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Advanced NDT-Based Assessment of Prestressed Concrete Railway Bridges - A Standardized Multi-Step Procedure

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Abstract

Prestressed concrete bridges on the Italian railway network represent a small portion of the overall asset inventory but a significant share of the total span count, with a predominance of pre-tensioned simply supported decks. Their potential vulnerability—particularly in post-tensioned systems—combined with evolving regulations and testing technologies motivates the adoption of standardized, repeatable investigation procedures. This paper presents a five-step assessment workflow comprising: historical review; preliminary homogeneity analysis (geometry, prestressing system, detailing, materials); targeted test campaign; homogeneity verification; and, when required, an integrative testing phase.

The methodology addresses constructive detailing, in-situ material characterization (concrete and rebar), and the prestressing system. Applied techniques include ground-penetrating radar for tendon profiling; ultrasonic tomography for post-tensioned ducts (validated via endoscopy and direct inspections); direct residual stress measurements on tendons (release tests and X-ray diffraction); and indirect concrete-release testing. Sample sizes are statistically calibrated—using Student's t-distribution for steel strength and hypergeometric sampling for defective-tendon detection—enabling appropriate knowledge levels through a balanced combination of direct and indirect tests.

The proposed approach reduces invasiveness, time and cost, supports structural assessments, when needed, and re-classification (axle loads and/or speed), and is formalized within the Rete Ferroviaria Italiana Guidelines issued for experimental application.

Keywords: prestressed concrete bridges, investigation plans, non-destructive testing, residual stress measurement, x-ray diffraction, release tests on concrete, levels of knowledge.

1 Introduction

The reliability of existing pre-stressed concrete (PSC) bridges remains a highly relevant and timely topic, particularly for post-tensioned concrete (PTC) structures built between the 1960s and 1970s. In recent years, increased attention to the structural performance of these assets—together with the evolution of national technical guidance, such as the Guidelines for the classification and management of risk, safety assessment, and monitoring of existing bridges issued in 2020 by the Superior Council of Civil Works [1]—has further emphasized the importance of accurate assessment and management strategies.

Rete Ferroviaria Italiana (RFI), part of the Ferrovie dello Stato Group, manages one of the most significant bridge assets in Europe. Across approximately 17,000 km of railway, there are around 18,000 bridges totalling about 40,000 spans. Prestressed concrete decks account for roughly 25% of all spans, although only about 3% of total spans are post-tensioned.

In recent years, notable steps have been taken toward the development of more structured approaches for the investigation of post-tensioned decks, although a fully consolidated and comprehensive methodology has not yet been formally codified within Italian technical regulations. Investigations of prestressing systems—intended to detect hidden defects, quantify residual prestress, and evaluate the mechanical properties of tendon steel—still typically involve partially destructive and operationally demanding procedures. This condition highlights the importance of adopting a calibrated investigative framework capable of ensuring an adequate level of knowledge while simultaneously minimizing invasiveness, cost, and operational time.

This paper outlines the methodology for defining standard investigation plans for existing pre-tensioned and post-tensioned decks, as reported in the "Guidelines for defining investigation plans for PSC bridges" issued by RFI in 2025 [2] for a two-year experimental application. The guidelines establish the type and number of tests required for the main typologies of prestressed decks on the Italian railway network. These typologies—characterized by strong structural standardization and industrialized construction processes—include several typological sections, shown in Figure 1. In general, the PSC railway viaducts managed by RFI are characterised by a high degree of repetition, due to the production process—which is mostly industrial and serial in nature—and to the standardisation implemented during both the design and construction phases. It should also be highlighted that RFI has always designed its PSC structures according to the concept of full precompression, which ensures the absence of tensile stresses in Serviceability Limit States (SLS) outside of the precompression transfer zone. Consequently, this results in the absence of cracking, improved performance of the prestressing reinforcement under fatigue phenomena, and greater durability of the structure.

