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Article

The Development and Statistical Analysis of a Material Strength Database of Existing Italian Prestressed Concrete Bridges

Michele D'Amato [1,*], Antonella Ranaldo [1,*], Monica Rosciano [1], Alessandro Zona [2], Michele Morici [2], Laura Gioiella [2], Fabio Micozzi [3], Alberto Poeta [3], Virginio Quaglini [4], Sara Cattaneo [4], Dalila Rossi [4], Carlo Pettorruso [4], Walter Salvatore [5], Agnese Natali [5], Simone Celati [5], Filippo Ubertini [6], Ilaria Venanzi [6], Valentina Giglioni [6], Laura Ierimonti [6], Andrea Meoni [6], Michele Titton [7], Paola Pannuzzo [7] and Andrea Dall'Asta [3]

[1] Department for Humanistic, Scientific and Social Innovation (DIUSS), University of Basilicata, Via Lanera 20, 75100 Matera, Italy; monica.rosciano@unibas.it
[2] School of Architecture and Design, University of Camerino, Viale della Rimembranza 3, 63100 Ascoli Piceno, Italy; alessandro.zona@unicam.it (A.Z.); michele.morici@unicam.it (M.M.); laura.gioiella@unicam.it (L.G.)
[3] School of Science and Technology, University of Camerino, Via Gentile da Varano III 26, 62032 Camerino, Italy; fabio.micozzi@unicam.it (F.M.); alberto.poeta@unicam.it (A.P.); andrea.dallasta@unicam.it (A.D.)
[4] Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy; virginio.quaglini@polimi.it (V.Q.); sara.cattaneo@polimi.it (S.C.); dalila.rossi@polimi.it (D.R.); carlo.pettorruso@polimi.it (C.P.)
[5] Department of Civil and Industrial Engineering (DICI), University of Pisa, Largo Lucio Lazzarino 2, 56126 Pisa, Italy; walter.salvatore@unipi.it (W.S.); agnese.natali@unipi.it (A.N.); simone.celati@phd.unipi.it (S.C.)
[6] Department of Civil and Environmental Engineering, University of Perugia, Via G. Duranti 93, 06125 Perugia, Italy; filippo.ubertini@unipg.it (F.U.); ilaria.venanzi@unipg.it (I.V.); valentina.giglioni@unipg.it (V.G.); laura.ierimonti@unipg.it (L.I.); andrea.meoni@unipg.it (A.M.)
[7] ITS Engineering Company Corte delle Caneve, 11, 31053 Pieve di Soligo, Italy; michele.titton@its-engineering.com (M.T.); paola.pannuzzo@its-engineering.com (P.P.)
* Correspondence: michele.damato@unibas.it (M.D.); antonella.ranaldo@unibas.it (A.R.)

Abstract

This paper reports a statistical analysis of a database archiving information on the strengths of the materials in existing Italian bridges having pre- and post-tensioned concrete beams. Data were collected in anonymous form by analyzing a stock of about 170 bridges built between 1960 and 2000 and located in several Italian regions. To date, the database refers to steel reinforcing bars, concrete, and prestressing steel, whose strengths were gathered from design nominal values, acceptance certificates, and in situ test results, all derived by consulting the available documents for each examined bridge. At first, this paper describes how the available data were collected. Then, the results of a statistical analysis are presented and commented on. Moreover, goodness-of-fit tests are carried out to verify the assumption validity of a normal distribution for steel reinforcing bars and prestressing steel, and a log-normal distribution for concrete. The database represents a valuable resource for researchers and practitioners for the assessment of existing bridges. It may be applied for the use of prior knowledge within a framework where Bayesian methods are included for reducing uncertainties. The database provides essential information on the strengths of the materials to be used for a simulated design and/or for verification in the case of limited knowledge. Goodness-of-fit tests make the collected information very useful, even if probabilistic methods are applied.

Keywords: post-tensioned concrete bridges; prestressed concrete bridges; material strength; database; prior knowledge; statistical analysis; goodness-of-fit tests

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1. Introduction

Nowadays, many existing transport infrastructures require special attention, as also demonstrated by several sudden failures of bridges that have occurred in the recent past [1–6]. Their aging and increasing traffic loads make it necessary to define a management plan taking into account priorities and available economic resources.

For the reason above, the scientific community is addressing many efforts to investigate how the residual service life of bridges can be estimated, including current material degradations [7,8]. Moreover, recurrent bridge typologies are being studied, paying particular attention to their design rules, as they were realized, and the frequent damages/defects that may be encountered [9]. Within this framework, the knowledge of materials' properties plays a crucial role, along with how they may degrade over time.

Within this scope, recently, the FABRE consortium (a Research Consortium for the Evaluation and Monitoring of Bridges, Viaducts, and Other Structures (https://www.consorziofabre.it/)) funded the research project "*A reviewed SAfety FOrmat for structural reliability assessment of post-TEnsioned concrete Bridges*" (briefly, the SAFOTEB project). The project aims to assess the residual life of existing post-tensioned concrete bridges, including their typical degradation mechanisms, and based on a partial factors format. Also, applications to some case studies were performed [9–13]. The research group included the University of Basilicata, the University of Camerino, the Politecnico di Milano, the University of Pisa, the University of Perugia, and the ITS Engineering company.

In this paper, some results obtained within the SAFOTEB Work Package 1 (WP1)–Material Properties are illustrated and commented on. In particular, in this WP, a database was developed by examining a stock of 168 existing prestressed Italian bridges, including both pre- and post-tensioned concrete beams (pre-TCBs and post-TCBs, respectively). The sample under examination includes several Italian bridges that the project's research units investigated in previous activities carried out within and funded by the FABRE consortium.

The investigated bridges are located in several Italian regions, built between 1960 and 2000. In particular, the database stores the strength details of the following materials: steel reinforcing bars, concrete, and prestressing steel. These properties were gathered from design nominal values, acceptance certificates, and in situ tests, all derived from the available documents for each bridge examined.

At first, a brief state-of-the-art review on prestressing technology is introduced. Then, the organization of the database is illustrated, and the main results related to the materials' strength are discussed. Finally, a statistical analysis is completed by means of two goodness-of-fit tests, which are the Shapiro–Wilk and D'Agostino–Pearson tests, for testing the assumption of a normal distribution for steel reinforcing bars and prestressing steel, and a log-normal distribution for concrete. Statistical tests are executed only for variables having a significant number of data points.

This research carried out is important within the structural engineering community, since it is widely known that prior knowledge of a material's mechanical characteristics is indispensable for the initial performance assessment, to be later complemented by specific investigations, reducing uncertainties [9–11]. To date, several investigations have been performed, involving Bayesian updating approaches for integrating additional information obtained from experimental tests with prior knowledge. They allow us to assume more accurate mechanical parameters, calibrating reasonable values of confidence factors [14]. By employing Bayesian frameworks for inference, probability distributions of structural modeling parameters may also be updated [15]. Developments and applications of Bayesian approaches for updating the numerical models of buildings and bridges may be found in [16–19].

Moreover, the scientific community has made significant efforts to deepen the understanding of the mechanical properties of materials used in existing constructions. These initiatives have primarily focused on existing buildings through the development of statistical analyses and dedicated material databases. Among others, it is worth mentioning the study reported in [20–23] related to reinforced concrete structures, the steel database available in [24], as well as the probabilistic models proposed in [25], based on a significant amount of data collected from previous work. On the contrary, only a few studies are available in the literature regarding the mechanical properties of materials used in existing bridges. Among these, a study on the material properties of weathering steels is available in [26]. Recently, the California Department of Transportation (Caltrans) has provided documents reporting guidelines and best practices for bridges, where the material properties of historical structural steel are also specified [27].

In this context, the objective of this paper is to reduce the gap between existing concrete bridges and buildings, given that the materials used for existing bridges have characteristics generally different from those used in existing buildings; structural elements in existing bridges have different environmental exposure and degradation, resulting in different aging compared with those in existing buildings; and procedures for estimating the mechanical characteristics of the existing materials are available for existing buildings but not for existing bridges.

2. Concrete-Prestressing Technology

Prestressed concrete (PC) was pioneered in the early 1900s by Eugène Freyssinet [28,29] for the construction of an arch using prestressing cables. However, this technology became firmly established only after the Second World War. Initially, prestressing with reinforced steel tendons proved ineffective because the steel tensioning level was inadequate. Once high-strength steel was introduced, prestressing became widely used.

PC has been widely applied for building bridges and other types of constructions, providing several benefits with respect to elements made of ordinary concrete, such as tensile stress reduction, higher durability, slender beam cross-sections, longer spans, and limited deformability. Additionally, PC prefabricated elements ensure construction efficiency with higher quality control, offering design flexibility to create different structural shapes [28,29].

Prestressing is realized by means of compressive forces, contrasting with the external loads generated by steel tendons or cables, tensioned and anchored to the concrete. It may be applied in different ways, such as internal, external, and mixed, where wires, bars, strands, and braids may be applied as steel tendons. Moreover, PC technology may be applied in two different systems, such as pre- or post-tensioning, that is, before or after the element's concrete curing, respectively [28,29]. As for post-tensioning, several anchoring systems have been patented, such as, among others [29], the STUP system, employing the method indicated by Freyssinet for the first conical friction anchor, and the Magnel, Barredo, Morandi, Dywidag-Finsterwalder, B.B.R., and Lee-McCall systems.

Figure 1 shows the prestressing procedure for pre-tensioning (Figure 1a) and post-tensioning (Figure 1b) by considering a concrete beam. As for the pre-tensioning system, the tendon is tensioned by jacking against an anchor frame before concrete pouring. When the concrete has obtained sufficient strength, the tendons are released from the external anchors, thus transferring the force to the beam through the bond between the pre-tensioned steel and concrete. On the contrary, for post-tensioning, the tendon is tensioned after the element curing using a jack, and the resulting force is transferred directly onto the hardened concrete through the tendon anchor [28]. In this case, tendons are placed within sheathing or a duct refilled with coating grease for unbonded applications or grouted ducts, grout caps, and grout vents for bonded applications.

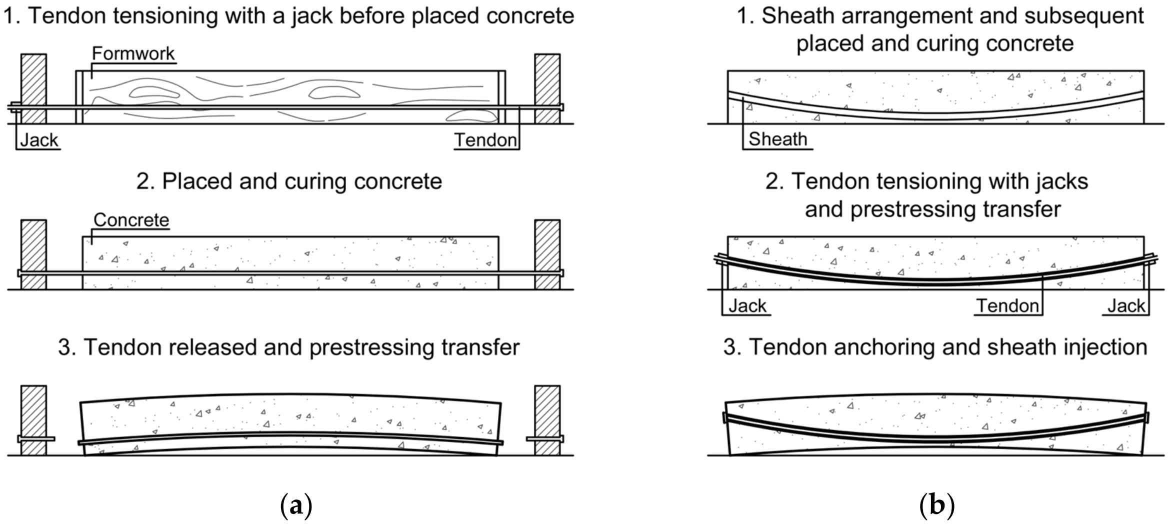


Figure 1. Concrete beam prestressing technology: (**a**) pre-tensioning; (**b**) post-tensioning.

