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The IRRADIA research project for the advanced management of infrastructures

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Abstract

AISICO and 'Sapienza' University of Rome are working on the project IRRADIA, a research program aiming to investigate the use of Artificial Intelligence for the structural assessment of railway and road infrastructures. The starting point is the BRIGHT method (BRIdGes Health Testing method, patented by AISICO), already applied on a large data set of information, and essentially based on the automatic detection of damages on structural elements of bridges and viaducts. The results carried out on 80 railway bridges provide new ideas to the sector of monitoring and control of existing infrastructures in terms of automatization. Then, the BRIGHT method, built on the railway specifications described by DOMUS, has been recently expanded to meet the requirements of the 2022 Italian Guidelines for existing road bridges and viaducts (DM 204, 1/07/2022). These require to fulfill several defect sheets for each structural element (e.g., beams, transversal beams, slabs, piers, abutments, supports, and so on), with a proper evaluation, for each defect, of type, extension and intensity. It follows that the damage evaluation requires usually a large number of operations with a high level of repetitiveness. Therefore, the use of AI techniques is a promising tool for the near future, to acquire and collect the images with unmanned aerial vehicle, from one hand, and to fulfill the defect sheets, from the other one, reducing time and cost. In this framework, one of the main goals of the cited IRRADIA research project is the investigation of the results obtained with the BRIGHT method extended to 2022 Italian Guidelines, that is, to road infrastructures. In this contribution the first results obtained on two bridges, the first in reinforced concrete and the second with a masonry structure, are presented and discussed.

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1. Introduction

The evolution of Artificial Intelligence (AI) techniques is revolutionizing the field of structural engineering, in the evaluation of the safety and state of degradation of existing structures. The research and application of AI in this area promise to significantly improve the efficiency, accuracy and speed of many engineering activities, especially in terms of management and control, see for example Zhang and Yuen (2022). A great boost in this area is also due to the use of intelligent wireless monitoring systems. These advanced systems, which exploit synchronized and high-quality data, offer a significant contribution in the management of both preventive maintenance and emergencies, marking a notable progress in the field of all structural engineering; for a deeper explanation see the work of Karunkuzhali et al. (2022).

A recent study by Lin et al. (2017) thoroughly explored the applications and potential of AI in structural engineering, highlighting how it can be used to improve prediction, risk analysis, decision making, resource optimization, classification and selection issue, as well as construction, maintenance, and management of many structural engineering problems. In particular, the work highlights the significant benefits of using AI, including greater accuracy, efficiency and cost-effectiveness, compared to conventional methods. In another recent contribution by Paduano et al. (2023), the authors offered an additional perspective on AI-based image analysis and technologies for use in the field of civil engineering, highlighting recent developments and new directions on the topic. The paper highlights the importance of integrating AI into engineering practices, not only for damage assessment, but also for a wider range of applications in the construction sector.

These developments highlight the crucial role that AI can play in assessing bridge safety, not only improving the efficiency and accuracy of current assessments, but also opening new avenues for risk prevention and emergency management. In particular, the use of deep learning algorithms for automatic defect recognition has shown promising results, as demonstrated by recent studies that have applied advanced techniques – namely YOLOv3 – for the detection of bridge surface defects, see Teng et al. (2022), and deep learning-based visual inspection systems for the investigation of the substructure of reinforced concrete bridges, see Kruachottikul et al. (2021).

The "Guidelines for the classification and management of risk, safety assessment and monitoring of existing bridges" (LG22) issued by the Italian Superior Council of Public Works (CSLLPP (2020), first issuing, CSLLPP (2022), updating, and ANSFISA (2022), operating instructions) provide a regulatory framework for the Italian infrastructures, establishing standards and procedures which in the future can be further optimized relying on the obtained results and experiences. Specifically, the multi-level approach of the LG22 provides: a first phase of rapid risk assessment divided into Level 0 (census and document analysis), Level 1 (inspection activity), Level 2 (evaluation of the risk through attention classes), and a more detailed second phase, conditioned on the results of the first, of safety evaluation, divided into Level 3 (preliminary evaluation of the structure) and Level 4 (accurate safety evaluation). Level 5 procedures, relating to network resilience, are cited by LG22, but basically still in progress.

