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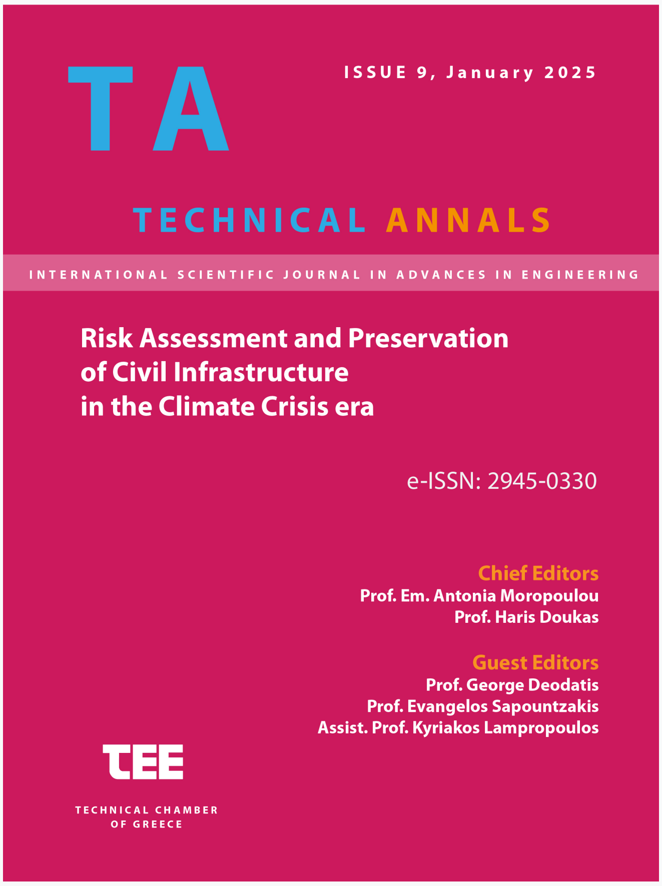

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Bridge inspection, evaluation and maintenance, within the Greek framework: Challenges and prospectives

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Abstract. Bridges are invaluable elements of European transportation infrastructure. Inspection, evaluation and maintenance are key processes for the safe operation, efficient management and improved resilience of bridges. The relevant legislation for the systematic implementation of these processes is reviewed, as it sets the basis for addressing lasting challenges faced by the national bridge stock. The establishment of central data repositories and the gradual implementation of real time structural health monitoring on certain bridges of the national stock aim to improve the safety of bridges and contribute to the optimized utilization of the limited technical and financial resources for bridge management and maintenance. The national-specific limiting factors are analyzed, which hinder the direct adaptation of international expertise. The key drivers towards an enhanced inspection, evaluation and maintenance methodology are described, focusing on an expanded preliminary inspection of the bridge and its environment; state-of-the-art documentation methods and approaches; non-destructive assessment of the bridge structure, its environment and the bridge-environment interaction; assessment of the static, dynamic and seismic behavior of the bridge. Finally, the potential and limitations of both Building Information Modeling (BIM) and Bridge Information Modeling (BrIM) are briefly discussed in this work.

Keywords: bridge, inspection; evaluation; maintenance, legislation, non-destructive testing; building information modeling; bridge information modeling

1 Introduction

Bridges are invaluable elements of European and national transportation infrastructure. Nonetheless, both bridge construction legislation and technical standards, as well as management, inspection, condition assessment and maintenance procedures vary between European countries [1]. Furthermore, due to historical, political and financial conditions, bridges have received varying levels of maintenance even in well developed countries. This situation is becoming more acute as the available financial and technical resources are distributed over an ever-expanding infrastructure stock that is subjected to the increasing impact of climate crisis [2] and amplified traffic loads.

Recent bridge failures, such as the collapse of the Morandi bridge in Genoa [3], have highlighted the need to offer efficient and economical bridge inspection and assessment procedures. The development of recent legislation [4-7], at national level, aims to standardize such procedures. However, such legislation generally focuses on assessing and monitoring the load-bearing capacity of the bridge, without extensively analyzing the interactions between the bridge and its surrounding environment, other than observing and documenting the impact of such interactions on the bridge structure. Effectively, most inspection processes still focus on identifying current or potential failures, without thoroughly considering the mechanisms and predicting the creation thereof. Although this is reasonable, as the priority regards the safety of bridges, in the long term such an approach does not provide the necessary tools and information for the effective and reliable enhancement of the durability and resilience of bridges against varying environments (climate crisis) and increasing traffic.