3. Database Development

A database collecting the material strengths of reinforced concrete (RC) girder bridges having prestressed concrete beams (PCBs) was developed. A stock of 168 bridges built in Italy between 1960 and 2000, having both pre-TCBs and post-TCBs, is analyzed. The number of bridges and their geographical locations are shown in Figure 2a. Meanwhile, as illustrative examples, Figure 2b reports some images of the bridge typologies considered.

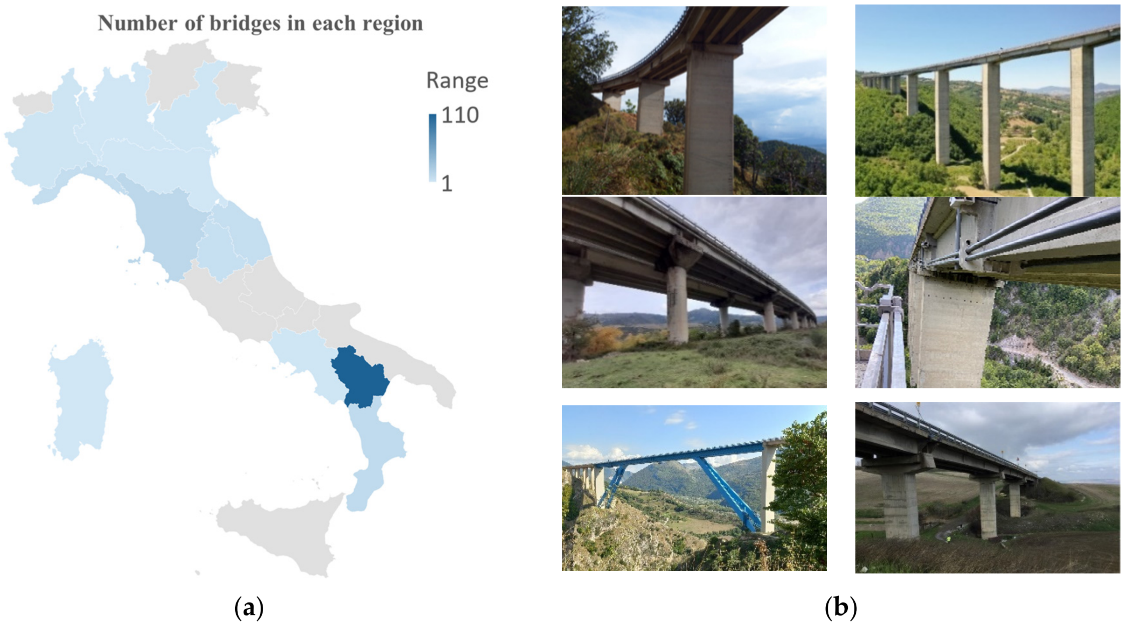
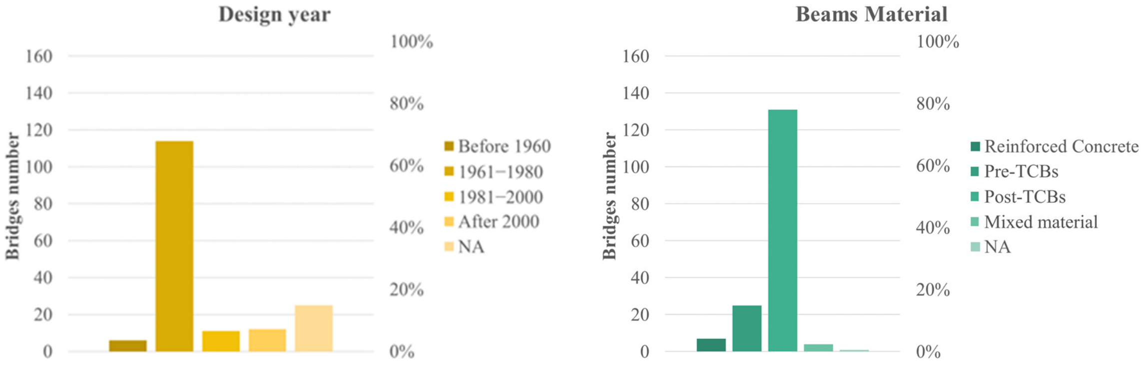


Figure 2. (**a**) Number of bridges analyzed in each region of Italy; (**b**) bridge typology examined.

Figure 3a shows the distribution of bridges for several design year intervals. The analyzed sample is predominantly composed of bridges designed between 1961 and 1980 (68% (114 bridges)), reasonably in accordance with the Circular of the Ministry of Public Works of 14 February 1962, no. 384 [30]. Moreover, a noticeable percentage of bridges lack a specific design year (indicated as not available (NA)).



(**a**) (**b**)

Figure 3. Bridges' distribution for (**a**) design year; (**b**) beams' construction material.

It is possible to analyze the sample of bridges obtained in terms of the adopted materials. According to this criterion, Figure 3b shows that 93% (156 bridges) of the sample is composed of PCBs, of which 78% (131 bridges) were realized with post-TCBs and the remaining 15% (25 bridges) with pre-TCBs. Meanwhile, only 4% (7 bridges) were realized with RC beams, and 2% (4 bridges) with beams resulting from mixed materials (such as steel and RC associated with PC). Finally, there is a negligible percentage of bridges where the construction type is NA.

The database is divided into three main sections, each collecting, in anonymous form, details about the strength of the materials used. In particular, to date, the following materials are analyzed: steel reinforcing bars, concrete, and prestressing steel. For each of these materials, the following data are archived with the related source: design nominal values retrieved from original design documentation (such as drawings and reports); mechanical values measured during the structures' execution and reported within acceptance test certificates; and values measured with recently performed in situ tests. As examples, design drawings and photos of in situ tests carried out are shown in Figure 4. In the current version, the database does not report any data pertaining to recent structural interventions, like those due to repairs or maintenance.

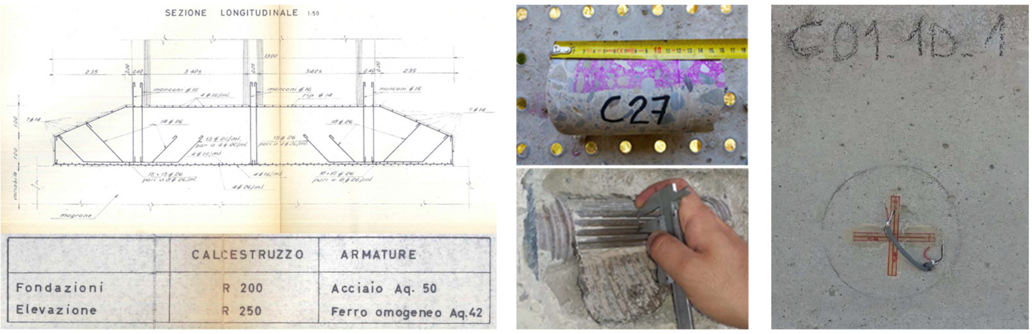
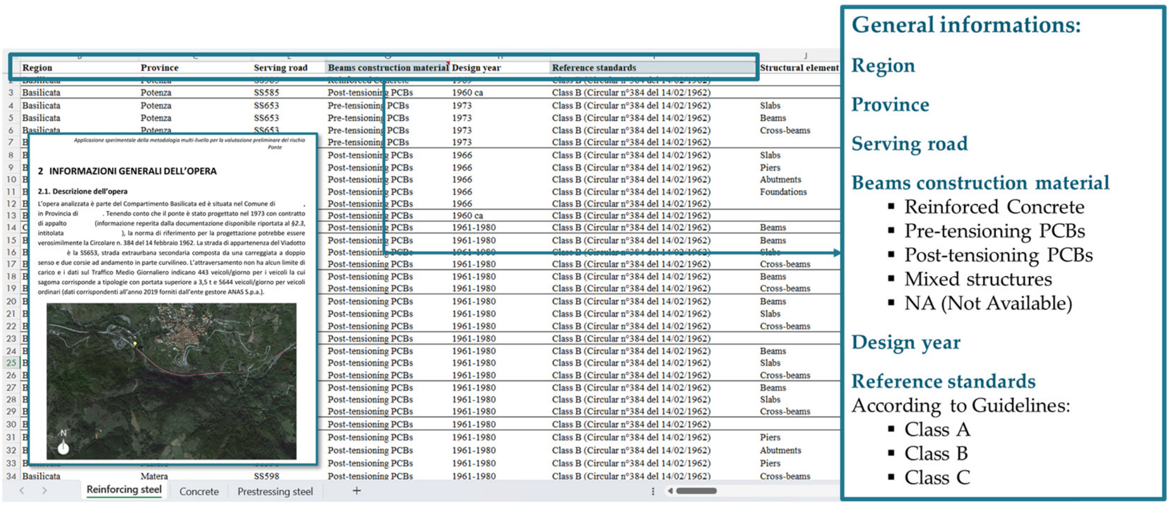


Figure 4. Some design drawings and photos of in situ tests analyzed.

The database comprises a total of 4899 records. However, only 4574 complete entries were used in the statistical analyses presented in this work, while incomplete records were excluded. These incomplete entries typically contain only the material's declared category without the corresponding mechanical properties. In some cases, the construction material of the beams is known, yet the accompanying information—such as the category and mechanical properties—is partially missing. The 4574 complete records originate from 168 inspected bridges, also including an additional 3788 records containing results from prestressing steel acceptance certificates issued by the Materials Testing Laboratory at Politecnico di Milano. The final application of these materials remains unknown.

First of all, general information is collected for each bridge, including the region, the province, the road it serves, the construction material of the beams, the year of design, and the reference design standards (Figure 5). The latter is recorded according to the Italian Bridge Guidelines [31], which provide a classification system for bridges lacking specific design data. In such cases, bridges are assigned to one of three classes—Class A, Class B, or Class C—based on their year of design and span length. Class A includes category I bridges designed before 1952 and category II bridges designed before 1990. Class B encompasses category I bridges designed between 1952 and 1990 for spans under 10 m, and between 1952 and 2005 for spans over 10 m. For category II, Class B covers bridges designed in 1990 for spans under 10 m, and between 1990 and 2005 for spans over 10 m. Finally, Class C comprises both category I and II bridges designed from 2005 to the present for spans under 10 m, and from 2008 to the present for spans over 10 m. Table 1 summarizes the bridge classification system according to the Italian Bridge Guidelines [31].