Among all the operations required in this process, the recognition and defect analysis to be carried out at Level 1 assumes fundamental importance, since it decisively conditions both the structural and foundational attention class and the seismic attention class. At present, LG22 provides that this recognition is done by assimilating the state of places with specific defects schemes, codified in Annex C of CSLLPP (2020) and CSLLPP (2022). The next step is to compile the defect sheets, which must be drawn up for each individual structural element, specifying not only the type of defect, but also their extension and intensity. It follows that the evaluation of the state of degradation requires the execution of a potentially very high number of operations with an equally high level of repetitiveness.

It is therefore clear that the use of AI techniques is destined to play soon a central role in this process. Specifically, AI can be applied in at least two ways:

- assisted recognition of defects starting from photographic survey, potentially performed with the aid of drones;
- support for the evaluation of the extension and intensity of the defects (K1 and K2 coefficients of the LG22, respectively).

In this context, AISICO and 'Sapienza' University of Rome are working on the IR-RAD-IA project (Inspections and Representations based on Assisted Defect Recognition and Artificial Intelligence): the main goal is the performance analysis of artificial intelligence techniques in the recognition and classification of defects for reinforced concrete and masonry bridges.

In detail, AISICO has recently developed the software called Automated Defect Detection_Bridge ADD_B © (vers. 2) for the automatic recognition and classification of defects. The ADD_B © code, originally applied to railway bridges, and briefly described here in paragraph 2, has recently been extended to road infrastructures. Here the software is applied on two reinforced concrete piers (pier 4 and pier 9) of the case study 1 and a masonry pier (pier 2) of the case study 2. The two viaducts will be briefly described in paragraph 3. The aim is to compare the assessments carried out with the traditional procedure, i.e. identifying the defects during the visual inspection and reporting them on the defect sheets, with those obtained using the software. This comparison aims to demonstrate how in the near future the integration of AI in this area will lead not only to accelerating inspection procedures, but also to improving the accuracy of assessments, helping to preserve the infrastructural heritage through more objective and targeted maintenance operations.

Nomenclature

AI	Artificial Intelligence
ADD_B	Automated Defect Detection_Bridge
IR-RAD-IA	Ispezioni e Rappresentazioni basati sul Riconoscimento Assistito dei Difetti e sull’Intelligenza Artificiale (Inspections and Representations based on Assisted Defect Recognition and Artificial Intelligence)
LG22	Guidelines on Risk Classification and Management, Safety Assessment and Monitoring of Existing Bridges, Italian Ministry Decree n. 204/2022
RC	Reinforced Concrete
PRC	Prestressed Reinforced Concrete
CNN	Convolutional Neural Networks

2. Description of the software ADD_B

The software ADD_B © (Automated Defect Detection) developed by AISICO, is a copyrighted software for the automated identification and classification of surface anomalies on structural elements of structures, such as bridges and viaducts, within transportation infrastructures. The results generated by this automated process are subsequently subject to verification by expert operators in accordance with standard practices and then validated as defects. The software can be used to assist operators in the analysis of orthophotos of structural elements, as specified in structure surveillance manuals, to determine the state of degradation during visual inspections.

In detail, orthophotos are obtained from 3D models created by capturing images using drones and applying aerophotogrammetric techniques. ADD_B © facilitates operators in defect detection and classification, as well as in compiling inspection reports, serving as a preliminary analysis tool. This preliminary process precedes the final evaluation by the expert operator and is particularly crucial in the assessment phase of degradation in terms of defect extent and intensity.

From a computational viewpoint, ADD_B © employs advanced image design and digital image processing techniques, utilizing artificial intelligence models such as Convolutional Neural Network and Deep Learning. This software is an essential component of the BRIGHT method, an innovative patented approach developed by AISICO for the detection and management of the state of bridge and viaduct networks. The interaction of ADD_B © with Structural Health Monitoring (SHM) systems is an integral aspect of this methodology.