To achieve this, the current inspection and maintenance procedures need to advance from a mentality of "minimum" checks that ensures short- or mid-term safety to one of a "holistic" analysis that safeguards the integrity, safety and performance of the bridge and takes into account the interaction with its environment in much larger spatial and temporal scales. An enhanced inspection and maintenance methodology should address the specific requirements and limitations of the national bridge stock and the natural and man-made environment in Greece.

This work presents an overview of the Greek legislative framework for bridge inspection, evaluation and maintenance, while highlight the national-specific limiting factors that require an optimization of the existing framework and the necessary issues to be addressed. A viable methodology is presented, tailored to the Greek bridge stock, based on know-how developed for the protection of built cultural heritage (BCH). Although it may be deemed as odd, this field is relevant to bridge inspection and maintenance processes, since BCH is characterized by the inherently limited knowledge of the asset's past states, past interventions and the complex interactions with the environment, as is often the case with most of the bridge stock, at least at national level. The development of such extensive know-how is more than applicable for bridge applications, which face similar challenges and can benefit from analogous approaches.

2 Bridge inspection, evaluation and maintenance within the Greek framework

Bridges are complex civil engineering constructions, demonstrating a large variety of types, sizes and building materials. Bridge technology has evolved, achieving bridge spans and scales hitherto never anticipated. The know-how regarding bridge performance and safety has evolved concurrently. Nonetheless, inspection and maintenance procedures, largely, still focus on critical engineering parameters such as the residual strength of the load bearing parts, arch/span/deck deformations and displacements, and presence of cracks/damage/wear, in order to evaluate the safety of a bridge. While in principle such an approach directly monitors those critical parameters indicative of and pertaining to bridge parts failure, in effect it does not analyze adequately the causality of such failure phenomena. Regular or preventive maintenance, wherever applied, often alleviates the need to thoroughly analyze failure phenomena; however, in the long term, it does not necessarily eliminate their occurrence, with disastrous results.

The lifecycle of a bridge initiates at its feasibility study, continues with funding, development of the appropriate technical studies, actual construction of the bridge, its operation and maintenance and ends with the bridge's decommissioning. All stages are designed and implemented based on the behavior of the bridge under different actions, by taking into account the following general limit states (LS):

- Serviceability LS, e.g. small earthquake, damage at joints, decks, railings
- Ultimate LS, e.g. after the occurrence of maximum design earthquake (Greek code for seismic resistant structure, zones I, II, III)
- Durability of the bridge, i.e. its resistance to the effect of time (ageing), e.g. corrosion/decay of structural elements, building materials, plasters, coatings, etc
- Resilience, i.e. the capacity of the bridge to withstand and recover quickly from an extreme event, e.g. due to climate crisis (floods, extreme heat waves, extreme precipitations, etc.) or an accident

The above LS are taken into account in inspection, evaluation and maintenance processes, to ensure the safety of users, quality of service, crisis management and preservation of infrastructure for its designed lifespan and beyond. To achieve these goals, bridge authorities or bridge operators employ comprehensive bridge management procedures [8] that regard:

- The utilization of the appropriate inspection methods and techniques to evaluate and monitor the state of preservation and performance of the bridge
- The assessment of the interactions between the bridge and its environment
- The combined processing of multispectral data and their incorporation into models to evaluate and simulate the bridge behavior at the aforementioned LS
- The organizational processes to prioritize and to implement inspections, evaluations and maintenance activities, and to allow operation of the bridge
- Handling and sharing all necessary data and information (big-data management)

2.1 National Legislation framework for bridge inspection and maintenance

After many years of preparation, the Bridge Inspection and Maintenance Regulation (K.E.SY.GE.) [4] and the establishment of the Bridges Administrative Authority (BAA) [5] were finally approved on 10.11.2023 by ministerial decision 321681/2023, based on the provisions of Law 4903/2022. This national legislation institutionalizes the procedures for the registration of existing and new bridges in the National Bridge Registry (NBR) [6], as well as the rules and procedures for the inspection, evaluation and maintenance of bridges.