	Region	Province	Serving road	Beams construction material	Design year	Reference standards	Structural element
3	Basilicata	Potenza	SS585	Post-tensioning PCBs	1960 ca	Class B (Circular n°384 del 14/02/1962)	
4	Basilicata	Potenza	SS653	Pre-tensioning PCBs	1973	Class B (Circular n°384 del 14/02/1962)	Slabs
5	Basilicata	Potenza	SS653	Pre-tensioning PCBs	1973	Class B (Circular n°384 del 14/02/1962)	Beams
6	Basilicata	Potenza	SS653	Pre-tensioning PCBs	1973	Class B (Circular n°384 del 14/02/1962)	Cross-beams
7	B			Pre-tensioning PCBs	1973	Class B (Circular n°384 del 14/02/1962)	
8	B			Post-tensioning PCBs	1966	Class B (Circular n°384 del 14/02/1962)	Slabs
9	B			Post-tensioning PCBs	1966	Class B (Circular n°384 del 14/02/1962)	Piers
10	B			Post-tensioning PCBs	1966	Class B (Circular n°384 del 14/02/1962)	Abutments
11	B			Post-tensioning PCBs	1966	Class B (Circular n°384 del 14/02/1962)	Foundations
12	B			Post-tensioning PCBs	1966	Class B (Circular n°384 del 14/02/1962)	
13	B			Post-tensioning PCBs	1960 ca	Class B (Circular n°384 del 14/02/1962)	
14	C			Post-tensioning PCBs	1961-1980	Class B (Circular n°384 del 14/02/1962)	Beams
15	B			Post-tensioning PCBs	1961-1980	Class B (Circular n°384 del 14/02/1962)	Beams
16	B			Post-tensioning PCBs	1961-1980	Class B (Circular n°384 del 14/02/1962)	Slabs
17	B			Post-tensioning PCBs	1961-1980	Class B (Circular n°384 del 14/02/1962)	Cross-beams
18	B			Post-tensioning PCBs	1961-1980	Class B (Circular n°384 del 14/02/1962)	Beams
19	B			Post-tensioning PCBs	1961-1980	Class B (Circular n°384 del 14/02/1962)	Cross-beams
20	B			Post-tensioning PCBs	1961-1980	Class B (Circular n°384 del 14/02/1962)	Beams
21	B			Post-tensioning PCBs	1961-1980	Class B (Circular n°384 del 14/02/1962)	Slabs
22	B			Post-tensioning PCBs	1961-1980	Class B (Circular n°384 del 14/02/1962)	Cross-beams
23	B			Post-tensioning PCBs	1961-1980	Class B (Circular n°384 del 14/02/1962)	
24	B			Post-tensioning PCBs	1961-1980	Class B (Circular n°384 del 14/02/1962)	Beams
25	B			Post-tensioning PCBs	1961-1980	Class B (Circular n°384 del 14/02/1962)	Slabs
26	B			Post-tensioning PCBs	1961-1980	Class B (Circular n°384 del 14/02/1962)	Cross-beams
27	B			Post-tensioning PCBs	1961-1980	Class B (Circular n°384 del 14/02/1962)	Beams
28	B			Post-tensioning PCBs	1961-1980	Class B (Circular n°384 del 14/02/1962)	Slabs
29	B			Post-tensioning PCBs	1961-1980	Class B (Circular n°384 del 14/02/1962)	Cross-beams
30	B			Post-tensioning PCBs	1961-1980	Class B (Circular n°384 del 14/02/1962)	
31	B			Post-tensioning PCBs	1961-1980	Class B (Circular n°384 del 14/02/1962)	Piers
32	B			Post-tensioning PCBs	1961-1980	Class B (Circular n°384 del 14/02/1962)	Abutments
33	B	Matera		Post-tensioning PCBs	1961-1980	Class B (Circular n°384 del 14/02/1962)	Piers
34	Basilicata	Matera	SS598	Post-tensioning PCBs	1961-1980	Class B (Circular n°384 del 14/02/1962)	Cross-beams

Applicazione sperimentale della metodologia multi-livello per la valutazione preliminare del rischio Ponte

2 INFORMAZIONI GENERALI DELL'OPERA

2.1. Descrizione dell'opera

L'opera analizzata è parte del Compartimento Basilicata ed è situata nel Comune di , in Provincia di . Tenendo conto che il ponte è stato progettato nel 1973 con contratto di appalto (informazione reperita dalla documentazione disponibile riportata al *§2.3*, intitolata), la norma di riferimento per la progettazione potrebbe essere verosimilmente la Circolare n. 384 del 14 febbraio 1962. La strada di appartenenza del Viadotto è la SS653, strada extraurbana secondaria composta da una carreggiata a doppio senso e due corsie ad andamento in parte curvilineo. L'attraversamento non ha alcun limite di carico e i dati sul Traffico Medio Giornaliero indicano 443 veicoli/giorno per i veicoli la cui sagoma corrisponde a tipologie con portata superiore a 3,5 t e 5644 veicoli/giorno per veicoli ordinari (dati corrispondenti all'anno 2019 forniti dall'ente gestore ANAS S.p.a.).

General informations:

Region

Province

Serving road

Beams construction material
- Reinforced Concrete
- Pre-tensioning PCBs
- Post-tensioning PCBs
- Mixed structures
- NA (Not Available)

Design year

Reference standards
According to Guidelines:
- Class A
- Class B
- Class C

Figure 5. Storage of general information.

Table 1. Bridge classification according to the Italian Bridge Guidelines [31].

Class A		Class B		Class C
Category I	**Category II**	**Category I**	**Category II**	**Category I and Category II**
Bridges designed before 1952	Bridges designed before 1990	Bridges designed between 1952 and 1990 for spans under 10 m	Bridges designed in 1990 for spans under 10 m	Bridge designed from 2005 to the present for spans under 10 m
		Bridges designed between 1952 and 2005 for spans over 10 m	Bridges designed between 1990 and 2005 for spans over 10 m	Bridge designed from 2008 to the present for spans over 10 m

For reinforcing steel bars, the following data are stored: structural elements (beams, cross-beams, slabs, piers, pier caps, abutments, foundations, box girders, and half-joints), steel type (smooth or ribbed reinforcing bars), data source (nominal design values, acceptance certificates, or in situ tests), bar shape (square or circular), bar diameter/side, yielding strength (f_y), tensile strength (f_u), and ultimate elongation (A_{gt}) (Figure 6).

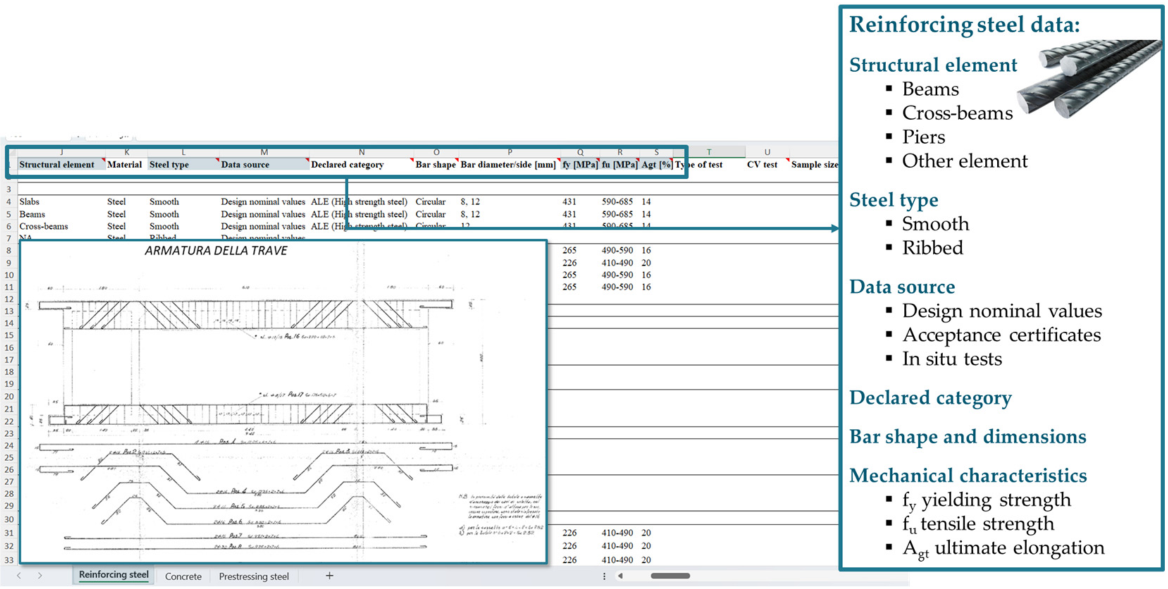


Figure 6. Storage of reinforcing steel data.

The data records for concrete include structural elements (as above, for reinforcing steel bars), data source, cube side or cylinder dimension, and compressive strength (R_c or f_c) (Figure 7).