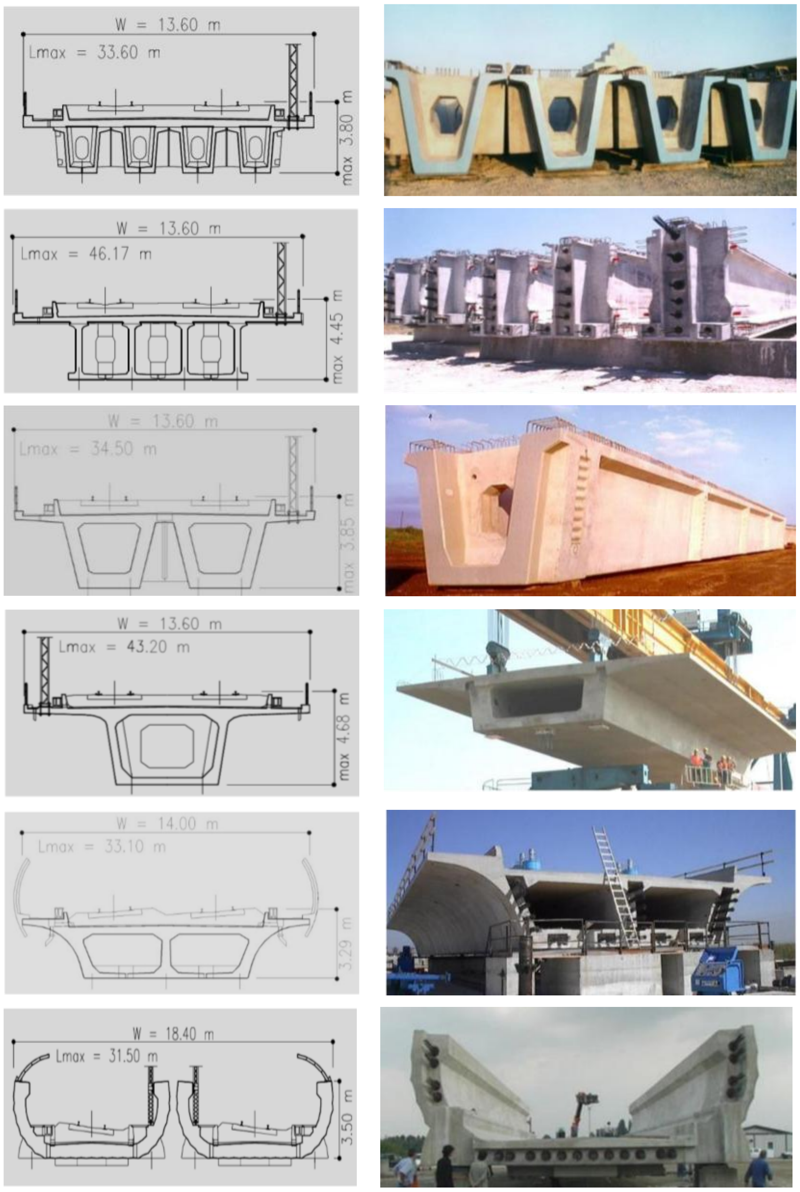

Figure 1: From top to bottom - 4 parallel box girder, beam girder, 2 parallel box girder, single cell box girder, two-cell box girder, through deck

These considerations have led to the introduction, within the methodology described below, of the concept of homogeneity for multi-span viaducts; if verified, this allows for a reduction in the number of tests required for the characterisation of materials and construction details. Furthermore, statistical analyses have been introduced regarding the definition of the main characteristics and any hidden defects associated with post-tensioned prestressing systems.

2 Experimental program

Given the significance of evaluating the safety of existing prestressed concrete decks (particularly those that are post-tensioned), RFI has launched a series of targeted initiatives aimed at constantly improving assessment standards and ensuring increasingly careful and prompt management of its assets.

This includes a two-year research initiative, conducted in collaboration with Politecnico di Torino, with which a 2023 contract was signed for the experimental analysis and assessment of prestress conditions in existing railway viaducts. The initiative involved direct experimentation on three prestressed concrete viaducts on the Italian railway network. During this period, various investigative techniques—both traditional and innovative—were tested, contributing to the development of standard investigation plans.

Some details regarding the viaducts included in the experimental programme, are described below and shown in Figure 2:

- Bridge 1: prestressed concrete girder deck (pretensioned), 20 m span.
- Bridge 2: post-tensioned box-girder bridge deck, 25 m span.
- Bridge 3: post-tensioned voided-slab bridge deck, 35 m span.