The role of the Bridges Administrative Authority regards a) the guarantee of transparency and the control of compliance with the institutional framework regarding the inspection and maintenance of all bridges in Greece; b) the institutionalized organization of the regulatory and supervisory role of the State; and c) the observance and compliance with all the rules and procedures defined by the K.E.SY.GE.

The K.E.SY.GE. establishes the procedures for the registration of existing and new bridges in the NBR, the rules and procedures for their inspection, evaluation and maintenance, the organization and performance of periodic and special inspections through the National Bridge Inspection and Evaluation Manual (NBIEM) [7], and the actions required after their evaluation. Within this framework, the obligations of bridge operation and maintenance organizations are clearly defined and a methodology for recording and monitoring the condition and maintenance of the national bridge stock is specified. The regulation applies to all bridges of the road and railway network of Greece with a clear span of more than 6 m, constructed by reinforced or prestressed concrete, steel or composite structures of steel and concrete, or stone. Historic bridges that have been classified as monuments are covered by Law 4858/2021 [9].

The NBR is an information system, currently under development by the Greek Ministry of Infrastructure and Transportation. The platform will provide the relevant services with the necessary tools for a comprehensive system of recording, inspecting, evaluating and maintaining the country's stock of bridges. It will outline the rules and procedures for inspection and maintenance and the obligations of the relevant operation and maintenance authorities and bodies. The NBR will form part of the National Registry of Public Works (see below).

In addition, and because bridges are public works constructed of various materials and containing numerous structural and non-structural systems, the construction, operation, inspection and repair processes must comply to a vast number of relevant regulations, directives, circulars, legal provisions etc. Indicative relevant national legislation includes the Eurocodes 1-8; EN 1504 series European standards; Greek Technical Specifications (ETEP) [10]; Greek Code for reinforced concrete (EKOS 2000) [11]; concrete technology Code (KTS 2016) [12]; reinforced concrete steel technology Code (KTX-2008) [13]; Greek Code for seismic resistant Structures (EAK 2000) [14]; Greek Code of structural interventions (KAN.EPE.) [15], Greek Code for the assessment and structural interventions of masonry structures (KADET) [16].

2.2 Bridge inspections

Inspections assess the condition of a bridge and identify any issues that could potentially compromise its safety or serviceability. According to national legislation [4-7], inspections are categorized based on their content and frequency of conduction. They are classified as a) routine inspections, i.e. scheduled inspections that aim to reveal damage, wear or signs of deterioration of the bridge's equipment and materials, or b) special inspections, conducted when specific concerns or unusual conditions arise.

2.2.1 Routine inspections

The *basic inspection* is conducted every three years and intends to identify any damage, wear or signs of deterioration and to monitor the evolution thereof as identified during previous inspections, to address, repair or prevent them accordingly. It concerns inspection of the bridge equipment (railings, joints, piping, E/M systems, railway systems, etc.), of the bearings, of the geometry and visible deformations and displacements of the superstructure (decks, girders, trusses, cables), of the piers/columns of the bridge, and the presence of wear/damage/decay on the bridge surfaces and building materials and the state of preservation of the remainder parts of the bridge (foundations, river slopes, etc). It is conducted with the aid of NBIEM [7] with visual means, from the deck level or from the ground/sea level, occasionally supported by unmanned aerial systems for improved access.

The *main inspection* is conducted every six years and similarly intends to identify any damage, wear or signs of deterioration and to monitor the evolution thereof as identified during previous inspections, and to identify any other findings that can adversely affect the performance and safety of the bridge. It is analogous in scope with the Basic Inspection; however, the visual inspection is conducted at close range (<1m) for each examined part of the bridge (thus, necessitating specialized access equipment such as ladders, scaffolding, telescopic baskets/cranes, etc), both at the exterior parts as well as at the bridge's interior parts (box structure of decks, hollow piers, etc.). It includes specific tests: for concrete bridges, the carbonization depth of concrete is determined, and presence of chloride ions is detected; for stone bridges, the masonry humidity is measured; for steel bridges, hardness tests are implemented and the corrosion level is assessed with electron microscopy.

The *inspection of equipment due to special specifications*, regards equipment other than the structural parts of the bridge. These include the bearings, the joints, the railings, the drainage and waterproofing systems, seismic insulation systems (e.g. dampers, special insulators, etc.), and all systems that comprise the bridge equipment and contribute to the static behavior and functionality of the bridge and the safety of the users. Such equipment is inspected according to the OEM specifications, procedures and intervals, independently of the aforementioned basic or main inspections.