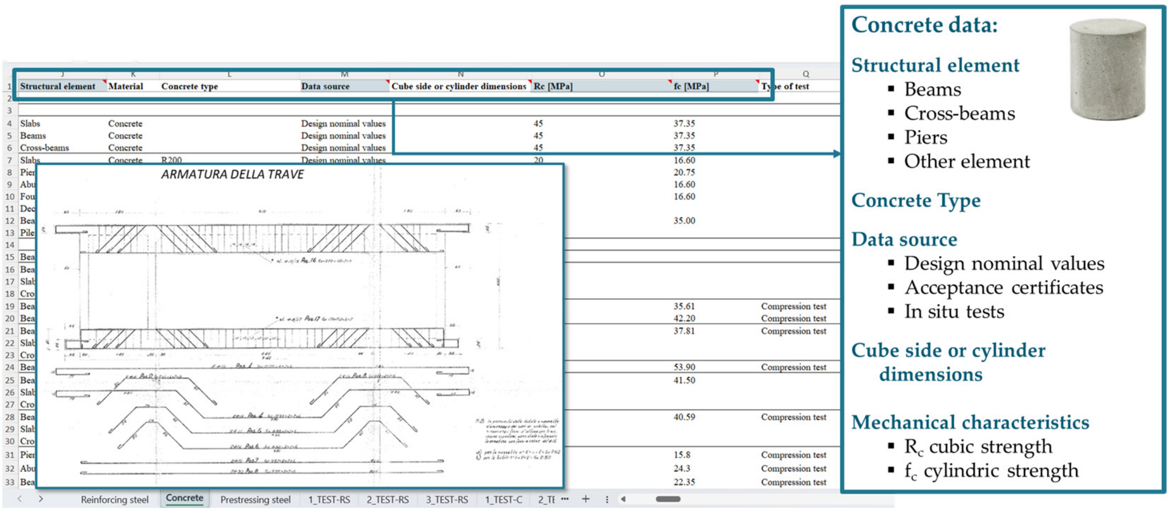
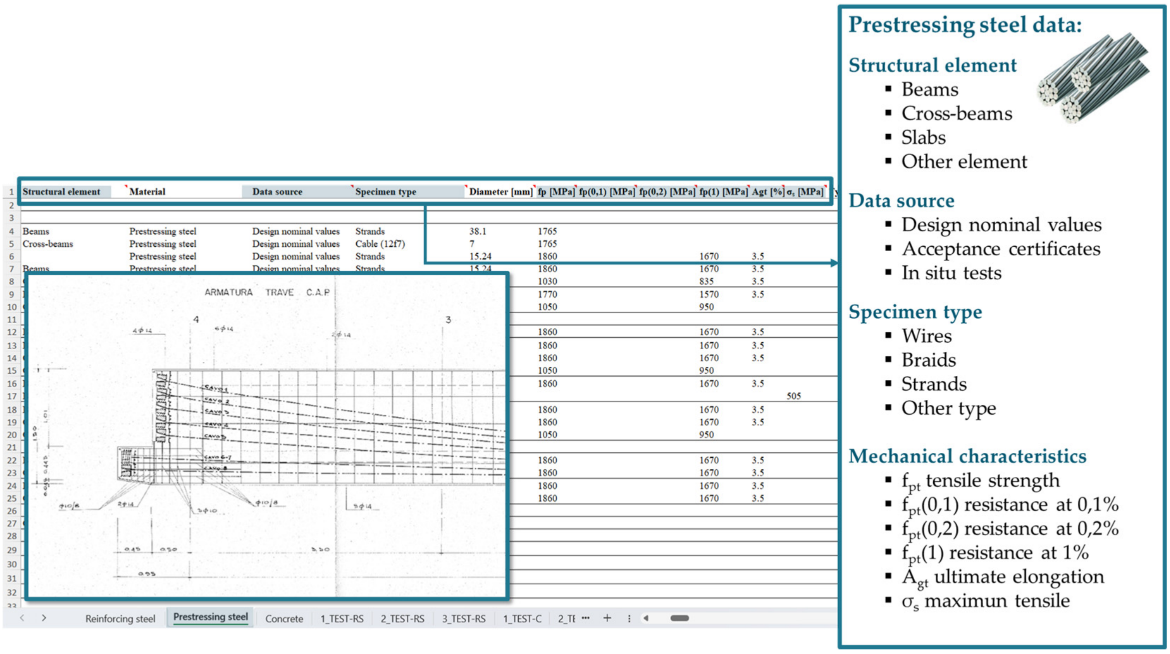


Figure 7. Storage of concrete data.

Finally, for prestressing steel database archives, the data records include the following: structural elements (beams, cross-beams, slabs, and other elements), data source, specimen type (strands, wires, cables, bars, braids, and other types), tensile strength (f_{ptk}), strength at 0.1% of residual deformation [$f_{p(0,1)k}$], strength at 0.2% [$f_{p(0,2)k}$] of residual deformation, strength at 1% of total deformation [$f_{p(1)k}$], elongation at the maximum strength (A_{gt}), and maximum allowable stress (σ_s) (Figure 8). It is important to clarify that for prestressing steel, the current version of the database includes a stock of 3788 records reporting information collected from acceptance certificates issued by the Materials Testing Laboratory at Politecnico di Milano, for which the final applications are not known. In this case, the date and reference standards of the issued acceptance certificate, specimen type, yield and ultimate tensile strength, and maximum stress drops (r%) are reported. Furthermore, an ID for identifying, in anonymous form, each producer and establishment is archived, too.



	Structural element	Material	Data source	Specimen type	Diameter [mm]	fp [MPa]	fp(0,1) [MPa]	fp(0,2) [MPa]	fp(1) [MPa]	Agt [%]	σ_s [MPa]
4	Beams	Prestressing steel	Design nominal values	Strands	38.1	1765					
5	Cross-beams	Prestressing steel	Design nominal values	Cable (12f7)	7	1765					
6		Prestressing steel	Design nominal values	Strands	15.24	1860			1670	3.5	
7	Beams	Prestressing steel	Design nominal values	Strands	15.24	1860			1670	3.5	
8						1030			835	3.5	
9						1770			1570	3.5	
10						1050			950		
12						1860			1670	3.5	
13						1860			1670	3.5	
14						1860			1670	3.5	
15						1050			950		
16						1860			1670	3.5	
17											505
18						1860			1670	3.5	
19						1860			1670	3.5	
20						1050			950		
22						1860			1670	3.5	
23						1860			1670	3.5	
24						1860			1670	3.5	
25						1860			1670	3.5	

Prestressing steel data:

Structural element
- Beams
- Cross-beams
- Slabs
- Other element

Data source
- Design nominal values
- Acceptance certificates
- In situ tests

Specimen type
- Wires
- Braids
- Strands
- Other type

Mechanical characteristics
- f_{pt} tensile strength
- $f_{pt}(0,1)$ resistance at 0,1%
- $f_{pt}(0,2)$ resistance at 0,2%
- $f_{pt}(1)$ resistance at 1%
- A_{gt} ultimate elongation
- σ_s maximun tensile

Figure 8. Storage of prestressing steel data.

4. Database Analysis

The data on the strengths of steel reinforcing bars, concrete, and prestressing steel are analyzed and discussed in this section.

In particular, the strength distributions of all materials are analyzed across several material sub-samples, which were derived by considering different data sources, including design nominal values, acceptance certificates, and in situ testing results. All percentages presented in the following histograms are calculated based on the number of data points available for each specific material sub-sample. It should be noted, however, that for many of the analyzed bridges, data completeness was lacking across various structural elements, material types, and data sources.

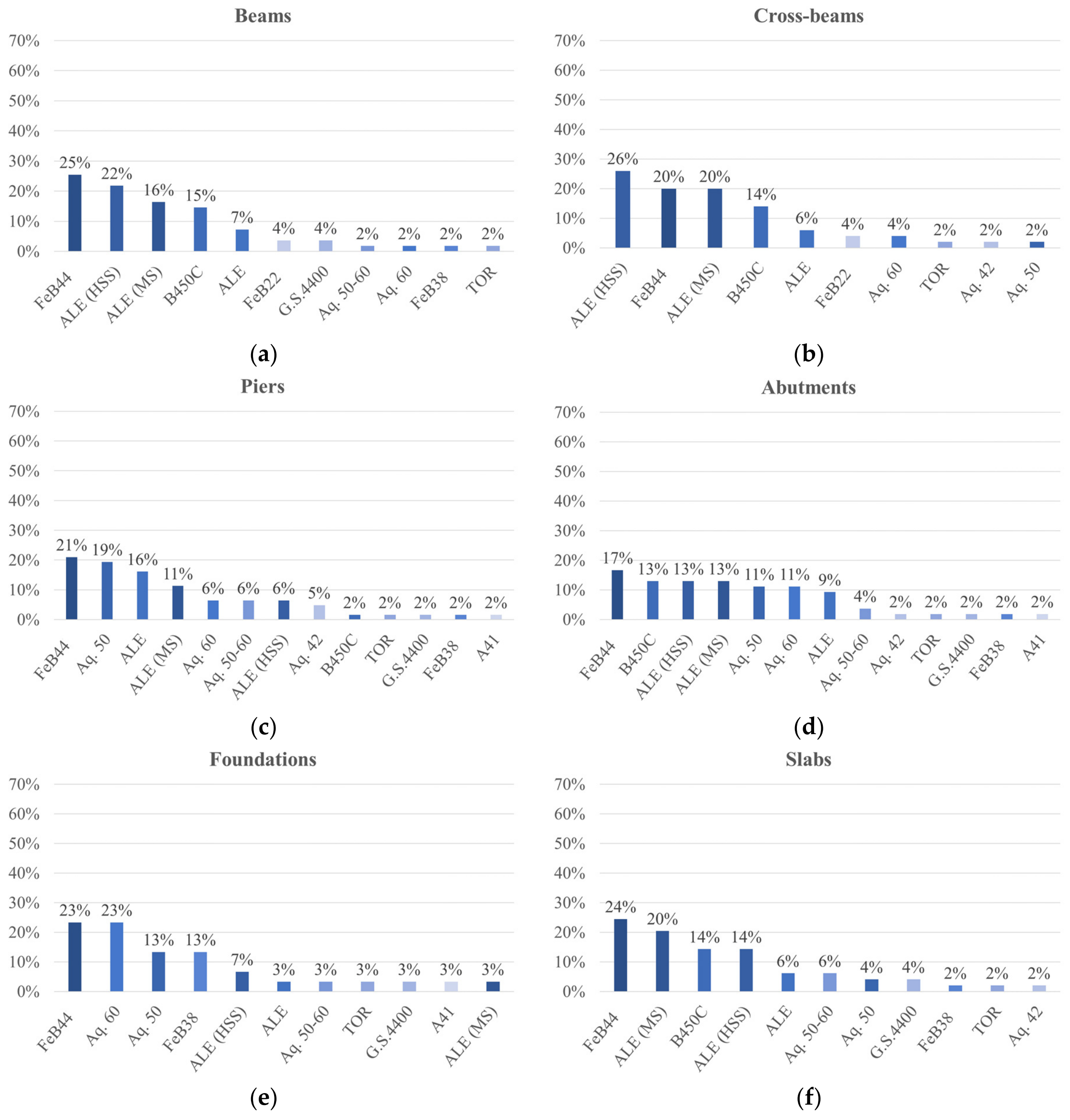
4.1. Reinforcing Steel

A sample of 374 records referring to the reinforcing steel of all structural elements is herein examined. It is composed of 90% design nominal values (338 records), 3% values derived from acceptance certificates (13 records), and 6% values provided by in situ tests (23 records), the latter obtained within recent experimental campaigns.

Figure 9 presents, in histogram form, the percentage distribution of steel classes used in various structural elements: beams, cross-beams, piers, abutments, foundations, and slabs. Figure 9a–f show, for each element, the identified steel classes based on all available data sources, including design nominal values, acceptance certificates, and in situ tests. The most commonly observed steel classes are as follows: for beams (55 records), FeB44 (yield strength f_y = 440 MPa) appears most frequently, with a share of 25% (Figure 9a); for cross-beams (50 records), ALE (high-strength steel; f_y = 430 MPa) is most recurrent, with a frequency of 26% (Figure 9b); and for piers (62 records), abutments (54 records), foundations (30 records), and slabs (49 records), FeB44 is, again, the most frequently found class, with respective frequencies of 21%, 17%, 23%, and 24% (Figure 9c–f).

