ce/papers Proceedings in civil engineering

Ernst & Sohn A Wiley Brand

ORIGINAL ARTICLE

EUROSTRUCT

A methodological proposal for the analysis of bridges inspections data according to the Italian Guidelines

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Abstract

The question of maintenance and monitoring of bridges gained attention during the last decade, especially in Italy, after some serious collapses. The first emergency phase was the census and the visual evaluation of the state of maintenance and preservation of existing heritage to highlight the critical conditions for security. For this reason, in 2020 the Italian Ministry of Transport and Infrastructure enacts Guidelines, based on a multilevel approach, which allows to save time and resources by deepening the analysis only on the bridges in the worst state of conservation. After two years of inspections, a lot of data had been collected. The data concerns both the geometrical/typological characteristics and the defectiveness of bridges. In the present work, the authors discuss the data of a sample of inspected bridges belonging to some Regions of the Italian infrastructural system trying to analyse them from a statistical point of view. The objective is to standardize an analysis methodology and apply it to a larger number of samples to obtain useful and significant information to refine the inspection procedure and, eventually, to educate algorithms for the a priori provision of the defectiveness level, suggesting a possible prioritization of the bridges to be inspected.

Keywords

Existing Bridges, Bridge inspections, Defectiveness, Quick survey, Structural Assessment, Prioritization, Data Analysis, Risk Management, Bridge Management System, Artificial Intelligence in Bridge Management

1 Introduction

The multiple cases of partial and whole bridge collapse that occurred in the last decades all over the world highlighted the urgency of facing the problem of the management of existing bridges through a unified and scientifically-based approach. Some well-known issues need to be highlighted before addressing this problem, which requires a holistic approach to be tackled effectively [1]. First, bridges and viaducts are exposed to a variety of hazards, not only linked to the structural aspect but also to the environment in which they are located. In this sense, an exhaustive set of natural hazards (e.g., floods, earthquakes, wind, landslides, etc.) should be considered to evaluate the effective risk associated with the structures. Next, most existing bridges were built during the Seventies of the last century, therefore, aging seriously compromised their health conditions. Moreover, a significant increase in terms of traffic volume and weight in conjunction with a lack of adequate maintenance through the years exacerbated the deterioration process [2]. Finally, nowadays is quite impossible to have an exhaustive overview of the condition of the national bridge stock because of mixed ownerships that alternated over the decades, a situation that resulted in a lack of well-organised and structured data. These issues highlight the urgent need to at least know the conservation state of existing bridges as the starting point for their efficient management, which has, among all, two relevant key points to solve:

1. the necessity of a national database that stores structured data for comparisons and decision-making activities.
2. the necessity of a standard methodology to evaluate the safety of bridges that considers all types of risks to which they are subjected.

In Europe, bridge management is regulated at the national level, as well as the inspections procedure, evaluations of conservation status, specific insights, and the procedure of prioritization for economic investments [1]-[9].

In Italy, to address the first point, the Italian Ministry of Transport and Infrastructure instituted the so-called *Archivio Informatico Nazionale Opere Pubbliche* – AINOP

https://doi.org/10.1002/cepa.2102

with the Ministerial Decree n.430/2019 [10]. The first move toward a national bridge database has been taken. This database contains all types of infrastructures and collects data fed by Owners/Managing Bodies. Nevertheless, the platform still frequently contains poor or no data. The second question is faced with the entry into force of the new Italian Guidelines [10] and the early published Operative Instructions [11], which introduces a mandatory innovative multi-risk and multi-level methodology for the evaluation of existing bridges, which standardises a shared approach to be followed. This new approach relies on the general philosophy of deepening the knowledge of structures the more they are prone to be damaged by different relevant sources of risks, to optimize the time and economical resources to invest. Six levels of assessment are foreseen: the first three must be applied to all bridges (Levels 0 to 2), while the last three (Levels 3 to 5) only for the bridges which are characterised by high risk deriving from the analyses of the previous levels.