The *continuous monitoring* regards two inspection levels: a) Visual monitoring focuses on the regular operation of the bridge, traffic control, road assistance etc. and the macroscopic (visual or video) identification of potential wear/damage that affect safety; b) *Structural Health Monitoring* (SHM) through permanent instrumentation that aims to monitor and evaluate specific parameters of the bridge, continuously and throughout the bridge's lifetime that relate to its static and dynamic performance and compliance to the designed loads.

The subject of SHM is not limited by national legislation. It is specified by the bridge operator and authority responsible for its maintenance, based on the importance, size and risk level of the monitored bridge. Typical SHM equipment may include the following systems:

- 1D/3D accelerometers installed on pylon/piers or deck (earthquake or wind induced vibrations), on ground (earthquake), or on cables (wind induced vibrations)
- Temperature and humidity sensors, to monitor basic hygrothermal parameters of the bridge, its materials or the deck pavement and railway superstructure
- 3D anemometers to monitor wind intensity and orientation distribution
- Load cells on cables to monitor cable load variations
- Sensors for the expansion of joints

- Strain gauges, e.g. on lateral restrainers for wind induced lateral loads monitoring

The project *"Smart Bridges"* (see below) regards the application – at national level – of real time structural health monitoring (RTSHM) on several Greek bridges. However, due to the extensive bridge stock involved (250 bridges) and the limited financial resources, it may not be as extensive as the RTSHM performed on large bridges by private highway networks operators (e.g. Rio - Antirrio Bridge [17]).

The *annual inspection* concerns only railway bridges to comply with UIC IRS 70778-4 [18], as conducted by the Hellenic Railways Organization (OSE). It aims to identify observable damage and deterioration to the structural members of the bridge with emphasis on safety issues for rail transportation. The annual inspection is similar to the basic inspection but is conducted annually and places additional emphasis on railway superstructure and equipment.

2.2.2 Special inspections

The *detailed inspection* aims to thoroughly investigate the damage/wear/deterioration developed on parts or elements of a bridge or to monitor its evolution as already detected by previous inspections; identify bridge elements or parts that can affect the safety of users and bridge; and support the load/condition rating of the bridge and contribute to the selection of remedying measures. The detailed inspection follows the same methodology as the main inspection, but includes complementary detailed instrumented, slightly destructive or non-destructive tests and measurements at laboratory or on-site. These tests concern two main categories. The first category focuses on the preservation and deterioration of the bridge materials and elements. For example, it includes tests for the compressive strength of concrete, carbonization depth, sulfate and chloride concentrations, rebar corrosion, corrosion potential of metal parts, strength of steel parts, state of preservation of rivets, screws/bolts and welds, etc. The second category focuses on documenting and evaluating the bridge's behavior under static or dynamic loads and environmental actions. It regards the measurement of bending arrows, longitudinal/transverse/vertical displacements, expansion of joints, permanent deformations of steel elements, crack detection, analysis of oscillations, damping, geotechnical tests (e.g. foundation or slope checks), and any other specialized tests and measurements as required per bridge characteristics and the results of corresponding main inspections.

The *emergency inspection* is conducted after a sudden event, such as earthquake, flooding, vehicle or ship collision, fire, foundation subsiding, slope slip. Its scope is to identify damage on the bridge and its surroundings, due to the sudden event that affects the safety and load capacity of the bridge. It is used for the re-evaluation of the load/condition rating of the whole bridge or its affected parts and supports the prioritization of the remedying measures. It follows the methodology of basic inspection but can be updated directly to detailed inspection in severe events.

The *reconnaissance inspection* refers to cases of extended bridge stocks that have not been inspected and aims to accelerate the inspection, evaluation and maintenance processes. It follows the methodology of basic inspection to conduct a general inspection and identify problems and damages present up to the inspection date. Based on its findings the appropriate type of inspection can then be determined.

The *inspection of the superstructure of railway bridges* is required due to the special nature of railway bridges. It involves specialized inspection procedures for the railway superstructure (rails, sleepers, electrical cabling, signaling, E/M rail systems, etc) as specified by appropriate technical standards and norms and may necessitate specialized train sets.