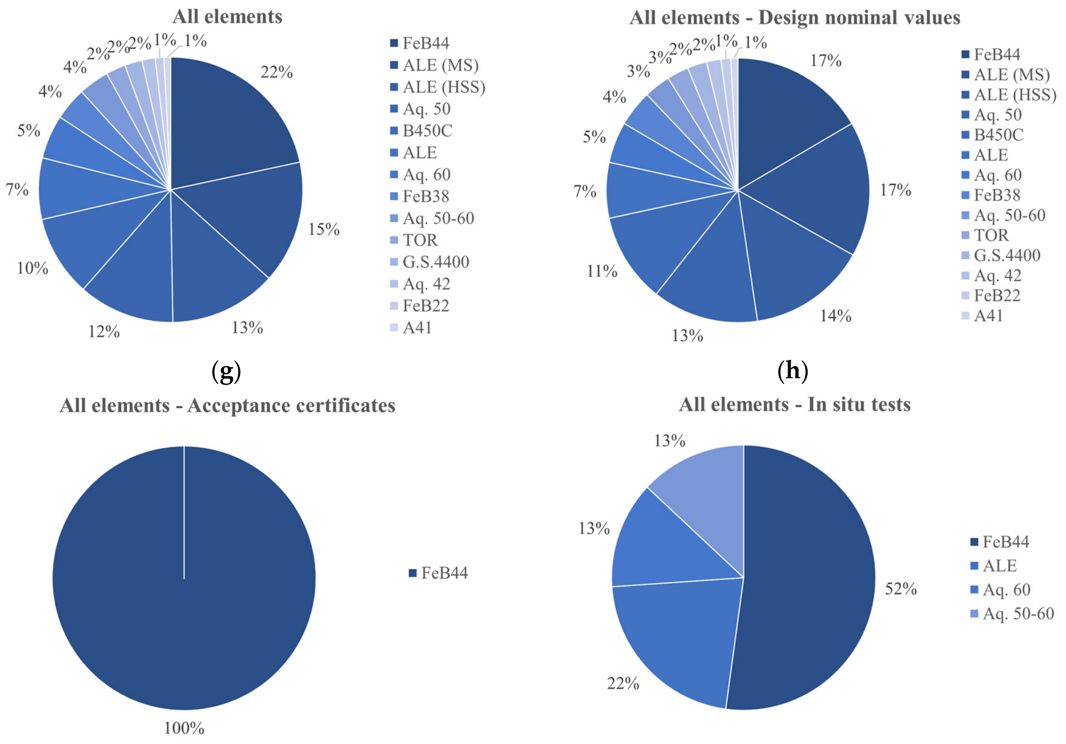
Figure 9g, differently from Figure 9a–f, shows the frequencies of all steel classes found considering a unique sample for all structural elements and all data sources (374 records) (Figure 9g–j). In this case, FeB44 is the most frequent steel class, having a 22% frequency within the sample considered, followed by ALE (mild steel) with 15% and ALE (high-strength steel) with 13%. For completeness, Figure 9h–j report a further partitioning between data sources (design nominal values, acceptance certificates, and in situ tests). In particular, Figure 9h depicts the design nominal values (338 records), confirming that FeB44 and ALE (mild steel) (both comprising 17%) are the most frequent steel classes within the sample considered. The sample containing the data obtained from acceptance certificates is limited (13 records), and the FeB44 steel class is the only one present, referring to the piers (Figure 9i). Finally, as for the in situ test values, also in this case, the sample is limited (23 records). The steel classes present in this sub-sample are plotted in Figure 9j, where the FeB44 (52%) and ALE (22%) steel classes are mainly derived from piers.

Finally, Figure 10 reports the average yielding strength and coefficient of variation (CV) of the steel tensile strength measured from acceptance certificates (Figure 10a) and in situ tests (Figure 10b) and considering all elements. Again, from acceptance certificates, data are available only for FeB44 steel, providing an average yielding strength of 508 MPa, with a CV of 7%. Meanwhile, in the case of in situ tests, the average yielding strength is available for FeB44, ALE, Aq. 60, and Aq. 50–60, where the highest CV is obtained in the case of ALE, with 8%. Note that in the cases of Aq. 60 and Aq. 50–60, the CV is NA.



(**a**) (**b**) (**c**) (**d**) (**e**) (**f**)

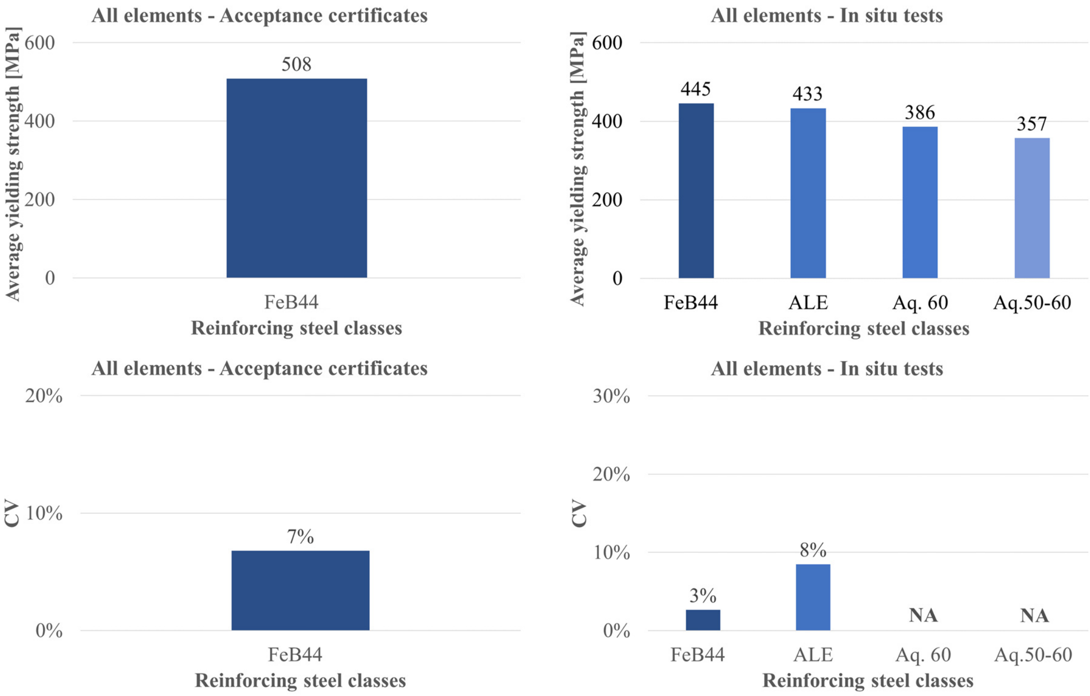
Figure 9. *Cont.*



(g) (h)

(i) (j)

Figure 9. Reinforcing steel classes breakdown obtained for (**a**) beams; (**b**) cross-beams; (**c**) piers; (**d**) abutments; (**e**) foundations; (**f**) slabs; (**g**) all structural elements; (**h**) all structural elements (only design nominal values); (**i**) all structural elements (only acceptance certificates); and (**j**) all structural elements (only in situ tests).



(a) (b)

Figure 10. Average yielding strength and CV of reinforcing steel for all structural elements derived from (**a**) acceptance certificates; (**b**) in situ tests.

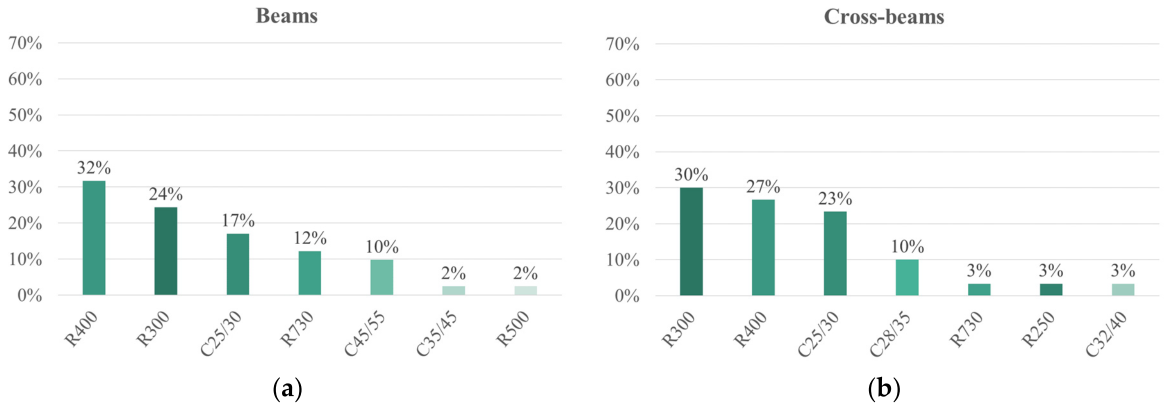
4.2. Concrete

A sample of a total of 282 records referring to concrete class is obtained (including all structural elements), where the available data sources are design nominal values (92% (259 records)), acceptance certificates (3% (8 records)), and in situ tests (5% (15 records), conducted within recent experimental campaigns).

In the Figure 11a–f plot, for each structural element, the concrete classes are found, including all data sources. In more detail, as for beams (41 records), the most recurrent class found is R400 (with a compressive strength of R_{ck} = 40 MPa), with 32% (Figure 11a). Meanwhile, R300 (with a compressive strength of R_{ck} = 30 MPa) is the most recurrent class for cross-beams (30 records), piers (39 records), and slabs (32 records), with frequencies of 30%, 46%, and 28% for cross-beams, piers, and slabs, respectively (Figure 11b,c,f). For abutments (45 records) and foundations (38 records), the concrete class R250 (with a compressive strength of R_{ck} = 25 MPa) has the highest percentage, with, respectively, frequencies of 38% and 47% (Figure 11d–e). Note that R250, R300, and R400 are concrete classes used before the Ministerial Degree of 30 May 1972, no. 190 [32].

Figure 11g illustrates the concrete class frequency by considering a sample comprising all structural elements and including all data sources (282 records). In this case, R300 results as the most frequent class, with 28%, followed by R250, with 20%. A further partitioning between data sources, i.e., design nominal values, acceptance certificates, and in situ tests, is reported in Figure 11h–j. In particular, Figure 11h depicts the design nominal values (259 records), confirming that R300 (28%) and R250 (20%) are the most frequent concrete classes within the sample considered, mainly used for cross-beams, piers, and slabs. The data obtained from acceptance certificates are limited (eight records), resulting in R400 (50%) as the most recurrent concrete class applied for beams (Figure 11i). Few data are also found in the case of in situ tests (15 records). In Figure 11j, it is possible to note that R400 (67%) and R300 (33%) are the most recurrent concrete classes, mainly applied for piers.

Finally, Figure 12 plots the average compressive strength and the CV calculated for the data found within acceptance certificates (Figure 12a) and in situ tests (Figure 12b). In this case, the cylindrical compressive strength is considered. As one may note, the average compressive strengths are compatible with the nominal values, resulting as not being widely dispersed. The CV is less than 12% for acceptance certificates and less than 29% for in situ tests.



(**a**) (**b**)

Figure 11. *Cont.*

(**c**) (**d**)

(**e**) (**f**)

(**g**) (**h**)

(**i**) (**j**)

Figure 11. Concrete class breakdown obtained for (**a**) beams; (**b**) cross-beams; (**c**) piers; (**d**) abutments; (**e**) foundations; (**f**) slabs; (**g**) all structural elements; (**h**) all structural elements (only design nominal values); (**i**) all structural elements (only acceptance certificates); and (**j**) all structural elements (only in situ tests).