Focusing on the first three levels, Level 0 consists of a census of all the existing bridges, collecting registry data mainly deriving from the existing documentation. Level 1 consists of visual inspections, which are used to point out the conservation status of the bridge and the surrounding area. Level 2 provides for a risk-based classification starting from the data previously collected, and the risk categories considered are: the structural and geotechnical risk, the hydraulic risk, the seismic risk, and the landslide risk. Each risk is defined as a combination of vulnerability, hazard, and exposure (each of this parameter depends on other relevant factors that are collected and defined in the previous two levels of the method). For each risk, the "warning class" is evaluated, and the combination of the different classes brings to the global one. The method proposed in the Guidelines [10] for the risk assessment is scientifically based and made by experts in this field [12], but not analytical. Indeed, to be easily and fast applicable to many typologically and environmentally different structures, the method consist in analysing the collected data of the previous levels and follow logical flows to the evaluation of each parameter (vulnerability, hazard, and exposure) to the waring class, which is qualitatively defined: low, medium-low, medium, medium-high and high.

The results of the Level 2 set the basis to planning all the consecutive activities, basing on the obtained class: visual inspection planning for all the bridges, structural monitoring activities for the structures resulting in a medium or higher warning class, to the necessity of going deeper with the analysis and proceed with the deeper Levels for the more critical cases. In the latter case, Level 3, 4 and 5, consist in the accurate assessment of the safety level of the bridge, up to consider, eventually, the resilience of the network.

It is easy to notice the importance of the first three Levels for choosing and planning the consequent management activities. Anyway, from the perspective of a road manager, structuring these following actions could be tough since many bridges could be characterized by the same warning class. The Operating Instructions [11] already point out this issue, suggesting analysing the motivations for the resulting warning class: a high warning class due to high vulnerability because of defectiveness, or due to high exposure can lead to different management strategies. These considerations suggest the necessity of developing prioritization strategies to support the road managers in structuring the after-Level-2 management activities.

In this framework, this paper shows the basis for a prioritization method that has roots in the conservation status of the structure. Indeed, the level of damage, synthesized in the "Level of defectiveness" factor of the Guidelines [10], is reasonably the leading factor to the classification procedure, defining the structural vulnerability parameter (for the same warning class, it is more critical having high damage rather than criticalities in the hazard or exposure-connected factors). The goal of the proposed method is the evaluation of a numerical index that supports the "Level of defectiveness" qualitative evaluation. In this way, the bridges characterized by the same structural warning class and the same vulnerability can be "numerically ranked" and not only grouped in classes. The here proposed formulation of this index is validated through the statistical analysis of 704 inspections of bridges (inspected by the Authors and their research group themselves) belonging both to the primary and secondary road networks, performed by observing the New Italian Guidelines [10]. Hence, in paragraph 2, a few deeper and more relevant pieces of information are provided around the evaluation of the Level of defectiveness according to the Guidelines [10]. Then, paragraph 3 describes the methodology for the definition of the numerical index. Finally, paragraph 4 describes the application of the method to the sample of 704 inspected bridges.

2 The Level of defectiveness in the Italian Guidelines

The assessment of structural and geotechnical vulnerability depends on parameters that can be collected through the visual inspection (current defectiveness, static scheme, span length, material, and the number of spans) or which can be derived by the census of Level 0 (rapidity of defectiveness and Design Standards). The current defectiveness is one of the most important parameters to define since it describes the actual state of conservation of the bridge. Five levels of Level of defectiveness can be assigned: low, medium-low, medium, medium-high, and high. For each material and structural element are individuated the typical defects and ordered by a gravity scale from 1 to 5: 1 is the less serious, and 5 is the worst defect. These typical defects are gathered for each structural element in a form to be filled out by the inspector during the visual inspection. The inspector must evaluate the presence or the absence of the defects and assign to each a level of intensity and extension; both can assume values of 0.2, 0.5, or 1. The extension is defined as the ratio between the part of the surface affected by the defect and the total surface of the element. The intensity depends on the severity of the defect. The level of defectiveness of the single element depends on the number of defects with a certain extension and intensity detected, while the overall level of defectiveness of the structure depends on the one of each element [11].