2.3 Bridge evaluation

Bridge evaluation concerns the process of analyzing the data collected during inspections to determine the bridge's structural integrity and load-carrying capacity. Based on such an analysis, a grade is assigned to the bridge which helps the bridge operation and maintenance organization in making decisions regarding whether further monitoring, additional inspections, regular maintenance, repairs, strengthening or replacement works are required. The corresponding department is responsible for assigning such grades through its inspector engineers. This grade is then provided to the National Bridge Registry (see below) and updated after every inspection. This grade allows for the development and optimization of technical-economic planning of all actions required for the maintenance of the bridge examined.

The grading of damage, wear and failures on each structural element, part of the bridge or its equipment, is implemented based on the criteria specified by the NBIEM [7], taking into account the potential cause of the damage or failure, the location, extent, quantity, size of each individual damage or failure, the coexistence and correlation of different types of damage and failures, their influence on the structural integrity and safety of the bridge, and their influence on the durability and resilience of bridge's materials and systems. The overall evaluation grade of the bridge is defined by the worst grade of all partial grades assigned to its parts and sub-systems. It should be emphasized that such a rating aims to support asset management systems to schedule proper maintenance, at the most appropriate time, with feasible cost and within a proactive approach, rather than addressing failures or events after their occurrence. The following table summarizes the grading system for bridge evaluation [4,7].

Table 1. Rating of bridge evaluation and required actions based on K.E.SY.GE

Grade	Description	Required actions
1	Bridge in good condition	Regular maintenance
2	Bridge with structural parts and equipment in a sufficiently satisfactory condition revealing minor damage or wear or of localized character	Specialized maintenance
3	Bridge with structural parts severely damaged with extensive and severe deterioration and wear	Restoration/repair works
3E	Bridge in which its structural parts show severe failures with intense and critical alterations and damage/wear, and as a result, the operation of the bridge is considered unsafe	Immediate restoration/repair works and application of immediate interim measures
S	Bridge with grade 2, 3 or 3E with problems of random consequences on the safety of users	Immediate restoration/repair, amendment of the cause of risk
ME	Bridge or parts that no main inspection has been conducted or has been delayed beyond six years	Immediate implementation of main inspection

2.4 Bridge maintenance

Bridge maintenance concerns a wide range of technical, administrative and management actions during the lifetime of a bridge to maintain or restore it to a condition that meets the applicable safety and operation specifications and regulations. The maintenance strategy (Fig. 1) is defined by the bridge administrator or organization responsible for its maintenance and aims to ensure the specified performance and operation of the bridge while fulfilling several – often contradicting – requirements:

- Safety and any relevant regulations requirements that refer to the bridge's ability to attain imposed traffic and environmental loadings and to its fatigue resistance
- Functionality refers to the compliance to the specifications set for the designed operation of the bridge, at optimum cost
- Durability regards the ability of the bridge's structural parts, materials and equipment to retain their specified properties and performance over the designed lifetime of the bridge and under the influence of environmental actions, especially under climate crisis
- Resilience pertains to the capacity of the bridge to withstand and recover quickly from extreme events or accidents
- Minimal environmental footprint of the bridge and the applied maintenance works
- Aesthetic appearance in relevance to the public's perception for the safety of the bridge and the confidence in its use

Bridge maintenance is implemented on preventive and/or corrective approaches, based on the implemented maintenance strategy.

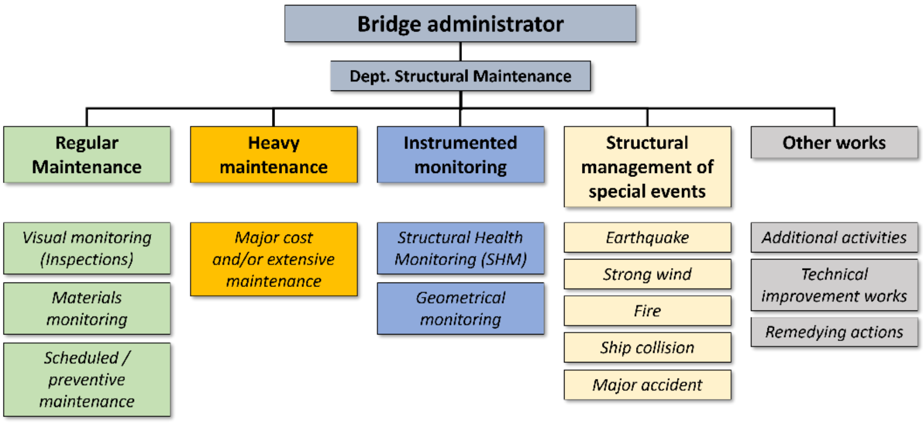

Fig. 1. Activities within an integrated bridge maintenance strategy

2.4.1 Preventive maintenance

Preventive maintenance refers to regular activities at predetermined intervals that aim to prevent the development of potential decay/damage/wear or to delay or control the evolution thereof. Preventive maintenance can be conducted at predetermined intervals without the need for prior inspection or due to findings from continuous monitoring, periodic inspections and checks.

