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SAFOTEB project: towards new approaches for the reliability assessment of existing prestressed bridge

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Abstract

This paper presents the structure of new collaborative research project entitled SAFOTEB "A reviewed SAfety FOrmat for structural reliability assessment of post-TEnsioned concrete Bridges". The research aims at assessing the reliability of the current safety format and developing specific suggestions for existing concrete bridges with post-tensioned cables. To date, no European code provides specific guidance for such a purpose. Indeed, the status of conservation and possible defects of the cables may be hidden, enlarging the uncertainties in the structural assessment of such constructions. The basic steps of the research are: (i) definition of the probabilistic models for the main variables concerning the assessment of existing post-tensioned prestressed concrete bridges; (ii) reliability assessment and calibration of updated safety coefficients for the partial factors method; (iii) evaluation of the residual life and model updating through real-time continuous monitoring systems. The full procedure will be applied on existing case study structures used as benchmarks. The project is funded by FABRE, an Italian research consortium composed by universities and research institutions aimed at the evaluation and monitoring of bridges, viaducts, tunnels and other structures.

Keywords

Post-tensioned prestressed concrete bridges, Partial factor method, Life cycle assessment, Special inspections, Degradation model, Reliability, Traffic model, Monitoring

1 Introduction

Italian transport infrastructures are characterized by road networks that show important critical issues. Many bridges date back to the post-World War II and their characteristics are far away from those required by current design Codes. For example they are subjected to the effects of natural hazard (e.g., earthquakes [1][2] and floods [3]) often not considered in the original design and the entities of the traffic loads used in the original design may be significantly lower than those envisaged by current Standards. In addition, material degradation processes can lead to a reduction in the performance of structural components due to limited maintenance operations or absence of efficient recognisance activities. This phenomenon can be particularly relevant for Post-Tensioned (PT) prestressed concrete bridges, where the cables are hidden under the concrete cover and inside corrugated ducts, making visual inspections not useful to depict the state of conservation. All these aspects endanger the transportation system, as recently highlighted by several bridge collapses such as the one of Fossano bridge in 2017 (Figure 1). Traffic limitations for heavy traffic or lane reduction on bridges can be implemented as temporary safety measures once degradation process are recognized and repair measures are ordered . However, traffic limitations can also pose risks of their own. Traffic congestion caused by the limitations, indeed, can increase the risk of accidents. Consequently, the decision making of transportation authorities and stakeholders should be driven by a correct evaluation of the current reliability of a bridge and its evolution over time, implementing traffic limitations only if explicitly required by a comprehensive risk assessment.

In this context, the Italian Government issued in 2020 the "Guidelines for Risk Assessment and Monitoring of Existing Bridges", successively upgraded in 2022 [4]: this standard proposes a process to assess the infrastructures based on a multi-risk approach. The framework is tai-

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lored to most of the construction techniques where the conservation status and the possible damages are easily detectable by visual inspections. However, given the particular characteristics of PT bridges, further efforts are being made and others are still necessary.

Figure 1 Collapse of Fossano bridge, 2017

Given the importance of the topic, considering that existing bridges are key components of road networks, the FABRE consortium (Research consortium for the evaluation and monitoring of bridges, viaducts and other structures) in 2022 made a competitive call to cofound research projects related to this topic, for a total of 200k € funded. The winning project was SAFOTEB: "A reviewed SAfety FOrmat for structural reliability assessment of post-TEnsioned concrete Bridges". The project is presented by a group of universities and one engineering company. The group includes University of Camerino, University of Pisa, University of Perugia, University of Basilicata, Politecnico di Milano and ITS Engineering. This paper mainly describes the aim and the structure of the project that is currently in its initial phase. Some specific preliminary results of the project are presented in other contributions submitted to this conference, while this paper aims to introduce and recap the overall research and the organization of the workplan.