The steps for using the ADD_B © software are as follows:

1. **Data/Input Organization**: In this initial phase, the RC or masonry structure is created and modified to describe the different structural parts, thus generating the structural elements and components;
2. **Pre-processing**: At this stage, photographs of each element and component (front, back, right side, and left side) are cataloged and prepared for the subsequent processing processes of the software;

3. **Setting**: Here, the previously selected photographs, uniquely identified by an ID code, are uploaded. The type of analysis is selected using Convolutional Neural Networks (CNN) and an evaluation method is chosen;
4. **Automated Diagnostics**: The CNN is initiated, and the processing is visualized; then starts the validation phase;
5. **Validation**: By appropriately setting filters based on the network confidence level and the size of the defect surface, the ‘anomaly’ table is generated. This table, after the addition of false negatives and the elimination of false positives, is validated, archived, and used for the continuous training of the network;
6. **Output Generation**: A series of outputs are produced, which include a summary table of defects, a table with a weighted overall degradation index and the Attention Class according to LG22. Also a table of specific Key Performance Indicators (KPIs), and a photographic report of each component with the defect IDs and labels are provided.

The ADD_B © software can automatically recognize different classes of defects starting from images acquired *in situ*. Each class is then associated with a different color which will be returned in the post-processing phase on the analyzed image if the associated defects are detected. The extension of the colored part is a first quick (visual) indication of the extension of the damaged area. For bridges in Reinforced Concrete (RC) and Pre-stressed Reinforced Concrete (PRC), the classes, their relative coloring, the defect identification code and the description of the defect are summarized in Fig. 1 (a); as regards masonry structures, the same information are in Fig. 1 (b).

a)

MATERIAL	N° Class	ADD_B CLASS	CLASS DESCRIPTION	COLOR
Reinforced Concrete & Prestressed Reinforced Concrete	1	CL_a	Cracking	
	2	CL_b	Efflorescence	
	3	CL_c	Infiltrations and washouts	
	4	CL_d	Execution defects	
	5	CL_e	Deterioration	
	6	CL_f	Exposed reinforcements	
	7	CL_g	Deteriorate successive repairs	

b)

MATERIAL	N° CLASS	ADD_B CLASS	CLASS DESCRIPTION	COLOR
Masonry	1	CL_a	Cracking	
	2	CL_b	Efflorescence	
	3	CL_c	Infiltrations and washouts	
	4	CL_d	Scaling and disintegration	
	5	CL_e	Loss of material in the joints	
	6	CL_f	Broken or missing elements	
	7	CL_g	Patinas and plants	
	8	CL_h	Deteriorated successive repairs	

Fig. 1. Description of defect classes for ADD_B © software: (a) RC and PRC; (b) masonry.

3. Case studies

Two Italian infrastructures situated in distinct regions have been chosen for the comparison. The selection of these structures is based on their different construction features and their relevant distinct tasks concerning maintenance and safety operations. To maintain brevity in this study, the analysis will specifically target two piers from the first case study and one pier from the second one.

3.1. Case study 1

The viaduct under investigation belongs to a railway line in Southern Italy. The structure comprises 30 spans supported by RC box piers. The bridge deck consists of four main girders connected by two end and three intermediate cross-beams. The static configuration of the viaduct varies along its length: for most spans, precisely 22, a simply supported beam scheme is used; for the remaining 8 spans, the structure is a frame system, as shown in Fig. 2.

Within the context of this study, specific attention is focused on two structural elements: piers number 4 and 9. The selection of these two piers is not arbitrary but is driven by their representativeness and strategic location within the structure, making them particularly significant for the analysis of the viaduct structural health.

Fig. 2. Panoramic view of case study 1.

3.2. Case study 2

The bridge being evaluated (Fig. 3) is in a region of Northern Italy and stands out for its historically valuable construction. Positioned along a railway line, the work is made up of 16 masonry arches that rise above a river. Each arch has a span of 25 meters (theoretical distance between the shutters), and the structure reaches a maximum height of 40 meters in the central spans. Overall, the bridge extends for approximately 400 meters and is a focal point for the railway traffic that passes through the area. Furthermore, the bridge is equipped with a pedestrian path that allows even pedestrians to cross the river.

In the context of this study, specific attention was focused on pier number 2. Also in this case the selection of the pier was carried out considering its significance.

Fig. 3. Panoramic view of case study 2.