3 Discussion and methodology proposal

Starting from the forms about the defectiveness filled for each structural element during the visual inspections, defect types can be reorganized by grouping the defects in homogeneous classes, defined upon the criteria of defects sharing the same triggering agent.

In this study, the different individuated classes are degradation because of water/moisture, cracks, physiological material degradation, defects in the foundation, detachment of the concrete cover and/or oxidation/corrosion of the defects due to execution issues, and Gerber saddles defects. In this preliminary study, only the presence/absence of a defect is considered, namely intensity and extension are not involved in the analysis.

By considering a value of 0 for the absence of a certain defect, and 1 for its presence, for each defectiveness class of the structure is obtained the sum of all the defects inspected, belonging to the same defectiveness class ($n_{def.class}$). By knowing the number of bridges belonging to the same defectiveness class ($n_{tot\ bridges\ \forall\ class}$), it is possible to obtain the average value of the considered homogeneous defect group in a bridge belonging to a certain defectiveness class ($m_{def.class}$).

$$m_{def.class} = \frac{n_{def.class}}{n_{tot\ bridges\ \forall\ class}} \quad (1)$$

Then, the "concentration index" ($i_{c\%}$) of a certain homogeneous group of defects can be computed by normalizing the average value $m_{def.class}$ on the sum of the average values of a certain homogeneous group of defects for all the defectiveness class ($\sum_{i=1}^{5} \overline{m_{def.class}}$, where $= 1$ is "Low" actual defectiveness, $i = 5$ is "High")

$$i_{c\%} = \frac{\overline{m_{def.class}}}{\sum_{i=1}^{5} \overline{m_{def.class}}} \quad (2)$$

4 Application of the proposed procedure to a sample of bridges

The previously introduced procedure is applied to a representative sample of Italian bridges belonging to different Italian regions. Previously, a statistical analysis of the main characteristics of the bridges belonging to the sample is proposed, and then some considerations about the typology of defects concerning a certain structural type and a defectiveness class are executed. This step represents the starting point of an analysis that aims to find out which are the most critical defects for a certain structural type.

4.1 Description of the sample

Data analysis is carried out on a sample of 704 bridges located along the primary and secondary roads of the Italian infrastructural system, belonging to the Regions Toscana, Liguria, Emilia-Romagna, Sardegna, Marche, and Calabria. In Figure 1 are highlighted the provinces in which the inspected bridges are located.

The assessment required by Level 0 and Level 1 of the Italian Guidelines is completed for each bridge, i.e. the census, and the structural and foundation risk assessment is defined by performing visual inspections. For 4 of the bridges, it was not possible to perform any inspection, so neither the main geometric nor structural characteristics could be recorded, while for 41 bridges it was not possible to carry out the visual inspection to assess the level of defectiveness due to problems related to the accessibility of the area. Finally, 37 of the structures are not properly bridges but culverts, so they are excluded from the analysis. Table 1 resumes the details of the previous discussion.

Figure 1. Provinces in which the inspected bridges are located.

The following considerations are derived from the analysis of the sample of fully assessed bridges according to Level 1 (626 structures).

Table 1 Details of the inspections

Description	N°
Total number of inspected bridges	704
Number of bridges not inspectable at all (no census)	4
Number of bridges not fully inspectable (no defectiveness determination)	41
Number of culverts	37
Total number of censed bridges (Level 0)	663
Total number of assessed bridges (Level 1)	626

Most of the structures are in masonry (45%) and another preponderant part is in Reinforced Concrete (R.C.) (37%); furthermore, a significant sample is represented by the Post-tensioned Concrete (P.C.) bridges (15%), while steel structures represent a minor percentage (3%). The most common structural scheme is the arch (56%) since all the masonry bridges have it and a part of the R.C. structures too. The pie charts in Figure 2 resume the number of bridges grouped in terms of material and structural scheme.