The first type of preventive maintenance is termed *regular maintenance*. It mainly concerns non-structural elements of the bridge and does not require specialized know-how or expertise. It includes cleaning and removal of all waste or debris that accumulated at the pier crowns, vegetation removal from the deck, piers and abutments, cleaning of bridge's sewage system, of all superstructure channels, of deck joints, walkways and safety railings and visual check for the deterioration and/or deformation of the bridge foundations safety measures and their restoration where required. Remote-controlled robotic systems (e.g. for internal inspection of channels or pipes, or difficult to reach areas), infrared thermography (e.g. to detect leakages) or UAVs (e.g. to inspect non-accessible areas of the bridge) are increasingly employed to enhance the effectiveness of regular maintenance.

The *special maintenance* is implemented when grade 2 findings are present after a periodic inspection. It aims to prevent the deterioration of a damage/decay/wear on bridge equipment, or a damage/failure of limited extent and size on structural parts of a bridge that does not pose a safety hazard for the load-bearing capacity of the bridge but which, if not repaired, may have an impact - in the short or medium term - both on the structural integrity and on the future cost of its restoration. It differs from regular maintenance, as it involves extensive works that often require the application of special technical specifications, methods and materials and, thus, involvement of experienced and qualified personnel.

Indicative special maintenance activities include the restoration/repair of metal parts (safety railings, signaling, access ports, etc), repair of road pavement, restoration of protective layers, cathodic protection and painting of load-bearing metal parts or metal reinforcements, restoration/repair of joints and bearing, repair or reconstruction of protective measures for the pier/pylon foundations, replacement of individual damaged/corroded rivets or bolts/screws, repointing of masonries (piers, abutments, foundations) and other limited extent activities.

2.4.2 Corrective maintenance

Corrective maintenance is implemented in cases when a bridge has been assigned a grade of 3 or 3E and aims to reinstate the intended performance of the bridge from the original construction study. It regards non-urgent cases of damage/failures that allow adequate timeframe for their amelioration, or urgent cases for which temporary safety measures have been applied to ensure the structural integrity of the bridge.

Corrective maintenance has two main prerequisites: implementation of a full assessment of the current state of the bridge after the conduction of a detailed inspection; and the development of a static study of the restoration. The bridge management and maintenance authority is responsible for the organization of the works and appropriate arrangements, supervision of the actual works and adherence to the methods, techniques and materials specified in the restoration study, as well as for the preparation of the final report for maintenance and restoration which will be examined by the supervising administrative authority [5].

2.5 Key developments in bridge inspection processes

In general, except for some contemporary bridges, a large percentage of the national bridge stock has not been subjected to thorough documentation and inspection processes, or even to systematic maintenance. The exemption regards, mainly, the bridge stock of the main Greek highways, where the management companies (e.g. Egnatia Odos, Attiki Odos, Nea Odos, Olympia Odos) implement systematic inspection and maintenance to their bridge stocks. The case of the Greek bridge stock is not a sole exception, as similar difficulties are encountered by other European countries even with longstanding legislation, technical expertise and resources. In the case of Greece, however, a major constraining factor is the general lack of appropriate documentation of the bridge's initial construction and subsequent maintenance records. More than often, the "ownership" of bridges is shared or transferred among various authorities with limited cooperation. As a result, most of the available records are widely dispersed and eventually not retrievable. This situation is even more complicated for the documentation and monitoring of the bridges' environment and surrounding infrastructures which are typically managed or monitored by various other authorities and stakeholders.

To some degree, the aforementioned inspection types, as specified by the national regulatory framework, reflect these limiting factors. This is highlighted by the importance of visual inspection as the prime method for the detection of surface damage, corrosion, cracks, deformation or displacements. Obviously, it is highly dependent on the experience and training [19] of the personnel involved with their qualifications being specified in relevant legislation [4,7].