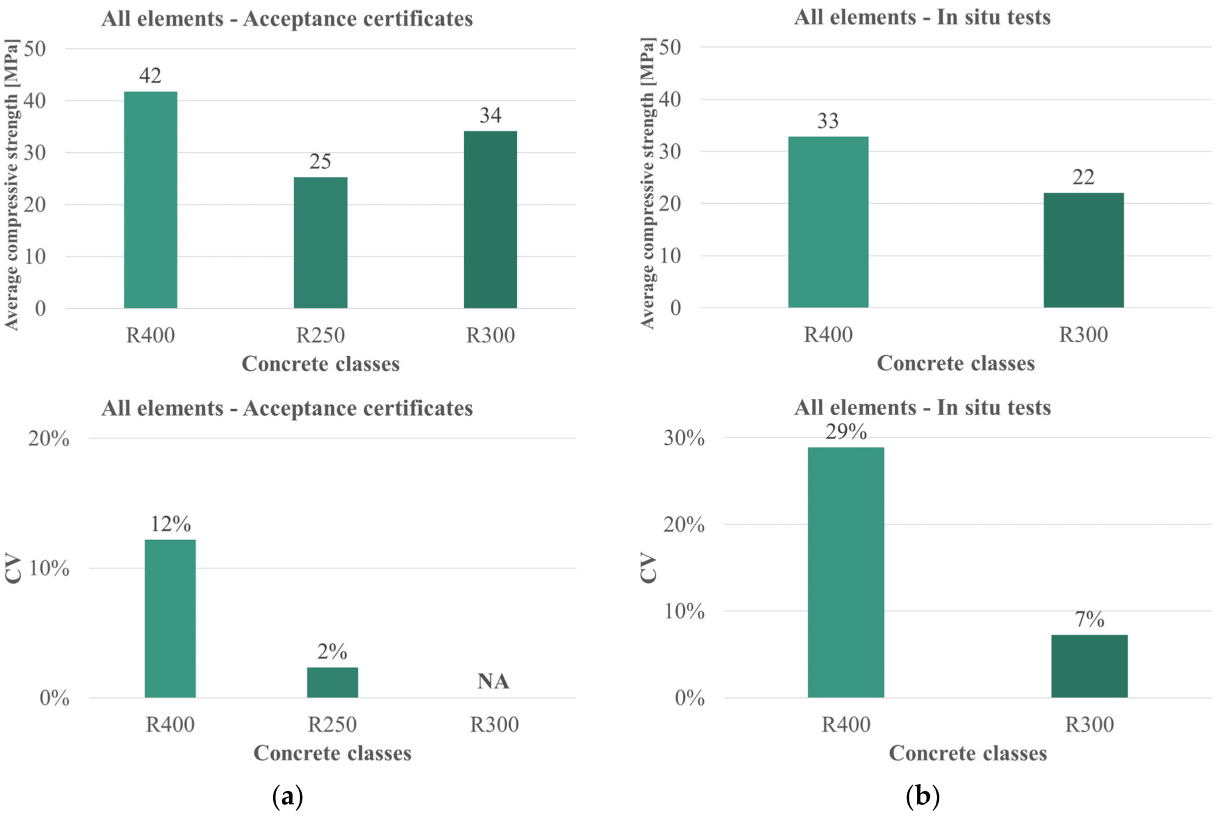


Figure 12. Average compressive strength and CV of concrete for all structural elements derived from (**a**) acceptance certificates; (**b**) in situ tests.

4.3. Prestressing Steel

As for prestressing steel, a sample consisting of a total of 3918 records is obtained, with 2.8% of data collected from design nominal values (111 records); 96.7% from acceptance certificates (3789 records) issued in the years 1985–2003 and referring to prestressing steel provided by 10 producers, of which the application is unknown; and 0.5% from in situ tests (18 records) conducted within recent experimental campaigns through detensioning tests.

Figure 13 illustrates the distribution of different types of prestressing steel elements, such as strands, braids, wires, cables, and bars, within the sample considered. Specifically, Figure 13a–d report the percentages for each structural element. For all structural elements examined, namely, beams (88 records), cross-beams (27 records), slabs (3 records), and structural elements (not available) (3788 records), strands emerge as the most frequently used prestressing elements. These typically have a design nominal tensile strength of f_{ptk} = 1860 MPa, and occur with frequencies of 43%, 37%, 67%, and 55%, respectively.

Meanwhile, Figure 13e analyzes the prestressing steel percentages referring to a sample of 3918 records, where all the structural elements are included. Also in this case, strands are the most frequent elements for prestressing, with a percentage of 55%. Figure 13f–h show the results obtained by partitioning this sample between data sources (design nominal values, acceptance certificates, and in situ tests). In particular, Figure 13f confirms that strands (43%) are the most recurrent elements found within nominal values and are mainly used for beams (111 records). The same result is found when acceptance certificates are considered as the data source (Figure 13g), with a 55% percentage (3789 records). On the contrary, in the case of in situ tests (18 records), the most recurrent values refer to cables, with 72%.

(a) (b) (c) (d) (e) (f) (g) (h)

Figure 13. Prestressing steel class breakdown obtained for (**a**) beams; (**b**) cross-beams; (**c**) slabs; (**d**) structural elements (not available); (**e**) all structural elements; (**f**) all structural elements (only design nominal values); (**g**) all structural elements (only acceptance certificates); and (**h**) all structural elements (only in situ tests).

It is interesting, also for this material, to plot the average tensile strength and the related CV by examining the available values derived from acceptance certificates (Figure 14a) and in situ tests (Figure 14b), including all elements. The average values found are compatible with the values of the prestressing elements analyzed, with CVs of less than 4% for acceptance certificates and less than 3% for in situ tests.

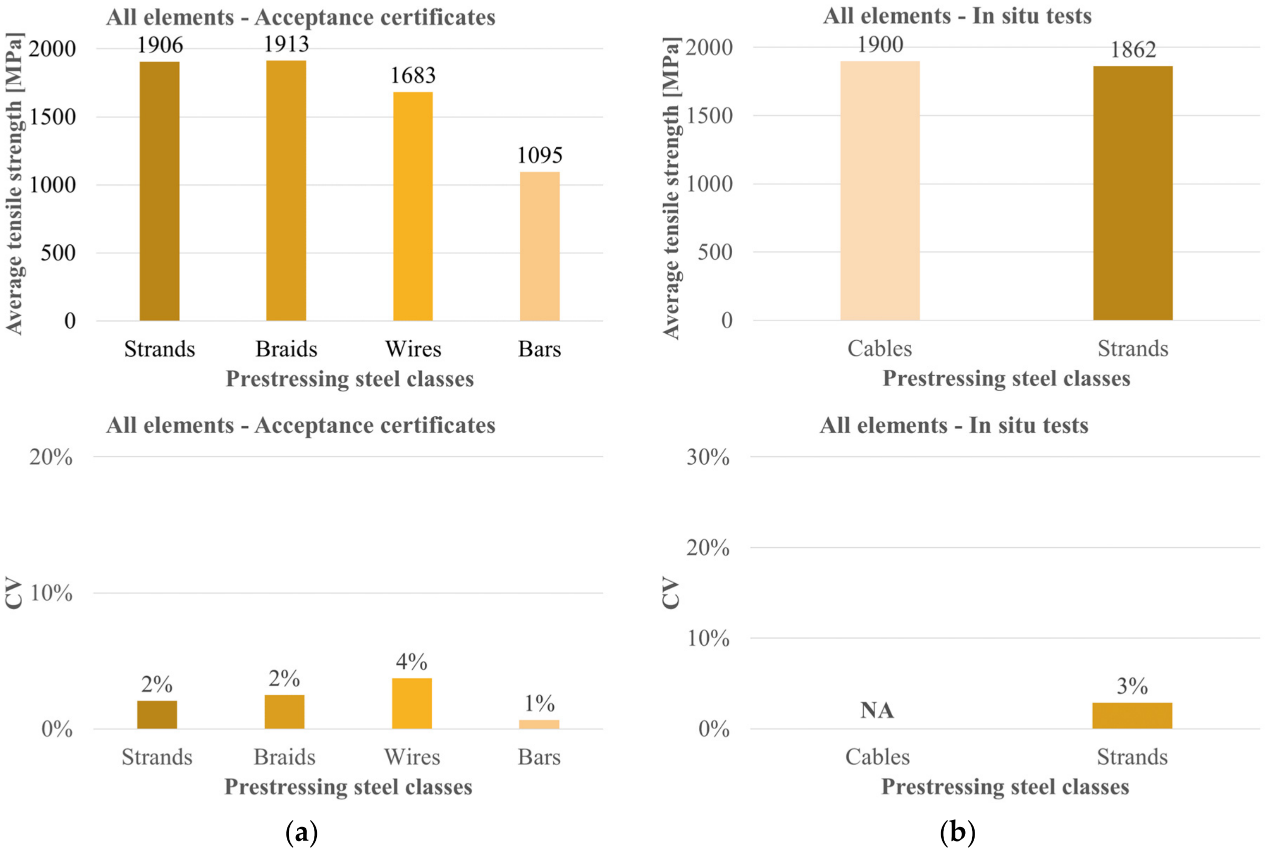


Figure 14. Average tensile strength and CV of prestressing steel for all structural elements derived from (**a**) acceptance certificates; (**b**) in situ tests.

5. Statistical Analysis of Data

5.1. Goodness-of-Fit Tests

Goodness-of-fit tests of a statistical model describe how well a set of observations (a set of x-values) agrees with a given population distribution by measuring the level of consistency or discrepancy [33]. The statistical hypothesis test checks if a given hypothesis, named the null hypothesis (H_0), fails to be rejected.

In order to verify if a variable is statistically significant, it is necessary to choose a significance level (α), typically 1% or 5%, to determine the area of acceptance and rejection in a statistical hypothesis test. Specifically, α determines the probability of committing a type I error, i.e., of rejecting the null hypothesis (H_0) when, in fact, it is really true. Then, a p-value is involved in order to determine whether to reject the null hypothesis. If it falls within the acceptance range, then the null hypothesis (H_0) cannot be rejected, and the result is said to be not statistically significant (NSS). On the contrary, if the p-value falls within the rejection area, then the test is rejected, and the result is considered statistically significant (SS) [33].

In this study, starting from the material strength data archived within the database, goodness-of-fit tests are performed, considering either values gathered from acceptance certificates or from in situ tests. In particular, two goodness-of-fit tests for normal distributions are used: the Shapiro–Wilk [34,35] and D'Agostino–Pearson [36] tests. A comparison between various tests may be found in [34]. Tests are performed only for those variables having a significant number of data points.

The Shapiro–Wilk test is considered one of the most powerful tests of normality, generally used for variables having a data numerosity greater than three. It is important to note that this test assumes the variable's data are unique, and, thus, without identical values, presuming a continuous distribution composed of ordered data. The test verifies distribution normality by dividing the square of an appropriate sample linear combination by the usual symmetric estimate of the variance [35], detailed as follows:

$$W = \frac{\left(\sum_{i=1}^{n} a_i \cdot x_{(i)}\right)^2}{\sum_{i=1}^{n} (x_i - \mu)^2} \tag{1}$$

where W is the Shapiro–Wilk statistic; a_i is a coefficient calculated as a function of the theoretical normal distribution, depending on the number of observations $x_{(i)}$; and x_i and μ represent the i-th ordered value of the observed sample and the mean value, respectively. If the data distribution is normal, then W is close to 1.