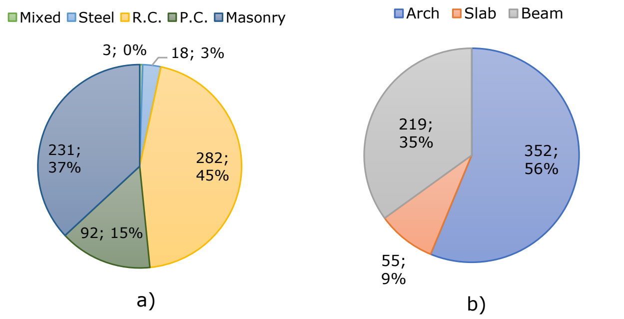

Figure 2 Distribution of bridge analised: a) number and the percentage of bridges made out of a certain material; (b) number and the percentage of bridges with a certain structural scheme.

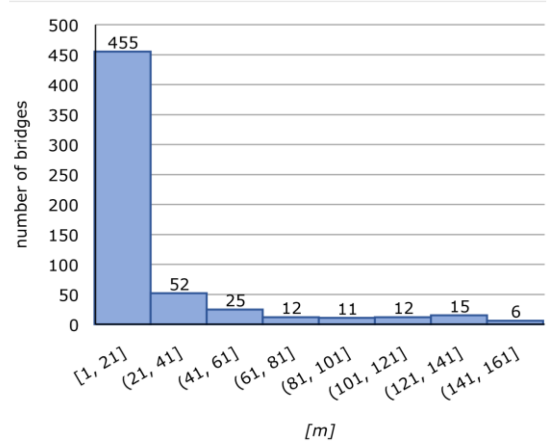

Figure 3 Distribution of the span lengths

Regarding the age of construction, most of the bridges (48%), were built before 1945; indeed, it can be observed that the percentage almost coincides with one of the masonry bridges. On the other hand, only 13% of the structures were built after 1980. Regarding the number of spans, 75% of the sample are single-spanned bridges and 22% have between 2 and 10 spans. The histogram in Figure 3 shows the distribution of the maximum length of the bridges (30 samples with a span length major to 161 are excluded to make the graph more readable and for 4 bridges was not possible to check the total length). A very consistent percentage of the sample has a span length minor to 21 m; the reason is that most of the inspected bridges are located on secondary road networks.

For each bridge is computed the actual defectiveness class, according to the Italian Guidelines. The distribution for each class is given in Figure 4; it can be observed that a large part of bridges results in classes between low, medium-low, and medium. Anyway, the sample is considered significant since no class presents less than 30 elements.

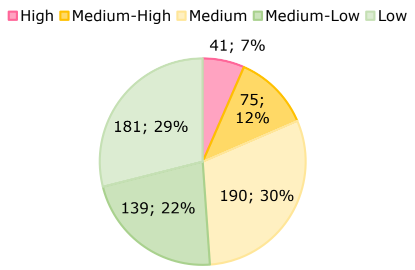

Figure 4 Distribution of the actual defectiveness

It is interesting to observe what happens by splitting the sample considering some significant characteristics. Figure 5 a) shows the percentages of the masonry and R.C. arch bridges in a certain defectiveness class. The tendency is very similar for the two different samples, and this could mean that in the case of arches, or in general thick structures, the defectiveness connected to the base material is less influent than the one inducted by defects that may affect the structural behaviour of the construction. The number of structures that falls in each considered sample is reasonably large: the arch masonry bridges are 231, while the arch R.C. ones are 119. Figure 5 b) shows the same tendencies but related to R.C. and P.C. beam samples. First of all, it's notable the difference compared with the arch bridges: there is a considerably higher percentage of bridges in the medium and medium-low defectiveness class.