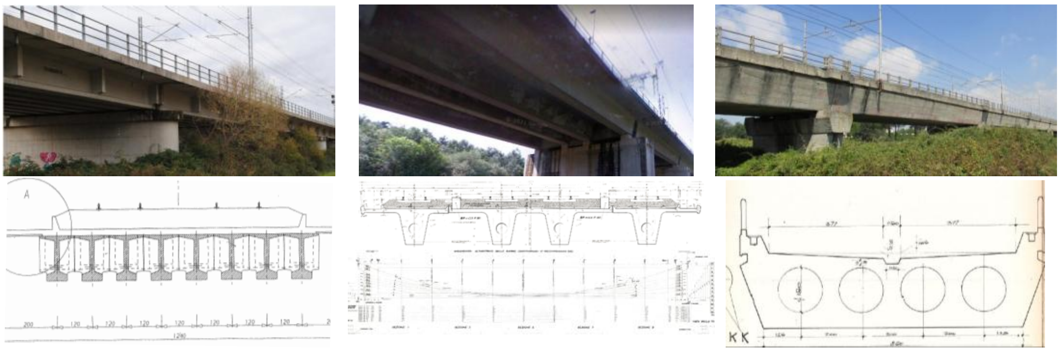

Figure 2: From left to right - bridge1, bridge 2, bridge 3

The experimental activities carried out focused on the following aspects:

- Structural investigations.
- Definition of typical investigation plans and analysis of the data required to perform structural assessments.
- Criteria for the definition of maintenance and structural strengthening interventions.

One of the objectives of the fieldwork was to test, in addition to more traditional methodologies, investigation techniques that are either more innovative or specifically tailored to the type of prestressed concrete bridge decks, such as:

- Ground-penetrating radar (GPR) surveys for determining the layout of the tendons.
- Ultrasonic tomography for assessing the grouting condition of the tendons.
- Tests for the determination of residual prestress: direct methods (X-ray diffraction and strand release tests) and indirect methods (concrete release tests).
- Dynamic identification tests.
- Acoustic emission monitoring (both in service and during strand release tests) to distinguish between potential strand/wire breakage and normal operational behaviour.

Particular attention was devoted to the measurement of residual prestress, which showed a substantial agreement between the values obtained through X-ray diffraction and those derived from strand-release tests on the steel wires.

Conversely, the values obtained from concrete-release tests led to an estimate of the total prestressing force that may either significantly underestimate or overestimate the "actual" value obtained with direct tests. Nevertheless, the results of the concrete-release tests, although not accurate in absolute terms, proved sufficiently consistent within each bridge. This suggests that such tests can be effectively used to verify the uniformity of the prestress state along the structure.

Figure 3 provides a comparison of the results obtained for the residual prestress measurements, showing the percentage variations of the values obtained through concrete-release tests and X-ray diffraction, relative to those derived from steel strand-release tests.

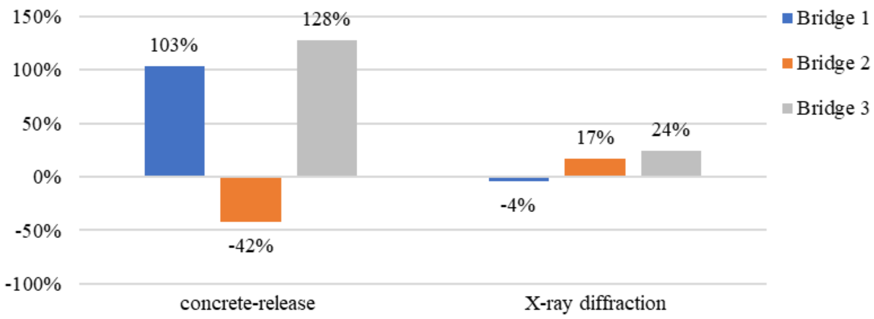

Figure 3: Percentage variations of residual-prestress measurements relative to steel strand release tests.

Figure 4 illustrates the trend of the coefficients of variation (CV), a statistical measure of relative dispersion, calculated as the ratio of the standard deviation (s) to the mean ($\bar{X}$), often expressed as a percentage ($CV = s/\bar{X} \cdot 100\%$), associated with the residual-prestress values measured on comparable elements belonging to the same bridge. The statistical sample considered consists of 18 concrete-release tests (Bridge 1: 4 tests, Bridge 2: 10 tests, Bridge 3: 4 tests).

