods require the mode shape or optimal natural frequency of the bridge, which is challenging to retrieve a priori. Selection of different frequency may provide varying degrees of accuracy in prestressing force estimations [12].

To gain an overview of the research carried out in this topic in previous years, papers found according to the criteria set in Section 2, were narrowed down to those addressing specifically testing methods. This procedure generated a reduced sub-database of relevant research papers which are analysed in Figure 3. Results of this analysis show that most of the previous research has been devoted to strain-based methods (hole-Drilling, saw-Cut, exposed strand, crack opening, strand cutting and crack initiation). In Figure 4, the cumulative number of papers for each one of the testing methods analysed is presented. Table 1. shows the starting year and the last year at which the respective testing method has been practiced in a published research document. It can be noticed how certain methods have been kept performed throughout the years meanwhile and how new testing techniques have the arisen since last decade.

According to the information presented on Table 1 and Figure 4, the following conclusions can be made:

1. Most of the methods have been performed under laboratory conditions, taking out of consideration the randomness of effect for being in a controlled environment.

2. Most of the testing methods have been applied for slab-girder bridges. Still, applications on Box-girder bridge have barely been recorded on research documents.

3. research on destructive methods is significantly higher than that devoted to non-destructive procedures.

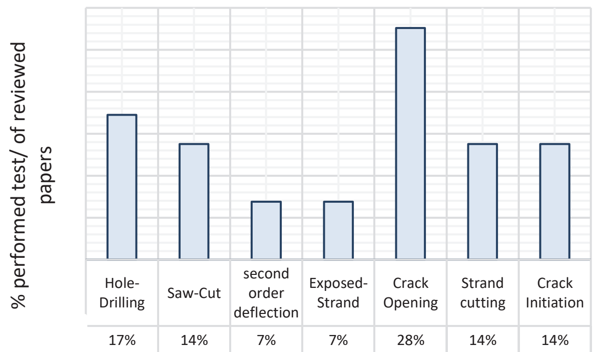

Figure 3. Testing methods.

Table 1. Time-line of main testing methods

Test	No. of papers	First Year	Last year	place performed: In-situ	place performed: Lab	type of beam: Rectangular	type of beam: I shaped	type of beam: Box girder
Hole-Drilling	5	1996	2020	x	x	x	x	
Saw-Cut	4	2008	2021	x	x	x	x	
second order deflection	2	2020	2021	x	x			
Exposed-Strand	2	1993	2014	x			x	
Crack Opening	8	1954	2019	x	x	x	x	x
Strand cutting	4	1954	2015	x			x	
Crack Initiation	4	1954	2020	x	x	x	x	