The D'Agostino–Pearson test represents another versatile and powerful tool, especially if the sample size is greater than eight data. Moreover, in this test, identical data (ties) can be considered too. The D'Agostino–Pearson statistic assesses distribution normality through the *Omnibus test* [36,37]. This test detects deviations from normality due to either skewness ($\sqrt{b_1}$) or kurtosis (b_2). To approximate a normal distribution, $\sqrt{b_1}$ and b_2 are transformed into standardized normal deviates (Z).

The D'Agostino–Pearson statistic (K^2) is given by the following equation:

$$K^2 = Z^2\left(\sqrt{b_1}\right) + Z^2(b_2) \tag{2}$$

where $Z^2(\sqrt{b_1})$ and $Z^2(b_2)$ are the normal approximations of skewness ($\sqrt{b_1}$) and kurtosis (b_2). The K^2 statistic has approximately a chi-squared (χ^2) distribution with two degrees of freedom when the population is normally distributed.

5.2. Test Results

Goodness-of-fit tests are conducted in order to determine how well specific probability density functions fit the measured data of material strength. In particular, the variables identified consist of data available in the database, which are broken down by material (reinforcing steel, concrete, and prestressing steel); data source (acceptance certificates and in situ tests); structural element; and declared strength class.

For the data of each variable, the Shapiro–Wilk test is performed at first. In doing so, the statistical indicators describing the characteristics of a distribution are identified, such as the central tendency (mean and median), dispersion (CV), and shape (skewness and kurtosis). They are calculated according to the formulations reported in Table 2 [38,39].

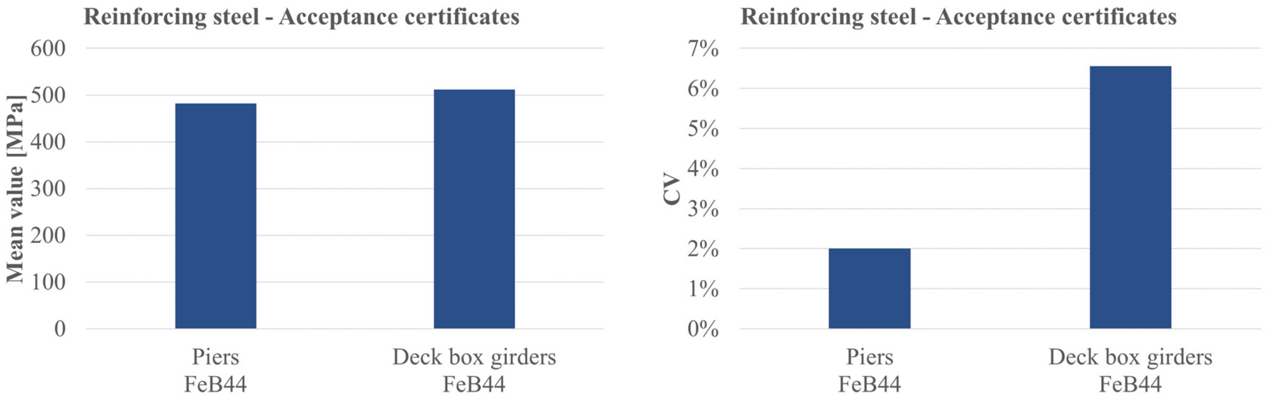
Then, the distribution normality test is carried out by removing, if present, the outliers. Table 3 summarizes the statistical indicators calculated for all the considered variables. For completeness, Figures 15–18 plot the mean values and CVs of all the variables indicated in Table 3.

Table 2. Formulations of statistical indicators of variables.

Statistical Indicator	Formulation
Mean μ	$\frac{1}{n}\sum_{i=1}^{n} x_i$
Standard deviation σ	$\sqrt{\frac{\sum_{i=1}^{n}(x_i-\mu)^2}{n}}$
Coefficient of variation (CV)	$\frac{\sigma}{\mu}$
Skewness (Fisher–Pearson)	$\frac{n}{(n-1)(n-2)}\sum_{i=1}^{n}\left(\frac{x_i-\mu}{\sigma}\right)^3$
Kurtosis (Fisher–Pearson)	$\frac{n(n+1)}{(n-1)(n-2)(n-3)}\sum_{i=1}^{n}\left(\frac{x_i-\mu}{\sigma}\right)^4-\frac{3(n-1)^2}{(n-2)(n-3)}$

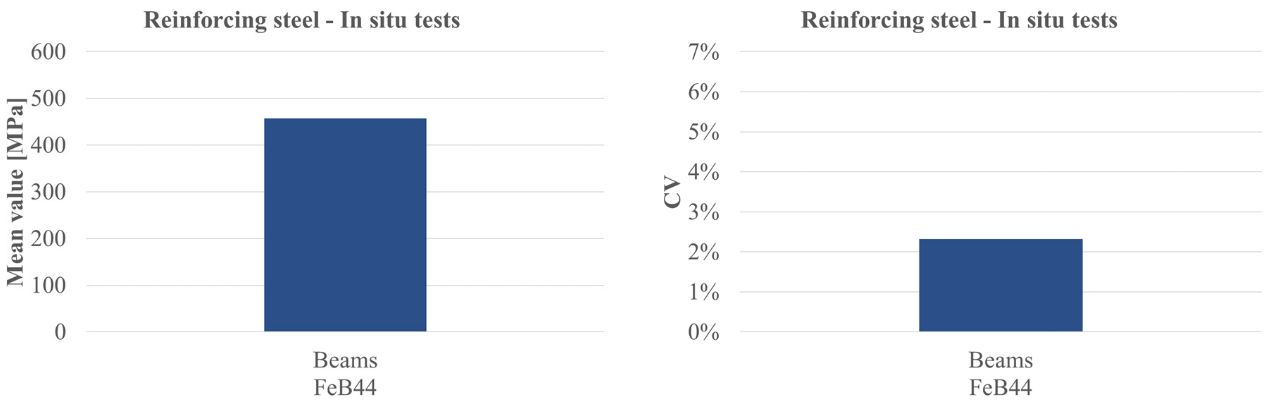
Table 3. Statistical indicators of variables.

Material	Data Source	Structural Element	Class	No. of Data	Mean [Mpa]	Median [Mpa]	CV [%]	Skewness	Kurtosis
Reinforcing steel	Acceptance certificates	Piers	FeB44	4	480.00	482.00	2.00	−1.015	0.578
		Deck box girders	FeB44	9	521.11	512.00	6.55	0.646	0.146
	In situ tests	Beams	FeB44	5	451.26	457.50	2.32	−0.561	−3.255
Concrete	In situ tests	Piers	R300	3	21.75	21.17	4.94	1.725	/
Prestressing steel	Acceptance certificates	NA	Bars 1050	107	1095.00	1095.86	0.65	−0.356	−0.598
			Braids 1860	155	1919.48	1916.72	1.14	0.044	0.101
			Braids 1900	53	1951.71	1947.36	1.67	0.665	−0.024
			Strands 1820	10	1883.03	1871.11	2.25	−0.094	−1.455
			Strands 1860	550	1907.55	1909.26	1.07	−0.181	−0.111
			Strands 1960	6	1990.93	1994.28	0.48	−0.250	−1.128
			Wires 1570	143	1642.39	1643.39	1.74	−0.002	−0.379
			Wires 1620	68	1687.11	1687.97	1.41	0.099	1.038
			Wires 1670	6	1699.85	1694.76	0.55	0.954	−1.744



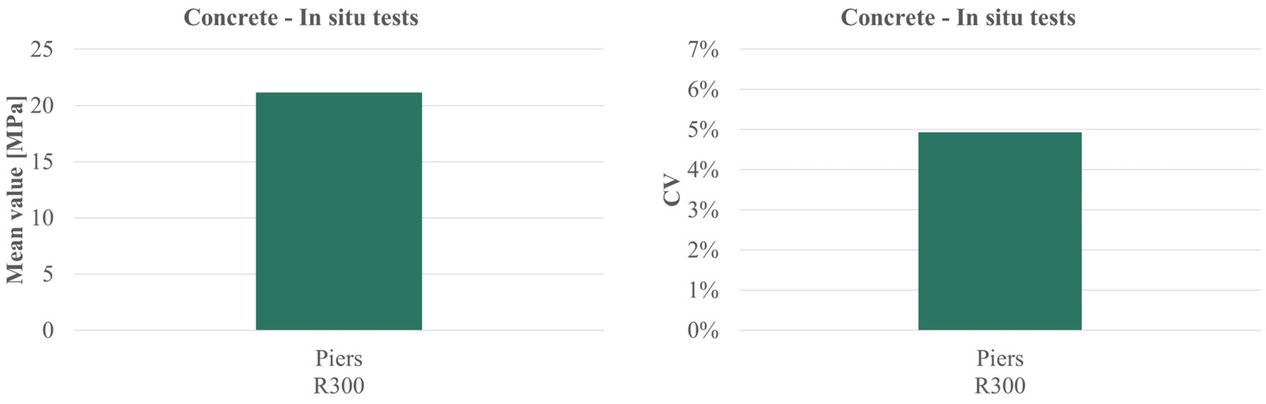
(**a**) (**b**)

Figure 15. Strengths of reinforcing steel derived from acceptance certificates: (**a**) mean values; (**b**) CVs.



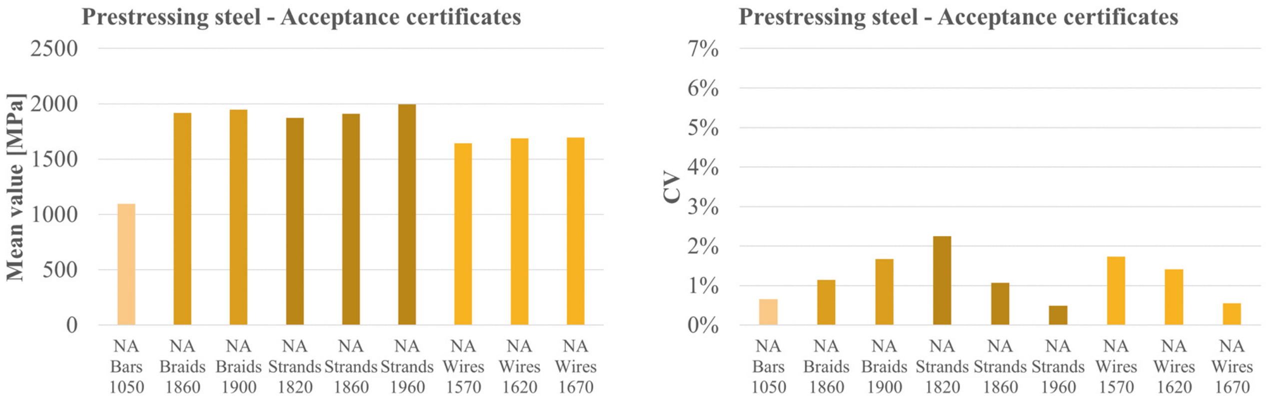
(**a**) (**b**)

Figure 16. Strengths of reinforcing steel derived from in situ tests: (**a**) mean values; (**b**) CVs.