Continuing technological developments such as Artificial Intelligence (AI) and Building Information Modeling (BIM) [20,21] promise to aid significantly in the systematic and faster inspection of bridges, especially in the identification and documentation of defects, damage and wear. Early on, the Technical Chamber of Greece (TCG), having recognized the benefits of a twin green and digital transition strategy [22] and prior to the regulation of a national strategy [23], has integrated this strategy in its various activities and services, and has co-organized a series of BIM conferences (2020-2024) [24] and relevant training workshops. Similarly, the enhanced digital and 3D capabilities of modern non-destructive testing (NDT) methods, the improved performance of wireless and inbuilt sensors, the wider range and resolution of modern strain gauges and accelerometers, the improved documentation capabilities of advanced laser scanning and photogrammetric techniques, and the extensive use of unmanned aerial vehicles, will have the potential to support the conduction of more systematic, effective and rapid inspections of all bridge parts.

2.6 Central Data Depositories of Public Works: The Greek Status

It is only recently that a Single Digital Map (SDM) and a National Registry of Public Works have become a reality by the TCG and are funded by NextGeneration EU. The SDM is an integrated information system that gathers, organizes, maintains, and disseminates statutory geospatial land-related information, generated by various public administration and e-government bodies, regarding urban planning and building permit regulations, planned land use and environmental protection, ownership, property assessment and exploitation. A key point in the design and completion of the SDM is the interoperability with other information systems of TCG or of other bodies (e.g. Ministry of Finance, the Land Registry).

The SDM encompasses a National Registry (NRPW) for documenting technical information on public works supervised by the Ministry of Infrastructure and Transportation. The NRPW is an information system, with geospatial reference, where all public infrastructure, such as bridges, road/flood protection/water supply/sewerage works and public buildings, are recorded by the relevant public authorities. The NRPW manages eight categories of information: General information; work phases; materials; plans of works; library of studies; multimedia; maintenance documentation; inspection results. All public infrastructure is gradually registered in the NRPW.

The SDM and NRPW are indeed fundamental national achievements to support inspection and maintenance procedures by the relevant stakeholders, towards a comprehensive program of nationwide renovation and upgrading of public works. Nonetheless, despite their virtues, SDM and NRPW currently only address a long-standing national need for systems to archive and manage administrative, inspection and maintenance information. NRPW does not present (nor was its main scope) an integrated methodology for public works inspection, condition assessment and resilience evaluation. In effect, users that upload information on the NRPW continue to perform inspections and maintenance processes according to their methodology (if existent), resources, relevant legislation and standards. The NRPW basically functions as a central depository of information without any restrictive framework of requirements, specifications, interrelation and practical integration of all deposited information. In the long term, this inherent deficiency in parametric deposition and management of information could limit the effectiveness of inspection and maintenance processes and most importantly the extent of correlation of public works either with their adjacent infrastructures or with their environment.

In principle, the application of AI methods can – in the future – exploit the vast information deposited in the NRPW. Hence, the value of NRPW in acting as a large-scale source of information. However, it can be argued that the effectiveness of AI tools to extract new information, develop correlations and aid in decision making processes will be hindered by the non-specialized deposition of information per type of infrastructure. In the case of bridges, thus, a more specialized form of data repository is required, with specific parameters monitored and recorded.

2.7 Real Time Structural Health Monitoring of Bridges: The national project “Smart Bridges”

TCG in cooperation with all thirteen Greek Prefectures, the Hellenic Railways Organization (OSE), construction and IT companies have initiated the relevant project “Smart Bridges” [25]. The project aims to develop a Smart Bridges Network (SBN) based on an IoT philosophy, for the fast, automatic and uninterrupted evaluation of the carrying capacity of bridges, mainly under real-time traffic loads, in order to enhance bridge safety through real-time structural health monitoring (RTSHM). The project will include 100 bridges of the railway network and 150 road bridges throughout Greece. Selected bridges are gradually being equipped with special structural response measurement systems with sensors/optical fibres, that will measure and record data such as the axial strain, vibrations, water levels, and temperature. The project aims to create digital twin technical folders of bridges, whereas the planned installation of IoT equipment will allow real-time measurements of certain aspects of the state of the infrastructure. The measurements from the RTSHM will be transmitted to a centralized platform for continuous analysis, enabling early detection of potential structural issues and supporting data-driven decision-making for timely maintenance, prevention of large-scale accidents, and the design of measures to prevent the effects of climate change.