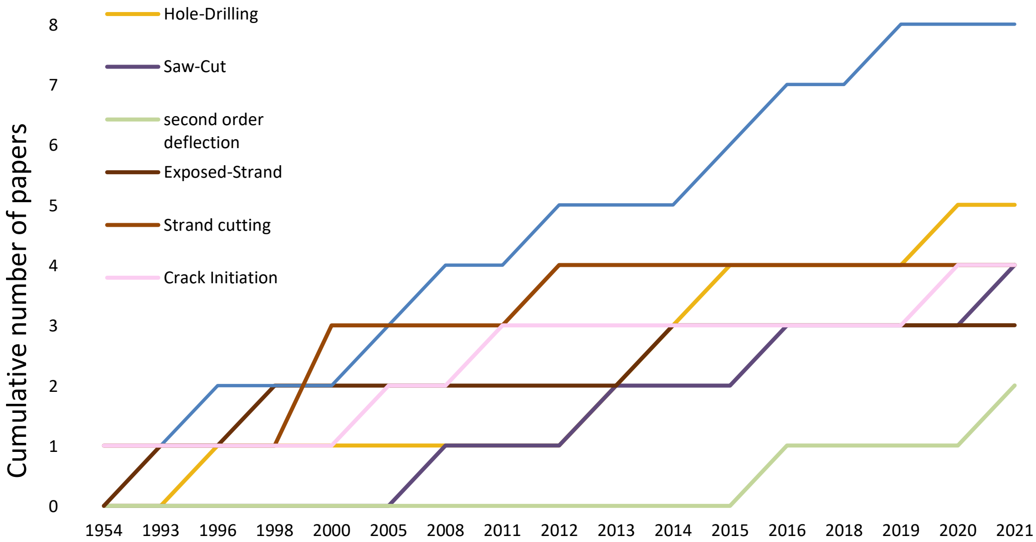

Figure 4. Time-line test performed over the years

In sections 3.1 and 3.2, a description of the main non-destructive and destructive available tests is presented. Dynamic-based tests are not included due to the abovementioned considerations.

3.1 Destructive Testing

3.1.1 Crack-initiation method

This method is based on the monitoring of the concrete strain of the loaded element until the first crack is reached. Load and unloading processes are carried out gradually and by set steps. Values of strain and load are then used to compute the cracking moment, M_{cr}. Load-strain curves are retrieved by means of the Navier´s formula, as expressed on eq. (1)**Chyba! Nenalezen zdroj odkazů.Chyba! Nenalezen zdroj odkazů.Chyba! Nenalezen zdroj odkazů.Chyba! Nenalezen zdroj odkazů.**, and used to determine the residual prestressing force (P_e).

$$\sigma = \frac{P_e}{A_g} + \frac{P_e e y_g}{I_g} - \frac{M_{sw} y_g}{I_g} - \frac{M_{cr} y_c}{I_c} \quad (1)$$

Where: σ = stress at the crack location; P_e = effective prestress force in the beam; A_g = cross-sectional area at the crack location; e =eccentricity of the prestressing force at the crack location; y_g = neutral axis location of the girder measured from the bottom of the beam at the crack location; I_g = moment of inertia of the girder at the crack location; M_{sw} = moment at the crack location due to self-weight; M_{cr} = cracking moment in the beam due to the externally applied load; y_c = neutral axis location of the composite section measured from the bottom of the beam at the crack location; and I_c = moment of inertia of the composite section at the crack location.The method requires to bear into the calculations possible existing cracks that may modify the expected results according to an initial linear expected behaviour. Prior knowledge of the mechanical characteristic of the materials will highly influence the accuracy of the results [13–15] and therefore, a detailed assessment of these parameters is required.

Mapping the crack formation is essential, representing a main drawback in large structure´s tests application. In order to detect cracks, digital image correlation (DIC) techniques can be useful, but still, the size issue remains [16].

3.1.2 Crack opening

also called load decompression method, follows a similar procedure to that of the crack-initiation method. After the structure has undergone the initial cracking load, strain gauges (or other strain measurement tools) are used to quantify the load at which the crack reopens so the stress at the tension fibre of the concrete girder is dismissed [2,10,15–20].

The decompression load is defined as the magnitude at which non-linear strain behaviour starts to be evident. Once this load is determined, the Navier equation, eq. (1), is used.

In case of secondary moments due to hyperstatic features, the procedure will follow an iterative sequence for determining the prestress force.

Different alternatives to this method have been developed to overcome unknown factors such as the compression zone depth of the cracked concrete due to non-linearities presented [5]. Based on FE analysis to simulate the loading history of the structure to introduce the crack which will be experimentally investigated. It is then possible to determine iteratively the prestress force that results in a simulated decompression-load similar to the one obtained from the measurements on the actual structure. This procedure has proved to be ideal to be incorporated in full-scale tests of bridges that will be out of service, measuring the opening of an existing crack or the concrete strains beside it.

3.1.3 Strand cutting method

The method consists of instrumenting wires from prestressing strands with a sensor and cutting the wires to observe the strain release. Different ways of cutting the strand after exposing it have been used over the years. Some authors as [15,21] have flame-cut the strands while data were collected. Others have cut them by using bolt cutters [22,23].