(**a**) (**b**)

Figure 17. Strengths of concrete derived from in situ tests: (**a**) mean values; (**b**) CVs.



(**a**) (**b**)

Figure 18. Strengths of prestressing steel derived from acceptance certificates: (**a**) mean values; (**b**) CVs.

In this study, normality tests are carried out by referring to a significance level α equal 1%. It should be noted that, due to the limited number of values, in the case of concrete, it is possible to conduct a goodness-of-fit test only for pier concrete, where the log-normality tests are applied by considering the logarithmic values of the variable.

Table 4 presents the results of the Shapiro–Wilk test applied to the variables with more than three data. It can be observed that several of the examined variables are classified as NSS. As a result, the assumption of normality cannot be rejected for reinforcing and prestressing steel. Conversely, for concrete piers, the data appear to be better represented by a log-normal distribution, which also cannot be rejected based on the test results.

Moreover, the Shapiro–Wilk test provides three SS variables, and, therefore, the assumption of a normal distribution may be rejected. These three variables of prestressing steel, corresponding to Bars 1050, Braids 1860, and Strands 1860, have many data (107, 159, and 550, respectively), including identical values. For this reason, in these cases, the D'Agostino–Pearson test is alternatively conducted. It permits us to improve the statistical power, carrying out a goodness-of-fit test where several repetitions (ties) are present. The D'Agostino–Pearson test results are shown in Table 5. As one may note, if data repetitions are properly considered, the Bars 1050, Braids 1860, and Strands 1860 data are also NSS, and, therefore, the normal distribution assumption may not be rejected.

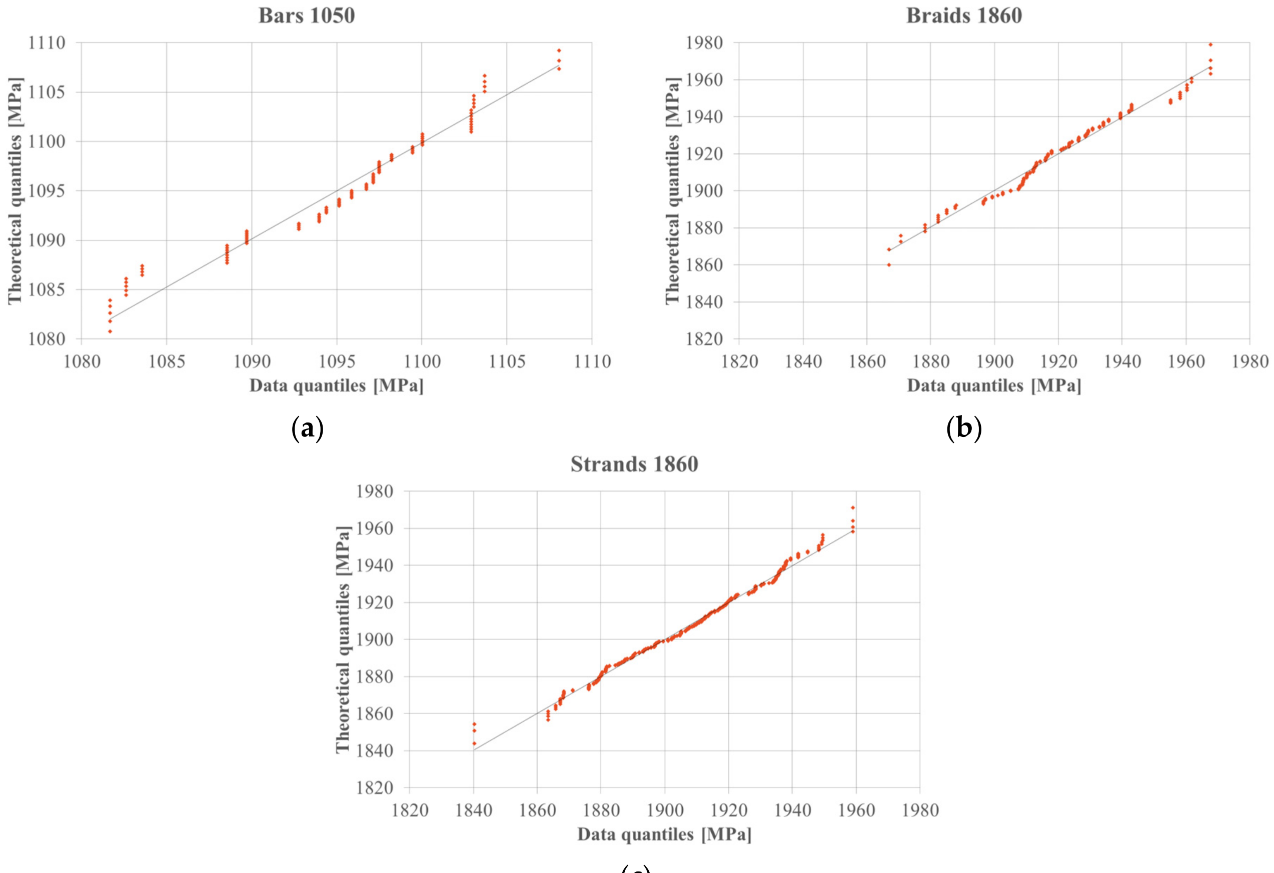
Table 4. Results of Shapiro–Wilk test. $\alpha = 0.01$.

Material	**Data Source**	**Structural Element**	**Class**	**No. of Data**	W	p**-Value**	**Significance**	**Distribution**
Reinforcing steel	Acceptance certificates	Piers	FeB44	4	0.942	0.6668	NSS	Normal
		Deck box girders	FeB44	9	0.959	0.7911	NSS	Normal
	In situ tests	Beams	FeB44	5	0.765	0.0406	NSS	Normal
Concrete	In situ tests	Piers	R300	3	0.777	0.0603	NSS	Log-normal
Prestressing steel	Acceptance certificates	NA	Bars 1050	107	0.946	0.0003	SS	Not normal
			Braids 1860	155	0.976	0.0091	SS	Not normal
			Braids 1900	53	0.940	0.0102	NSS	Normal
			Strands 1820	10	0.856	0.0687	NSS	Normal
			Strands 1860	550	0.992	0.0031	SS	Not normal
			Strands 1960	6	0.849	0.1553	NSS	Normal
			Wires 1570	143	0.989	0.2943	NSS	Normal
			Wires 1620	68	0.973	0.1422	NSS	Normal
			Wires 1670	6	0.734	0.0139	NSS	Normal

Table 5. Results of D'Agostino–Pearson test. $\alpha = 0.01$.

Material	**Data Source**	**Structural Element**	**Class**	**No. of Data**	K^2	p**-Value**	**Significance**	**Distribution**
Prestressing steel	Acceptance certificates	NA	Bars 1050	107	5.088	0.0785	NSS	Normal
			Braids 1860	155	0.231	0.8909	NSS	Normal
			Strands 1860	550	3.246	0.1973	NSS	Normal

As examples, Figure 19 shows data quantiles versus theoretical quantiles, usually indicated as Q–Q plots, in order to graphically evaluate whether the variables' data follow a normal distribution. In particular, these diagrams refer to Bars 1050 (Figure 19a), Braids 1860 (Figure 19b), and Strands 1860 (Figure 19c). All the Q–Q plots considered follow a linear trend, confirming that the normal distribution assumption may not be rejected, as obtained with the goodness-of-fit tests.



(**a**) (**b**)

(**c**)

Figure 19. Q–Q plot of data quantiles vs. theoretical quantiles for prestressing steel variables: (**a**) Bars 1050; (**b**) Braids 1860; and (**c**) Strands 1860.

6. Discussion

Based on the collected data, the statistical analysis conducted highlights some remarkable results that are worth emphasizing. It is important to note that data completeness varied significantly across the sample. For many bridges, material strength data were not available for all structural elements, for all materials considered, or across all data sources (i.e., design values, certificates, and test results).

Within the database, bridges featuring post-tensioned concrete box girders (post-TCBs) represent the most common typology, accounting for 78% of the sample. These typically employ strands as prestressing steel elements. Regarding the material strength data, the majority of values for steel reinforcing bars (90%) and concrete (92%) are design nominal values extracted from the original design documentation. In contrast, the strength values for prestressing steel are predominantly derived from acceptance certificates (96.7%), mainly issued by the Materials Testing Laboratory at Politecnico di Milano. However, the specific steel types and their final applications are not always clearly identified.

Goodness-of-fit tests were performed on both acceptance values and in situ test results. The tests did not reject the hypothesis of a normal distribution for steel reinforcing bars and prestressing steel or a log-normal distribution for concrete. These tests were applied only to variables with a sufficiently large dataset to ensure their statistical significance.

7. Conclusions and Future Development

The presented database compiles information on the mechanical properties of steel reinforcing bars, concrete, and prestressing steel used in the construction of about 170 existing Italian PC bridges, built between 1960 and 2000. The data were sourced from a variety of documents, such as design nominal values, acceptance certificates, and in situ test results, all retrieved from the original design documentation of each bridge considered.

Due to the heterogeneity of the design documents available, not all consulted documentation provided identical information. This very often led to significant data inconsistency, not just between different bridges but even within the same bridge. This issue was also observed in the case of more recently constructed bridges.

This database is one of the first systematic efforts to catalog and statistically analyze the material strengths of existing prestressed concrete bridges in Italy. The database is publicly available at [https://www.consorziofabre.it/progetti-di-ricerca/safoteb/] (accessed on 1 August 2025) and is intended as a valuable resource for researchers and practitioners involved in the assessment of existing bridges. It can be used as a reference for simulated design scenarios or as a verification tool in cases where limited knowledge is available.

In the future, the initial strength values of available materials may be compared with current measurements obtained through in situ testing. This comparison would enable correlations between strength reductions and present degradation conditions, such as reinforcing steel corrosion or concrete deterioration. Moreover, releases and expansions of the dataset may also be developed by other research groups, fostering collaboration and continuous improvement in this engineering field.

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Data Availability Statement: The data will be made available upon request. The material strenght database realized for this research is publicly available at FABRE consortium website [https://www.consorziofabre.it/progetti-di-ricerca/safoteb/] (accessed on 1 August 2025).

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Conflicts of Interest: Michele Titton and Paola Pannuzzo are from ITS Engineering Company. The authors declare that they have no conflicts of interests that could have appeared to influence the work reported in this paper.

Abbreviations

The following abbreviations were used in this manuscript:

PCBs	Prestressed Concrete Beams
WP	Work Package
Pre-TCBs	Pre-Tensioned Concrete Beams
Post-TCBs	Post-Tensioned Concrete Beams
PC	Prestressed Concrete
RC	Reinforced Concrete
NA	Not Available
CV	Coefficient of Variation
NSS	Not Statistically Significant
SS	Statistically Significant

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