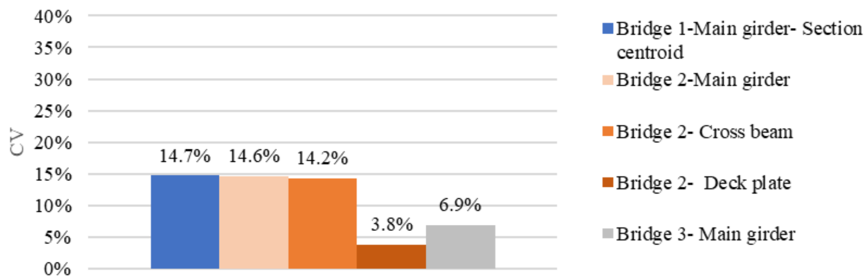

Figure 4: CV of the residual prestress from concrete-release tests.

The limited variability observed within each bridge for comparable structural elements indicates that stress-release testing on concrete may be reliably employed to extrapolate and complement the results obtained from direct testing methods.

3 Methods

This section outlines the theoretical framework adopted to define the required number of investigations on the prestressing system, as reported in Ref. [2]. The methodology and the assumption made take mainly into account the activity conducted in collaboration with Politecnico di Torino and the deliverables in Ref. [3].

The discussion is limited to the parameters that are most relevant for structural verification, namely:

- The yield strength of the prestressing steel.
- The residual prestress.
- The residual cross-sectional area of cables affected by degradation.

For verification purposes, both the yield strength and the residual prestress must be reduced by an appropriate confidence factor (CF), which depends on the knowledge level (KL) achieved, as defined in § 3.5 of UNI EN 1998-3:2005 [4]:

- KL1, Limited knowledge.
- KL2, Normal knowledge.
- KL3, Full knowledge.

In this context, the CF may be interpreted as an index quantifying the expected deviation between the sample mean and the true population mean of the parameter under consideration. Consequently, the confidence factor—and therefore the knowledge level—is directly related to the number of investigations performed.

In the adopted methodology, the number of tests required to estimate the yield strength and the residual prestress is determined through a statistical procedure based on a reverse application of Student's t-method, optionally incorporating technical information derived from design documents (prior knowledge vs. no prior knowledge), as further detailed in Section 3.1. This approach enables calibration of the sample size according to the residual uncertainty and the target reliability.

The knowledge level is also influenced by the number of investigations carried out on the construction details. For post-tensioned prestressed concrete bridges, assuming that the construction detail—defined in terms of tendon layout and type/size of wires or strands—is constant, the primary source of variability is the extent of cable degradation, typically associated with grouting defects and manifested as a reduction of the nominal cross-sectional area. For such structures, it is therefore necessary to design an investigation campaign aimed at identifying, with a prescribed probability, the proportion of defective elements within the population. In this perspective, the KL may be interpreted as the probability that the assumed percentage of degraded cables is representative of the actual condition. It is evident that the required number of investigations increases with the desired level of statistical reliability.

The sample size required to assess the residual area of degraded cables has been derived from the methodology proposed in FHWA-HRT-13-028 [5], assuming a hypergeometric distribution for the population of defective samples, as described in Section 3.2.

3.1 Yield Strength of Prestressing Steel and Residual Prestress

In order to determine the number of tests required to define the ultimate tensile strength of prestressing steel, the Student's t-test was applied in reverse. The same methodology was also used to determine the number of tests needed for estimating the residual prestress. First, the meaning of the confidence factor (CF) must be defined starting from the parameters obtained from the investigated sample specifically the sample mean $\bar{X}$ and the population mean μ, evaluated with a given confidence using the Student's t-test. From these, an estimate of CF can be obtained as an index of deviation between $\bar{X}$ and μ.

$$\frac{\bar{X}}{CF} \leq \mu \Leftrightarrow CF \geq \frac{\bar{X}}{\mu} \quad (1)$$