The length of the wires has to follow a specific criterion to ensure the predicted transfer length so that the prestress at this location would be the full effective prestress. The concrete along this set length is then removed to eliminate the steel-concrete bond and ensuring complete isolation for the wires to undergo deformations along the longitudinal axis.

The strain in the wires is measured by sensors which are oriented along the axis of the wires. the respective stress can be calculated by knowing the strain of the wires after relaxation, using Hooke's law.

Main drawbacks and concerns regarding the discrepancy of this method with respect to other testing procedures or standard codes are:

- Local loss of prestressing force due to removing of concrete cover and exposure of the strand which can result in a higher measurement.
- Inaccurate readings due to the shock of the strand snapping when cut which may damage the gauge.
- Questioning about the accuracy of results obtained instrumenting a single wire as representative for the entire strand [23].

3.2 Non-Destructive testing

3.2.1 Strain based tests

Hole-drilling test

The Hole-drilling test, also known as the stress-relief coring technique, has been the most widely used non-destructive technique in the past decade (see Figure 3). First applications can be found in literature since 1934 for steel structures (welded parts, rolled structural shapes, and finished structure [24]. For the case of bridges, the first documented application was performed in 1996 [17]. The procedure to apply the method has been summarized as a standard test method by the American Society for Testing and Materials [25]. It consists in determining the side pressure (hoop stress) required to close an induced crack in a small cylindrical hole drilled adjacent to the tendon in the tensioned flange of a PC girder [17,25–27], as shown in Figure 5.

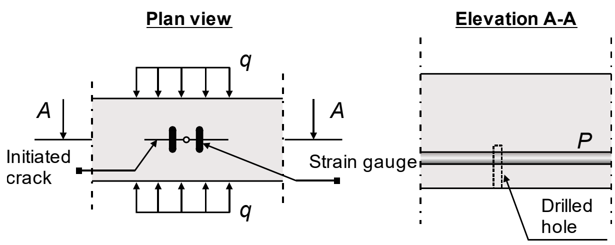

Figure 5. Hole-drilling test.

The standard normative provides the depth of the hole and number of holes with respect to the thickness of the element.

As assessing the hoop stress for arbitrary values of the side pressure at a specific location in concrete is a difficult task, a pre-cracking must be induced. This analysis requires a transformation function eq.(2)**Chyba! Nenalezen zdroj odkazů.Chyba! Nenalezen zdroj odkazů.Chyba! Nenalezen zdroj odkazů.** of the relieved strains into the residual stress state, *S*. This transformation is mostly achieved by a computational procedure in which calibration coefficients are given by a finite element simulation:

$$S = \frac{\gamma q}{\beta} = Kq \qquad (2)$$

where S is the axial stress, γ and β are concentration factors, and K is the ratio of the available stress S to the side pressure q at complete crack closure [17]. Numerical simulation can provide further knowledge of these factors.

Chyba! Nenalezen zdroj odkazů.Chyba! Nenalezen zdroj odkazů.Chyba! Nenalezen zdroj odkazů.Chyba! Nenalezen zdroj odkazů.Chyba! Nenalezen zdroj odkazů.Chyba! Nenalezen zdroj odkazů.Chyba! Nenalezen zdroj odkazů.Chyba! Nenalezen zdroj odkazů.Chyba! Nenalezen zdroj odkazů.*Saw cut*

The procedure of this method is similar to that of the aforementioned hole-drilling test. However, in this case, the stress relief is caused by sawing instead of pre-cracking. This testing method requires the progressive isolation of a concrete block at the tensioned flange of the beam by means of a saw-cut carried out under a loaded condition [16,28–30]. Subsequently, the applied saw-cuts isolate the concrete block from the acting forces, while the stress or strain change is measured in the area adjacent to the performed saw-cuts as appreciated in Figure 6.