The SAFOTEB proposal aims at creating a comprehensive process for assessing the reliability of existing PT concrete bridges. This involves analysing all key aspects related to reliability, such as material properties, traffic load, testing and survey process, and their uncertainties and levels of confidence. Probabilistic models are developed to calibrate the whole assessment process to achieve specific reliability levels. Additionally, a method for evaluating the residual life of post-tensioned bridges is integrated, considering typical degradation processes of such structures. Continuous data from monitoring systems are used to assess traffic loads, dynamic and static responses and other time-dependent parameters, increasing the knowledge of the bridge under evaluation, reducing uncertainties and consequently improving the reliability assessment. By integrating degradation models in the safety checks, it is possible to estimate the residual working life and make informed decisions about implementing or not traffic limitations or the closing of the bridge. This process will be tested on a set of case studies representative of the existing Italian infrastructure asset.

2 The project

2.1 Background: PT bridges

Post-Tensioned (PT) prestressed concrete bridges utilize high-strength steel strands or tendons to apply a compressive force in the cured concrete. This compressive force helps to counteract the tensile forces that are created by traffic loads, resulting in a more durable and long-lasting bridges. Prestressing technology enables engineers to build longer, more efficient bridges with fewer supports, resulting in cost savings and improved structural performance. PT bridges technology was largely used after the World War II as it offers several advantages over past bridge construction methods, including greater flexibility in design, reduced time and cost of construction, limited scaffolding and shuttering works and increased durability with respect to standard concrete bridges if no errors are made during the design and the construction. However, PT bridges showed that degradation process over time of post-tensioned cables, if present, is often hidden and even accelerated by the injection ducts. The main sources of degradation concern execution errors in the injection with grout (a grout-free section of tendons is greatly exposed to the risk of corrosion), or in their waterproof sealing, or in bridge drainage. The cable corrosion in combination with the tension stresses can lead to a fast loss of resisting area section of the steel. Consequently, the degradation process could be the main element influencing the final reliability of such kind of bridges.

2.2 Partial factor method and PT bridges

Many design Codes, including the Eurocode, have adopted the partial factor method [5][6], which is the most common method of structural design currently used. It can be generally characterized by the inequality $E_d(F_d, f_d, a_d, \theta_d) < R_d(F_d, f_d, a_d, \theta_d)$ where the design values of action effect E_d and structural resistance R_d are assessed considering the design values of basic variables describing the actions F_d, material properties f_d, geometrical dimensions $a_d + \Delta a$ and model uncertainties θ_d. The design values of these quantities are determined using their characteristic values (E_k and R_k see figure 2a), partial factors, reduction factors and other measures of reliability. Thus, the whole system of partial factors may be used to control the minimum level of structural reliability required. The partial factor format offers the possibility to harmonize reliability of various types of structures made of different materials, as long as calibration procedures were applied. However, specific issues arise for existing prestressed concrete bridges with post-tensioned cables. Uncertainties related to the definition of characteristics value (geometry, material properties, load effects, and models) are of great importance in the final reliability [7]. Moreover, further sources of uncertainty should be introduced for existing structures such as degradation process and potential inspection/intervention process [8]. Handbook 2 of EN1990 [6] at chapter V explicitly deals with the assessment of existing structure defining two basic rules: i) currently valid Codes for verification of structural reliability should be considered and ii) actual characteristics of structural materials, actions, geometric data and structural behaviour should be considered. The document also prescribes that the actual state of structures should be verified by inspections and, if appropriate, destructive or non-destructive inspections should be performed and evaluated using statistical methods. All these prescriptions are considered in the development of the SAFOTEB project.