To evaluate CF numerically, the unknown population mean needs to be estimated. For a fixed confidence level $(1-\alpha)$ and given a sample of size $n < 30$with standard deviation s, the following value can be computed:

$$\mu_{1-\alpha} = \bar{X} - \frac{s}{\sqrt{n}} t_{1-\alpha,n-1} \quad (2)$$

This represents the lower bound for the population mean μ. Consequently, the confidence factor CF becomes:

$$CF = \frac{\bar{X}}{\mu_{1-\alpha}} = \frac{1}{1-\frac{1}{\sqrt{n}}CV\, t_{1-\alpha,n-1}} \quad (3)$$

where CV is the coefficient of variation defined:

$$CV = \frac{s}{\bar{X}} \quad (4)$$

The minimum sample size is estimated by applying the Student's t-method in reverse, based on:

$$CF = \frac{1}{1-\frac{1}{\sqrt{n}}CV\, t_{1-\alpha,n-1}} \quad (5)$$

The inverse problem, —i.e., determining *n* given CF—requires an iterative procedure:

1. Select the desired confidence level $1-\alpha$.
2. Select the target confidence factor.
3. Choose an initial value of CV.
4. Compute the required number of tests *n*.
5. Perform the *n* tests and compute the actual CV.

The required number of tests may be reduced when prior information from original drawings or previous testing is available. Two scenarios are therefore distinguished—No prior knowledge and Prior knowledge—and the statistical parameters are reformulated as:

$$\bar{X}_u = \frac{n_0 \bar{X}_0 + n_1 \bar{X}_1}{n_0 + n_1} \quad (6)$$

with:
$\bar{X_0}$= characteristic value from design documents.

n_0= "equivalent" number of tests associated to $\bar{X}_0$.
$\bar{X}_1$= sample mean of tensile strength from testing.
n_1= number of performed tests associated to $\bar{X}_1$.

$$s_u = \sqrt{\frac{(\bar{X}_0-\bar{X}_u)^2 n_0+\sum_{i=1}^{n_1}(X_{1i}-\bar{X}_u)^2}{(n_0+n_1)-1}} \qquad (7)$$

Depending on the available information regarding *Prior knowledge*:

- $n_0 = 0$ → no design data available (*No prior knowledge*).
- $n_0 = 1$ → design specifications available (*Prior knowledge*).
- $n_0 = 2$ → original test certificates available (*Prior knowledge*).

These values are obtained by assuming a 50% reduction in the number of tests when the design specifications are known (compared to the absence of information, from extensive to limited), and a 67% reduction in the number of tests when test certificates are available (from exhaustive to limited), according to Ref. [4]. The expression for CF becomes:

$$CF = \frac{1}{1-\frac{1}{\sqrt{n_0+n_1}}CV\, t_{1-\alpha,(n_0+n_1)-1}} \qquad (8)$$

where $t_{1-\alpha;(n_0+n_1)-1}$ is the critical Student's t value, that depends on the selected confidence interval (1-α) assumed equal to 0.95 and on the number of degrees of freedom $(n_0+n_1)-1$. In the following figure, as an example, the sample size is shown as a function of the Confidence Factor for different assumptions of CV, under the hypothesis of no prior information. In particular, the values of CF equal to 1.35 (KL1) and 1.2 (KL2) are highlighted, as prescribed in Refs. [4, 6, 7].