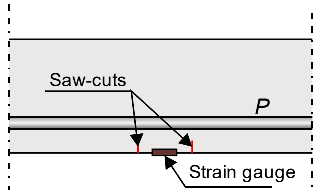

Figure 6. Saw-cut method

The concrete block is fully isolated if the increasing depth of saw-cuts does not lead in any significant strain or stress change in the isolated concrete block. This is usually verified using FEM simulations. Cutting small diameter reinforcement should not significantly affect the accuracy of the obtained results. Nevertheless, cutting larger diameter reinforcement must be avoided because it might jeopardize the structure's integrity and the results of strain measurement (stress change) could be significantly affected.

Crossbow test (exposed strand)

This method relates the tension in the tendon to the vertical deflection, δ(*F*), recorded when a known load (*F*) is applied to an exposed strand, as shown in Figure 7. Experiments have validated the efficiency of the method with strand diameters under 12.5 [mm]. An important part of this technique is the careful exposure of the prestressing strands (or wires) which should be properly repaired later [12,31,32]. The main drawback of this procedure is the necessity of reliable calibration data representing, for example, the strand's properties and its exposed length. Considerations regarding the friction of the specific instrument to apply the force on the strand needs also to be considered.

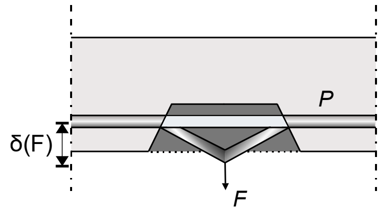

Figure 7. Exposed strand test.

Effects regarding the magnitude of the force applied to produce the required displacement remains unknown. In fact, surrounding concrete may be affected by the pull-out effect of the applied force. Moreover, in practice, it may sometimes be impossible to expose the strand on a prestressed concrete structure in service.

Deflection based tests

As shown in Figure 3, research on displacement-based test is significantly lower when compared to that of strain-based testing methods. However, available literature has shown promising results [9]. These tests are based on a reference Euler-Bernoulli beam model of the PC girder compressed by a prestressing force *N* with an eccentricity *e* with respect to the centroid of the cross section. After the application of the eccentric prestress force *N,* a camber curve v^0 is retrieved. A vertical load *F* is then applied to produce an additional bending deflection v^1 to the deflection curve v^0. The final deflection curve, v^{tot}, is the deflection curve after the application of the vertical load *F*. [9,33,34].

An accurate definition of the flexural stiffness of the beam will directly impact the result of the method. The definition of the deflection shape of the structure does not take into account second order effects with respect to the prestressing force applied. In this way, the magnification factor approach can be employed to identify the prestressed force.

The influence of vertical deflections induced by a moving vehicle along the bridge have not been investigated and requires future research. In addition, the constraint stiffness at the beams' ends must be evaluated for members with unknown boundary conditions.

4 Discussion and conclusions

Results of this paper show that research on destructive tests for evaluating the residual prestressing is significantly higher than that on non-destructive tests over the years. It was also found that strain-based tests are the most commonly studied/applied for both non-destructive and destructive methodologies.

However, strain-based methods neglect the influence of several factors, such as non-prestressed steel reinforcements, the interaction among the shrinkage, creep of concrete and stress relaxation, prestressing systems and long-term degradation processes, tendon relaxation, and parameters of the real environment which may be important for rigorous prediction of the prestress loss. Constrains as accuracy, feasibility, and impact over the structure, are inherent to all the methodologies, irrespectively of the approach in which they are based on.

For the case of non-destructive tests, further studies regarding their applicability in in-situ cases are required, as most of the reviewed results were performed under laboratory conditions. These conditions eliminate the randomness and uncertainties that in-situ testing present. In addition, all the analysed papers applied the tests on rectangular and I-shaped beams and there is not experimental evidence on their applicability on other type of prestressed elements (e.g., box girders, etc.)

Arising drawbacks for emerging methodologies, such as adaptability and both equipment and data processing procedures, must be developed to promote their implementation.

Finite Element Methods have been consolidated as fundamental tool both for calibrating the testing methods and for predicting their impact on the structure's behaviour. Nevertheless, future proposal for improvements of the testing methodologies should rely on a detailed comparison of experimental results (in situ and in laboratory), FEM and current standard codes.

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