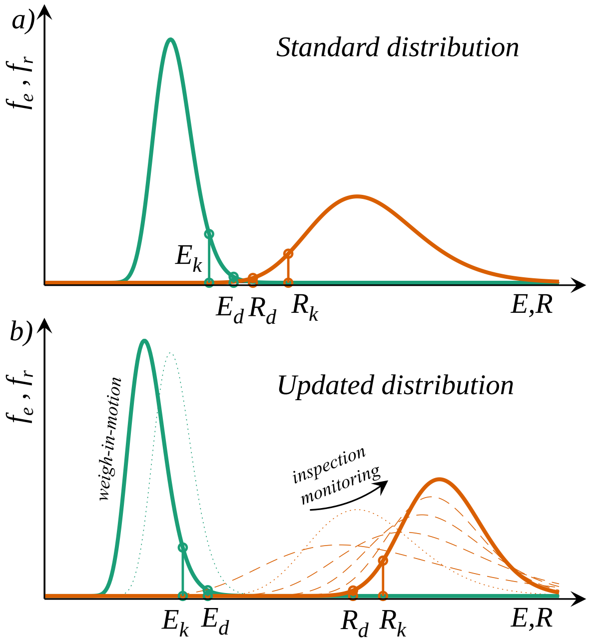

Figure 2 Initial and updated distributions of both action (E) and resistance (R)

One main aspect concerning existing structures is the flow of knowledge and how to correctly implement it in the safety assessment process. For example, starting from data of destructive and non-destructive tests, the characteristics values to be used in the partial factor framework can be estimated using prediction method, coverage method or Bayes' method [6]. Prediction method depends only on the test results, the sample size, and the hypothesis of known or unknown standard deviation of the distribution. In the coverage method also the level of confidence plays a role in the fractile estimation, with a value usually ranging between 0.75 and 0.95 (0.75 is the standard one). When using Bayes' method the previous experience available for random variables, the so-called prior knowledge related to existing PT bridges, can be also implemented. This is of great interest, especially if a large and complete database of existing PT bridges is available and the prior knowledge can be extended and used for the assessment of all the Italian PT bridges. Moreover the monitoring systems and in general any other source of discrete or continuous data can be always integrated in a Bayesian framework (see figure 2b). The use of the three different methods previously described clearly leads to different results, as they required specific choices for example on confidence required on the fractile estimation or hypothesis and data chosen on the prior knowledge. The SAFOTEB project specifically tries to assess how to use them to guarantee a sufficient level of reliability.

Similar considerations can be made also for loads. Referring to bridges, traffic load (in addition to permanent loads) is the most relevant for the ultimate limit state design in static conditions. Given the uncertainties related to traffic actions, the analysis of the real traffic flow (Figure 3) can be used to update the characteristics values, as also suggested by the draft of new Eurocodes for existing structures [9]. The analysis of traffic loads starts from the distribution analysis of the different vehicles categories. Then a probabilistic model is calibrated on data to deal with the expected traffic composition and the related uncertainties. This model may then be adopted to evaluate the characteristic traffic effect value to be used in the safety assessment. Moreover, a modified code traffic action similar to the Eurocode's one and equivalent in terms of load effects can be defined for a set of representative case studies to develop correction coefficients to tune the code traffic effect to the real traffic measured on infrastructures.

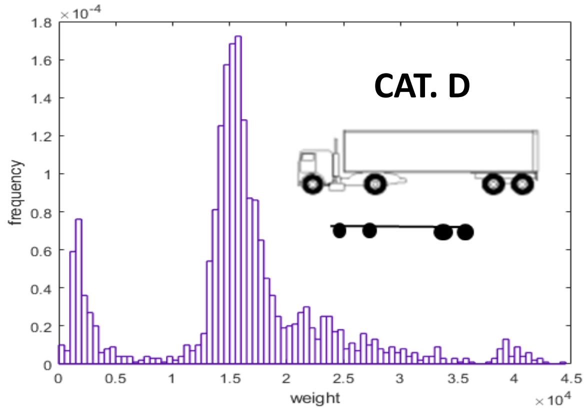

Figure 3 Example of traffic distribution data from a weigh-in-motion monitoring system