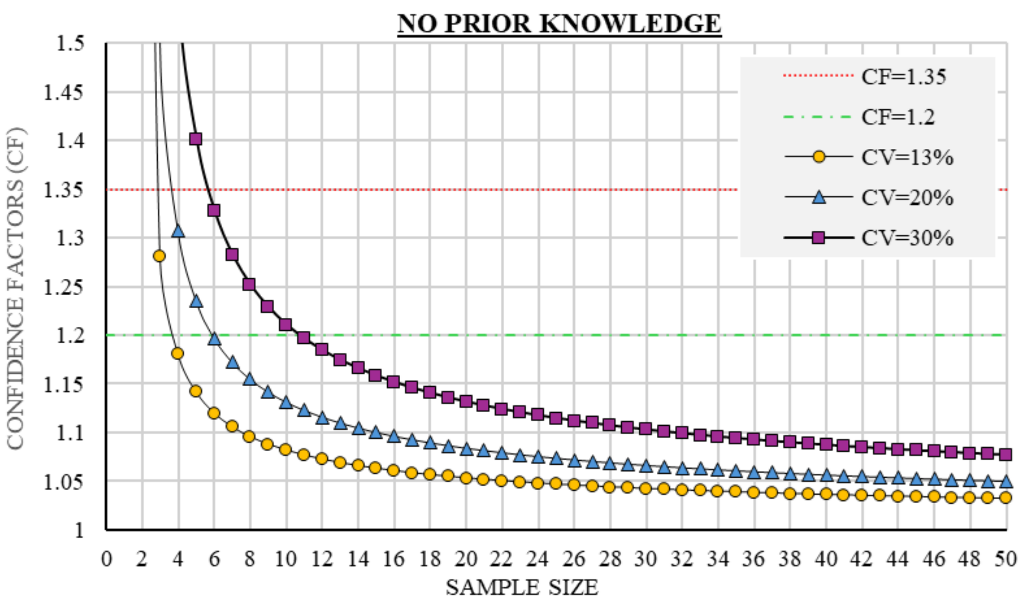

Figure 5: Simple size for different coefficient of variation (CV) values

It can be observed that, for a given CF, a larger number of tests is required as the sample's CV increases. The curves are asymptotic with respect to CF = 1; consequently, achieving a realistic KL3 would require adopting a conventional confidence factor greater than 1, which would substantially increase the sample size. For practical applications on RFI assets, KL2 with CF = 1.2 is generally adopted.

3.2 Percentage of defective tendons

The selection of the sample size, and therefore of the number of tests to be performed (n), is based on the assumption that the occurrence of defective elements within the population can be described by a hypergeometric distribution. In this framework, the Knowledge Level is defined using the cumulative distribution function (CDF) of the hypergeometric distribution, expressed as:

$$P(i \le k) = \sum_{i=0}^{k} \frac{\binom{m}{i}\binom{N-m}{n-i}}{\binom{N}{n}} \tag{9}$$

where:
i= number of sampled elements exhibiting the characteristic of interest
m= actual number of elements in the population exhibiting that characteristic
N= total population size
n= size of the extracted sample
k= size of the extracted sample i
$P(i \le k)$ = probability of finding at most k elements with the given characteristic

The aim is to determine the minimum number of samples required to detect at least one element exhibiting the prescribed characteristic. Since the CDF represents the probability of finding at most i such elements, the complementary probability provides the likelihood of detecting at least one:

$$d = 1 - CDF = 1 - P(i < k) \tag{10}$$

Setting k=1 yields:

$$Pd = 1 - P(i < 1) \tag{11}$$

Because the number of defective extracted elements cannot be negative, $P(i<1)$ reduces to $P(i=0)$, and therefore $Pd|1=1-P(i=0)$. In practice, it is sufficient to compute the probability of extracting a sample of n elements containing zero defective elements from a population of N elements of which m elements are actually defective. The estimate of the required number of tests n follows from the probability that the assumed defectiveness ratio ($m / N \cdot 100$) corresponds to the actual one. Consequently, the Knowledge Level (KL), interpreted as the degree of exhaustiveness of the investigation, is directly linked to this probability. As Pd increases—that is, as the probability of detecting at least one defective element (e.g., a corroded tendon) increases—the number of required tests, and thus the level of exhaustiveness, also increases.

For the three Knowledge Levels defined in Refs. [4, 6, 7], the corresponding values Pd adopted are reported in (Table 1).

Knowledge levels	KL1	KL2	KL3
Pd	85%	95%	99%

Table 1: Knowledge Levels vs. Pd

The minimum recommended number of sampled tendons depends, for a given target Knowledge Level, on the total population size *N* and on the acceptable fraction of defective tendons *m*. In the methodology of Ref. [5], this fraction is defined according to the risk associated with potential failure and the Structural Impact Caused by Sampling, as shown in Table 2.

Element Risk	**Structural Impact Caused by Sampling**		
	High	**Medium**	**Low**
High	20 % deficient	10 % deficient	10 % deficient
Medium	30 % deficient	20 % deficient	10 % deficient
Low	30 % deficient	30 % deficient	20 % deficient

Table 2: Acceptable fractions of tendons with deficient grout

In the methodology proposed by RFI for standard investigation plans on simply supported decks, an acceptable fraction of defective tendons equal to 10% is generally adopted, corresponding to the case of high element risk and medium structural impact caused by sampling.