4. Summary of the results

The analysis is developed with reference to multiple images of the investigated piers; in particular, the adopted strategy is the quadrant scheme dictated by the DOMUS Manual, provided by RFI Italian railway network (2019) for railway infrastructures (first field of application of the software ADD_B ©). This is a more detailed approach than the LG22, which allows to directly consider the entire pier to be analyzed. In detail, the type of investigated piers for both case studies, wall piers, leads to the processing of a total of 12 images for pier, where each image identifies a quadrant: 4 quadrants in the front part, 4 in the back part and 2 for each lateral face.

The level of detail with which the software describes the nature, extension and intensity of the defects is highlighted in the example in Fig. 4, where three photographs are shown, one for each of the investigated piles.

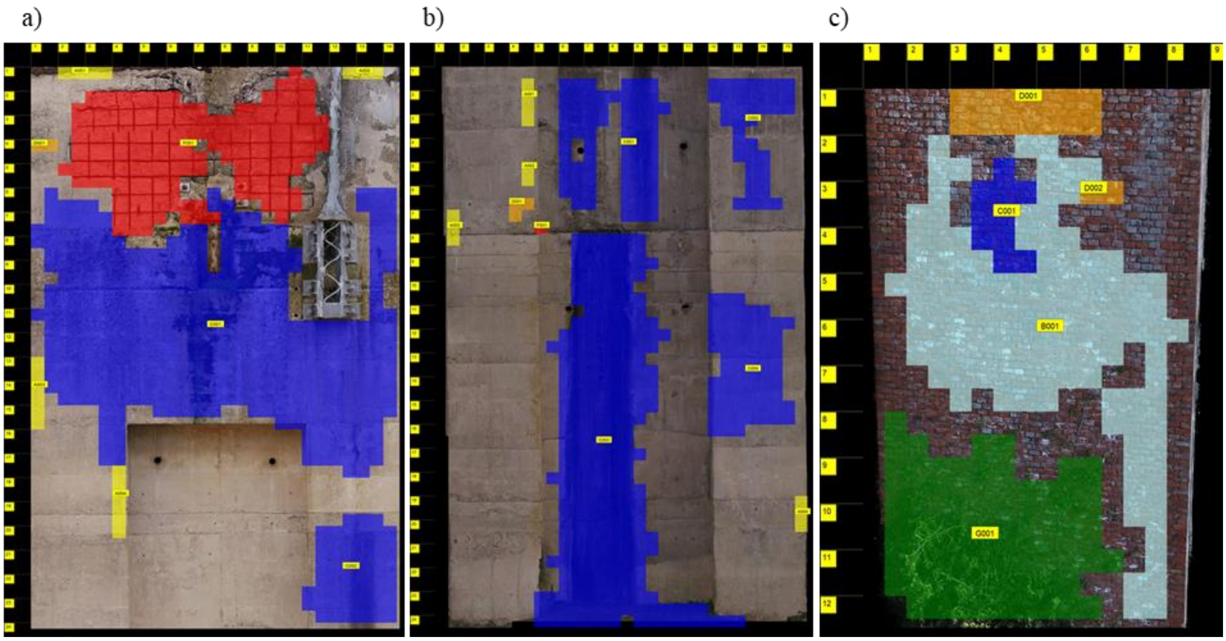

Fig. 4. Automatic defect recognition through the use of ADD_B ©: (a) quadrant 12 of pier 4, case study 1; (b) quadrant 11 of pier 9, case study 1; (c) quadrant 11 of pier 2, case study 2.

As can be seen from the images, the code recognizes the defects, assigning them to the relevant category (recognizable by the different coloring) and mapping their relative extension. Table 1 shows a summary comparison of the number of defects detected on the three piers by the code and by an expert technician specialized in the defect analysis of existing bridges and viaducts. The table shows that, compared to manual inspection methodologies, AI software tends to identify a greater number of defects. This discrepancy is mainly due to the specificity of the software to recognize and count the same defect separately even if present in multiple areas of a structural element, whereas manual inspections instead record the defect only once, regardless of its repetition in different areas.

Table 1. Summary of the number of defects detected with manual and AI procedures.