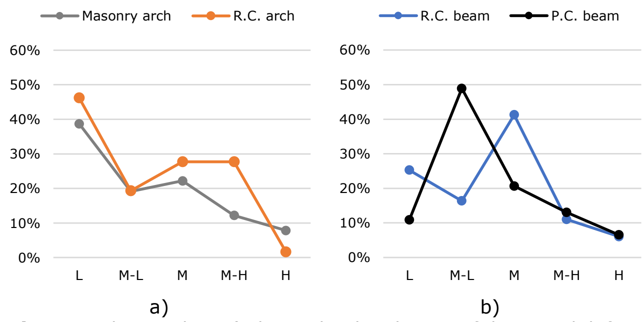

Figure 5 The graph in a) shows the distribution of the actual defectiveness classes for arch masonry and R.C. bridges, while the one in b) the distribution of such classes for P.C. and R.C. beam bridges

On the other hand, the R.C. concrete bridges have mostly a medium defectiveness, while the P.C. is mostly medium-low; this may be correlated to the major attention and control that, in general, is given in the P.C. casting process. Besides, the difference in the tendencies shows that it is important to split the "beam bridges" considering the construction technology (R.C. instead of P.C.).While for P.C. bridges there is no substantial difference considering the defectiveness levels for structures built before and after 1980 (Figure 6 b), R.C. bridges tend to be more defective if built before 1980, probably due to the physiological degradation of the concrete (Figure 6 a). Finally, the tendency given by the P.C. bridges built after 1980 is interesting since most of them present a low defectiveness class. The interpretation could be that these bridges are "young" and therefore still do not exhibit issues related to the degradation of the materials.

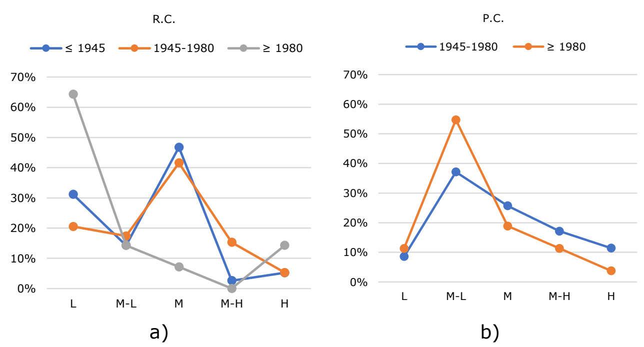

Figure 6 The graphs show the distribution of defectiveness classes compared with the years of construction, for R.C. bridges, in a), and for P.C. ones, in b).

The statistical analysis presented above is useful to consciously select samples to study and needs to be deepened by considering other potentially influencing characteristics. In the following, the proposed analysis is focused on the masonry arch bridges.

4.2 Analysis of the actual defectiveness

The influence of a certain defect family on the degradation of structures is discussed below concerning the "concentration indices" ($i_{c\%}$), analysed for the masonry arch bridges. A total of 231 masonry arch bridges are considered; in particular, according to the classification of the Italian Guidelines, 18 bridges present a high actual defectiveness, 28 medium-high, 52 medium, 44 medium-low, and 89 low (Figure 7). Approximately 60% of the structures have a low or medium-low actual defectiveness.

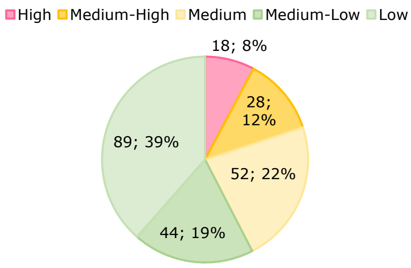

Figure 7 Actual defectiveness distribution of masonry arch bridges.

Being masonry arch bridges, the defectiveness families considered are degradation due to water/moisture (Figure 8a), cracks (Figure 8b), physiological material degradation (Figure 8c), and defects in the foundation (Figure 8d).