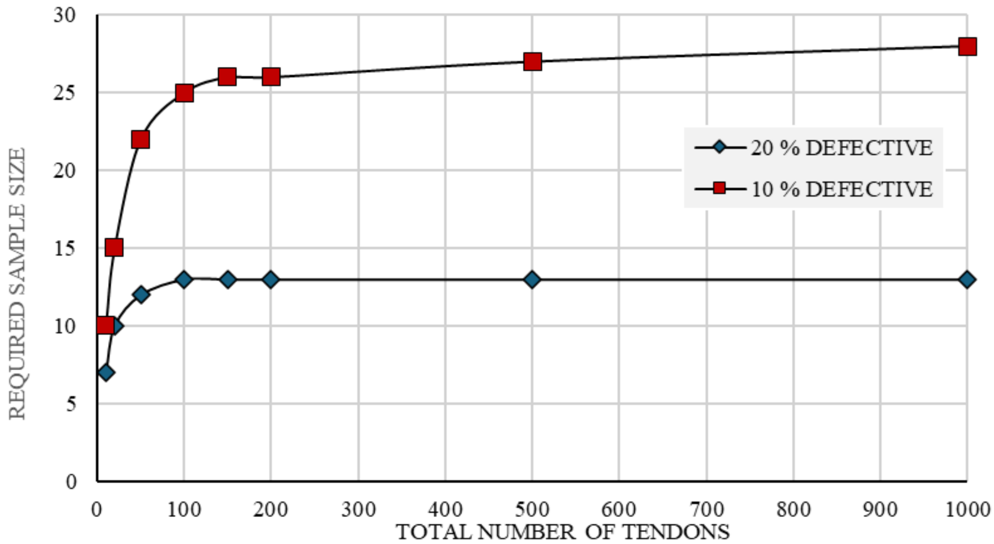

Figure 6: Minimum number of tendons required to detect at least one tendon with deficient grout assuming 10 percent and 20 percent of the samples are defective (Pd=95% - KL2)

As illustrated in Figure 6, the curves exhibit an asymptotic trend as the total number of tendons increases. For this reason, the RFI procedure allows the number of tendons to be investigated to be defined a priori, independently of the number of spans of the viaduct, distinguishing between multi-span viaducts (total number of tendons typically > 200) and single-span bridges (total number of tendons typically ≤ 50).

4 Five-step workflow

A summary of the procedure proposed by RFI for conducting investigations and surveys on prestressed, pre-tensioned and post-tensioned reinforced concrete decks is presented. The procedure is intended to standardize and optimize the number of tests to be performed, which is particularly advantageous for viaducts with a large number of spans. Investigation plans are calibrated to achieve Knowledge Levels KL1 and KL2; this choice stems from the very large number of tests that would be required to attain KL3, as shown in Figure 5, and from the resulting intrusiveness of such testing. If KL3 is required, the test set must be defined on a case-by-case basis in agreement with RFI.

The procedure comprises the following steps:

1. Critical historical analysis.
2. Assessment of deck homogeneity.
3. Investigation campaign.
4. Verification of span homogeneity.
5. If necessary, supplementary testing campaign.

4.1 Critical historical analysis

The first step consists of reviewing all available documentation related to the structure: design and as-built drawings, surveys, original material test certificates, data from previous investigation campaigns, and periodic inspections. This phase is essential because prior knowledge of the structure directly affects the number and intrusiveness of the tests to be performed.

4.2 Assessment of homogeneity

Given the repetitive and prefabricated nature typical of RFI simply supported prestressed concrete viaducts, the professional responsible for the investigation plan should evaluate whether the structure can be partitioned into one or more homogeneous portions (groups of homogeneous spans) to optimize the number of spans and investigations required.

In particular, the assessment of the deck's structural homogeneity, to be carried out by the appointed professional, shall address at least the following aspects:

1. Geometry — deck type, cross-section, span length.
2. Prestressing system — pre/post tensioning, tendon routing, prestressing steel strength, etc.
3. Construction details — non-prestressing reinforcement and execution details.
4. Materials — concrete properties and non-prestressing steel strength.