2.3 The inspection process and the in-situ tests

The assessment of the post-tensioned structures is a complex process because it is affected by many sources of uncertainty, mostly given by the not consolidated inspection procedures and consequently by the difficult interpretation of the inspections' outputs. An approach to the problem can be found in the CS 465 [10] which provides a risk-based assessment procedure aimed at risk management. That approach is only partial because it provides fundamental tools for risk management and assessment only from a qualitative point of view. Another important contribution can be found in the linked CS 464 [11] document, which provides recommendations about non-destructive tests methods and relevant instrumentation. The American Federal Highway Administration [12] is based on a different approach. The document provides the number of tests required to guarantee a minimum probability of detection of the possible defect starting from a statistical description of the problem; however, the approach is related only to the probability of sampling defective grout (i.e. presence of voids) inside the ducts and not the effective degradation of the cables. These two documents together were the basis of the guidelines for special inspections of PT bridges released by the technical table promoted by the Italian Ministry of Transportation and Sustainable Mobility. The guidelines took the "pros" of the two documents and developed a procedure consistent with the current Italian Building Code [13]. In the SAFOTEB project this procedure is revaluated and improved, in the light of the new Eurocodes.

2.4 Workplan of the project

A brief description of the workplan and the single work packages are presented hereafter (see Figure 4 for a graphic representation).

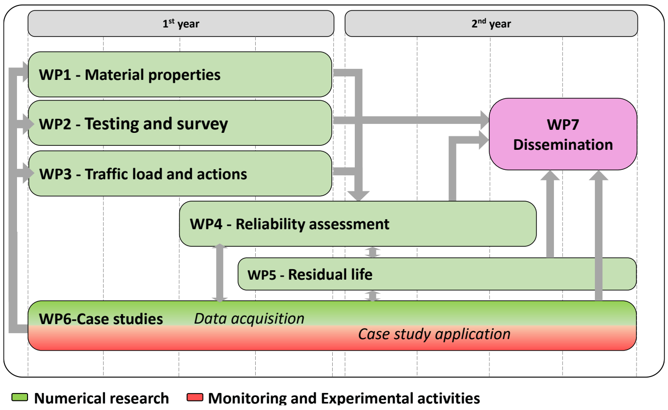

Figure 4 Workplan of the project

WP1 – Material properties.

A dataset containing mechanical and design characteristics of PT bridges is created, collecting data available by partners and retrieved from scientific literature. Then, the dataset, that is structured for being always updated, is analysed through a full statistical analysis in order to estimate, within a certain confidence interval, the main parameters of each data considered (such as concrete strength, concrete stiffness, cable strength, cable dimension, etc.). Theoretical distributions, based on available data and useful within a partial safety method, are evaluated taking into account also the materials degradation [14]. The inventory is consultable for any information collected (strength, structural element, test type conducted before the construction or in situ, etc.). Moreover, it allows comparative analyses among data collected, among which construction date, and geographic distribution.

WP2 – Testing and survey.

The aims of the WP are to review the current methodologies for inspecting PT systems, and to assess the related uncertainties. The WP consists of two tasks. In the first task current non-destructive techniques are reviewed, based on survey of literature and Standards, and ranked based on four categories: the accuracy, the ease of use, the cost and the impact on the operation of the infrastructure. A specific weight is assigned to each category, and finally a weighted sum model (WSM) is proposed which provides a final score for each method, given its individual score in the weighted categories. The goal is to provide decision-makers with a tool which can assist them in the selection of the optimal non-destructive technology available to detect a particular strand or grout defect accounting for different factors. In the second task, test methodology are assessed in terms of uncertainties on the results of each instrument/technology/procedure employed in order to implement this specific source of uncertainty in the probabilistic models of each measured basic variables. Special attention is made for the tests related to the identification of degrading process of post-tensioned cables such as section loss and breaking, and the quantification of the actual prestressing forces.

WP3 – Traffic load and actions.

Probabilistic traffic models are developed based on the analysis of literature and data from weigh-in-motion monitoring systems. The analysis of the real traffic flows allows to identify the main random variables for the several vehicles category (i.e. cars, light trucks, heavy trucks and so on). Operational restrictions, limiting the traffic load placed by the relevant authority, are also considered. The effects of the real-based traffic probabilistic model are analysed in terms of effects on different bridge configurations, and equivalent code traffic models are defined. Finally, a comparison between these equivalent traffic schemes and the Eurocode's one is done to set the basis for the calibration of new traffic load partial factors.