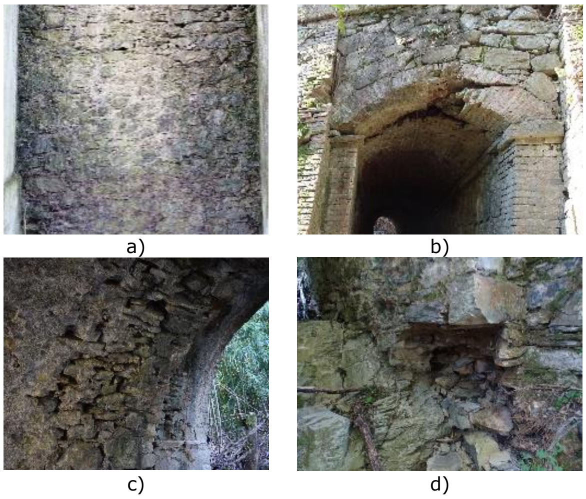

Figure 8 Examples of defects belonging to a homogeneous group.

The results of the evaluation of the concentration index are shown in Figure 9. It can be observed that there is a clear dependency between foundation defects and the cracks: major the concentration index, major the actual defectiveness. On the other hand, no tendencies seem to exist for the defects due to the physiological degradation of the material for the humidity/water action.

These results seem to affirm that the defects belonging to the latter two groups (physiological degradation of the material for the humidity/water action) do not influence the defectiveness level of a masonry structure and that therefore can be considered less important in the execution of the visual inspections. Moreover, in the field of the present research, the results could be used for the education of algorithms able to predict present defectiveness.

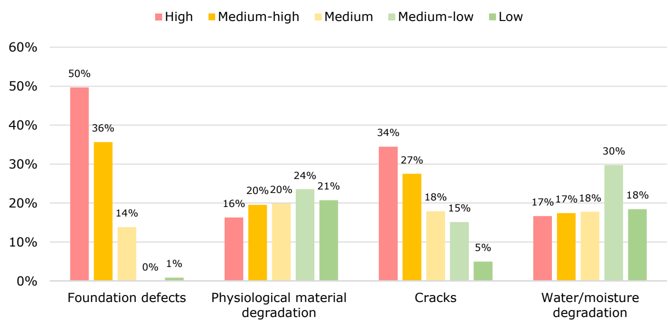

Figure 9 Concentration indexes (masonry arch bridges)

5 Conclusion and future development

The present study aims at proposing a methodology for the evaluation of a synthetic numerical index capable of depicting the current conservation status and level of defectiveness of a bridge as defined within the Italian Guidelines [10]. The Level of Defectiveness is indeed one of the most significant characteristics deriving from the visual inspections and leading the evaluation of structural vulnerability in the Guidelines' structural risk classification procedure.

The index proposed is named "concentration index" and points out the concentration of defects belonging to the same homogeneous class. Each class is defined based on the triggering agent of the defect. This index is evaluated for a sample of 704 bridges inspected by the Authors. In this paper, the analysis of the obtained results is showed for the masonry arch bridges, which are a total of 231 structures. Some significant information can be derived from this application such as: if the defects given from the physiological degradation of the material and the action of water/moisture seem not to influence the resulting defectiveness class, while the ones due by cracking and foundation movement strongly increase with the increasing of the defectiveness class.

As future work, this analysis will be extended to the other typologies of inspected bridges and also the intensity and the extension of a defect will be taken into account, to finally calibrate the representative index for the Level of defectiveness. As previously highlighted, this index could support Owners/Managing Bodies in prioritizing inspection activities of new-to-be-inspected bridges and also already-inspected ones characterized by the same warning class and managing decision-making processes. Besides, this index could furnish preliminary indications to train an algorithm capable to predict the defectiveness of bridges, given a standardized set of taxonomic information regarding the structures, to be then integrated into a national BMS platform to support.

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