4.3 Investigation campaign

For the main PSC deck types on the rail network (beam girders, small box girders, single-cell box girders, slab decks), the RFI Guidelines specify the types and overall numbers of tests as a function of the number of spans. The standard investigation set for the prestressing system—derived from experimental results and the statistical considerations summarized in §§2–3— may include:

1. GPR surveys to identify tendon routing.

2. Tensile tests on prestressing steel / hardness tests to determine steel strength.
3. Prestress release tests on the prestressing reinforcement / X-ray diffraction, with possible indirect release tests on concrete, to estimate residual prestress.
4. Ultrasonic tomography, with possible endoscopic inspections and visual probes, to detect injection defects in post-tensioned decks and to assess residual capacity.

The total number of tests to be performed on the entire structure (or on each homogeneous span group) for assessing prestressing steel strength and residual prestress was established taking into account the statistical method described and the plot in Figure 5, assuming a coefficient of variation CV = 13%. This value was established on the basis of the results of the experimentation carried out and may eventually be modified following the two-year trial period of Ref. [2]. The choice of CV = 13% also enables an optimized number of tests and provides a reasonable likelihood of not exceeding the target limits, in line with the available data. The guidelines in Ref [2] report the number of tests as a function of the target Knowledge Level (KL1 or KL2) and the availability of prior information.

Based on the experimental results reported in Chapter 2, the procedure allows replacing up to 75% of direct tests with concrete release tests ($CV_{conc\text{-}rel\text{-}tests}$ should be lower than 15%). Specifically, a limited number of direct measurements (prestressing release or X-ray diffraction) are performed to determine the residual stress state, together with a series of concrete release tests whose purpose is not to determine the absolute prestress value (these are known to be overly approximate) but to generalize direct test results to the remaining parts of the structure. When this approach is used, each direct reference test must be accompanied by a concurrent concrete release test in the same section.

The total number of tendons to be examined by tomography for injection defects recognition is determined using the same statistical method, generally assuming an acceptable defective-tendon fraction typically equal to 10%. However, when the number of tendons to be investigated is operationally constrained (e.g., single-span decks) or when access would require highly invasive works (high structural impact caused by sampling), this percentage may be raised to 20%, thereby reducing the number of tests.

4.4 Verification of Homogeneity

Following the investigation campaign, the assumptions on homogeneity must be verified. In particular, the homogeneity of reinforcement and of the prestressing system can be considered satisfied if, after the campaign (cover-meter surveys, GPR, visual probes, etc.), the inspected spans are consistent with one another or, where available, consistent with the design documentation.

Similarly, material homogeneity is considered satisfied if, after the campaign on a bridge (compression tests / SONREB on concretes; tensile tests / hardness tests on ordinary and prestressing steels), the test results show substantial consistency across the inspected spans or between the inspected spans and the design values where available.

4.5 Supplementary test campaign

If, after the investigations, spans or groups of spans cannot be regarded as homogeneous or are only partially homogeneous (e.g. from tests results one of some of the CVs assumed are trespassed), a supplementary testing campaign must be planned. The total number of integrative tests are reported in RFI's guidelines and are function of KL and prior knowledge.

5 Conclusions

The developed methodology provides a standardized, statistically grounded framework for planning investigations on prestressed concrete decks, enabling significant optimization of the number of tests and a reduction in intrusiveness compared with traditional approaches. The combined use of direct and indirect tests can be effective for characterizing residual prestress, while ensuring Knowledge Levels compatible with safety requirements. In particular, the results of the concrete-release tests, although not accurate in absolute terms, proved sufficiently consistent within each bridge. This suggests that such tests can be effectively used to verify the uniformity of the prestress state along the structure, in combination with direct test to determine the residual stress. The methodology is outlined in the "Guidelines for Defining Investigation Plans for PSC Bridges," issued by RFI in 2025 [2] for a two-year experimental implementation period. The input parameters and the presented methodology may be revised after this period, based on the results obtained from the investigations conducted on existing PSC railway bridges.

For Rete Ferroviaria Italiana, implementing this procedure can yield tangible benefits: greater consistency in investigation plans, reduced operational time and costs and enhanced reliability in structural assessments, when needed. Overall, the methodology offers a robust technical basis for more effective management of prestressed concrete structures across the network.

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