Number of detected defects				
Case studies	Element	Procedure		Δ [%]
		Manual	ADD_B	
Case study1	Pier 4	85	98	13.3
	Pier 9	74	82	9.8
Case study2	Pier 2	42	58	27.6

Adopting the additional datasheet provided by AISICO together with the processed images, a comparison in terms of type of defects is performed, see Table 2. Here the defects detected by the software have been grouped by type, so that they are counted only once for each quadrant.

Table 2. Summary of the type of defects detected by manual procedure and AI.

Type of defects detected for different elements				
Case studies	Element	Type of defect	Procedure	
			Manual	ADD_B
Case study 1	Pier 4	Efflorescence	12	10
		Infiltrations	32	10
		Exposed reinforcements	7	3
		Defects of execution	11	10
		Deteriorated successive repairs	2	0
		Cracks	10	11
	Pier 9	Efflorescence	10	10
		Infiltrations	27	10
		Exposed reinforcements	3	3
		Defects of execution	11	10
		Deteriorated successive repairs	4	0
		Cracks	14	11
Case study 2	Pier 2	Patinas and plants	10	8
		Efflorescence	12	11
		Material loss	7	5
		Exfoliation	5	9
		Infiltration	3	3
		Defects of execution	3	0
		Cracks	2	0

From table 2 it can be seen that the software captures with high reliability the defects on the RC elements relating to efflorescence and infiltration. The greater number of defects obtained with the manual inspections is essentially due to the presence of defects of different types which fall into the same category for ADD_B ©, such as, for instance, active humidity stains, deteriorated concrete, etc. As far as cracks and reinforcements, they have been precisely captured by the software except for very isolated cases in which cracks and oxidations are of modest intensity and/or extent. Regarding the detection of execution defects, the software has proven to be highly efficient in identifying various areas where honeycombing appears on concrete surface. However, zones subject to deteriorated successive repairs were not always detected. Nevertheless, this type of defect is of minor relevance and does not compromise the overall assessment of the structural degradation state.

On masonry elements, the reliability against defects such as: patinas and plants, efflorescence, loss of material, exfoliation and infiltration is again very high. On the other hand, the software detected nor execution defects (deteriorated successive repairs) nor cracks. This result is mainly due to adopted setting; indeed, the cited defects are of slight extension and modest intensity.

The use of ADD_B © therefore offers a detailed vision of the state of conservation of the structures, also leaving traces of the degraded areas and therefore potentially critical for the purposes of conservation of the work. Such a level of detail could be particularly useful not only for the purposes of the data sheets required by the LG22, but also for planning targeted maintenance interventions and optimizing resources.

5. Conclusions

The software Automated Defect Detection_Bridge (ADD_B © vers. 2) developed by the company AISICO aims to provide a contribution to the automated management of road infrastructures. It is a code based on the use of artificial intelligence and allows the recognition of defects on road bridges and viaducts in accordance with the standards of the current Italian guidelines (ministerial decree 204/2022).

Starting from the images acquired in situ, ADD_B © recognizes the defect and classifies it according to macro-classes consistent with the LG22. Each defect is then reported on the image through coloring covering the entire affected area. In post-processing, a table that lists the defects with their extension is also provided.

The two case studies reported here to investigate the applicability and efficiency of the new technology are a reinforced concrete bridge and a masonry one. The structural elements inspected in the paper are three piers, two for the first and one for the second case study. Through the observation and study of the two specific examples, it was possible to confirm the potential impact of AI systems in detecting and classifying structural defects. In particular, the results of the automated procedure were found to be consistent with those obtained manually by a technician expert in the defect analysis of existing bridges and viaducts. Thus, if the critical analysis by an expert engineer still remains a crucial step to correctly establish the impact of the results of the inspection procedures, the adoption of automated systems such as ADD_B © could reveal into significant savings in time and costs, with inspections which can be performed more frequently and with less need for direct human intervention. Furthermore, considering that the software also maps the detected defects directly on the images, it paves the way to enhancements in maintenance practices. Possible future developments concern: the analysis of other case studies, to generalize the conclusions here reported, the extension to superstructures, and the extension to other material types (wood, metals, etc.).

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