WP4 – Reliability assessment.

The current safety format of partial factor method is critically analysed in light of the peculiarities of existing PT bridges. The reliability of the partial factor method is assessed through analyses using all the probabilistic models of the basic variables developed in the WP1, WP2 and WP3. The process of knowledge is fully simulated, starting from prior knowledge available, and then going through the number and types of tests performed to investigate the bridge conditions. Moreover, sensitivity analyses are performed to assess the effect of the different choices that may be made in the process of knowledge (number and type of tests, confidence required, method applied in the computation of characteristics values, prior information and assumptions made). The degradation models developed in WP5 are also implemented in the reliability assessment.

WP5 - Residual life

The most common degradation phenomena affecting prestressed concrete bridges are analysed and degradation models are developed based on literature and data derived from experimental campaigns available. Moreover, the current monitoring techniques, for the continuous control of parameters involved in the reliability assessment, are evaluated. The project also assesses the capacity of continuous monitoring activities in reducing the uncertainties related to the definition of basic variables such as material strength, traffic loads and degradation, allowing to evaluate the reliability and the residual life of existing PT bridges in real-time. For this purpose, probabilistic models for the estimation of failure probabilities of different limit states will be defined. They will include the probabilistic definitions of parameters, materials characteristics, traffic loads, and the models elaborated for the effects of the most relevant degradation phenomena. The modalities to integrate the methodology with the process of updating models in continuous, using data collected through monitoring activities, will be studied and proposed. The possibility to exploit the real-time knowledge of the residual life in the decision-making processes for the management of existing PT bridges will be explored and discussed.

WP6 – Case studies

This work package manages and coordinates the data acquisition for the definition of all the probabilistic models of basic variables and, in general, all the collection of data available from each partner to build a comprehensive dataset specifically targeted on existing PT bridges. In addition, an application of the framework on a reduced number of significative case studies is carried out by simulating different path of knowledge process, hence comparing the estimated final reliability with respect to the "real one" (associated to the best knowledge-model available).

3 Current activities

The two-years project, started in October 2022, is in its initial phase. The activities of the first months (up to the submission of this paper) have been focused on the data acquisition and the implementations of the dataset to define a prior knowledge useful for the probabilistic models definition. A statistical analysis of the mechanical parameters already showed, as expected, the quite low dispersion of high strength steel used for the PT cables. The dataset will be further extended, and a full statistical analysis will be performed to derive general information regarding all the parameters acquired, looking at possible correlation between mechanical parameters and other information (e.g. design/construction year, location, general geometric characteristics). A list of the current test methodologies based on of the state of the art has been made, for a total of 20 different methodologies. The list defines for each methodology the operational principles, the limitations, bibliographic references and also ranks each of them based on these features: defect localization accuracy, severity estimation accuracy, cost, ease of use, impact on infrastructure. As the data acquired by in-situ tests are affected by the instrument accuracy, these information will be implemented in the simulation of the test procedure to understand how the use of different methodologies could influence the final reliability of the partial factor method. The traffic models are being developed based on data from weigh-in-motion currently active.

4 Conclusions

The results of the project are expected to significantly enhance the knowledge on uncertainties related to mechanical parameters and traffic loads. The project will also have an indirect technological impact by promoting the development of structural health monitoring systems and specific instruments for post-tensioned cables. The assessment of PT existing bridges will lead to more reliable road networks and important information for planning bridge maintenance. Consortium FABRE will increase the impact of the outcomes of the project through its connections with major highway network administrators, collaborating with them. Overall, the proposal provides an analytical and rigorous framework for post-tensioned cables, which can be applied to structures beyond those considered in the project and can significantly enhance knowledge and optimize resources for bridge maintenance.

Funding and Acknowledgement

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