Nonetheless, the parameters monitored, although of crucial importance, cover only a very narrow – yet fully necessary – range of parameters that indicate the structural health and relate to the safety of the monitored bridges. As pointed out above, although this is a high priority for bridge safety, especially in Greece with its chronic deficiency in this field, the system’s effectiveness in predicting the future behavior of the bridge, the interactions between the bridge and past, current and future environmental loads, and the bridge’s resilience against a wide variety of risks are hindered by the relatively few parameters recorded. Obviously, such monitored information is a prerequisite for a more sophisticated approach in bridge inspection and maintenance processes. However, there is a clear risk that “Smart Bridges” may be considered a satisfactory remedy, unintentionally diverting attention from the multifaceted problem and the multitude of factors influencing the health, performance and resilience of bridges. Project “Smart Bridges” should, thus, be considered as a valuable first step in the development of a much wider and eventually more efficient methodological framework, fully tailored to national priorities, resources and capabilities.

3 National-specific limiting factors

The interaction between the bridges and their environment can be expressed and monitored by various critical parameters. This interaction may be considered at two levels. At the level of the bridge, the type and value ranges of critical parameters such as deformations, displacements, wear, decay patterns, etc. represent the impact of the environment on the bridge structure and its materials and consider the interaction from the perspective of the bridge. These parameters are typically well defined, based on international and national experience and appropriate legislation, norms and standards. These parameters are the basic ones monitored by most SHM systems. At the opposite level, there exist parameters (e.g. precipitations, humidity, temperature variations, air pollution, wind fluctuations, river flow characteristics, geotechnical substrate, traffic flow, earthquake loadings) that represent the changing environments and risk conditions around the examined bridge. Some of these environmental parameters (e.g. temperature, relative humidity, river/sea level) are monitored by comprehensive SHM systems, but within a rather narrow spatial range, usually over the bridge. Nonetheless, the influence of such environmental parameters may originate from a wide spatial range (close vicinity of the bridge, local area, regional levels). This scientific field is the subject of continuous international research but is complicated by the vast range of bridge types and acting environments. As a result, most SHM systems and corresponding inspection and evaluation processes focus mainly on bridge-related parameters instead, that can directly and distinctively be measured and monitored.

At a national level, the limited use of SHM systems for much of the national bridge stock and the limited financial resources have shifted inspections and evaluations towards an approach based almost exclusively on a small number of basic bridge-related parameters. Consequently, there is observed a relative shortage of suitable information on the type and ranges of values of critical environmental parameters that describe the interaction of bridges and their materials with the changing environments and risk conditions present in Greece. Corresponding information from international scientific literature and use cases are obviously being used as a basis for reference and comparison, but this does not negate the need to define the relevant data at national level to better suit the national bridge stock and the changing environments and risk conditions specific to Greece. Adaptation of methodologies, technologies and documentation and analytical tools that have been developed internationally may not be an efficient approach, as they are usually optimized for and applied to infrastructure categories and environments different from those present in Greece. Moreover, such methodologies and tools usually rely on extended temporal characteristics of the analyzed data, exploiting access to data from past, systematic inspection, evaluation and maintenance activities; this is not readily feasible in the case of the national bridge stock.

Another national limiting factor is the availability of skilled personnel, specialized technological capacities and adequate financial resources. Due to the economic crisis that has affected Greece in the past two decades, and the diminishing implementation of large-scale projects like bridges, the Greek Construction Sector has been heavily affected. The temporary (yet prolonged) shrinkage of the construction market has resulted into a reduction in size or even disappearance of hitherto large Greek construction companies and a general conglomeration of the technical companies. In turn, this forced specialized personnel to seek employment abroad (brain-drain). From the construction companies' perspective, the reduced market and the priority for 'survival' have arguably delayed the absorption and adoption of the latest technological developments. Although the Greek construction sector shows positive signs of recovery, the decade-long "gap" of construction has strained the financial capacity of most technical companies, which in turn – for the time being – are more conservative regarding R&D or introduction of innovative technological advancements. This situation is even more severe in the case of government authorities (Ministries, Prefectures, Municipalities. Diminishing budgets were regularly being shifted to other priorities, whereas a chronic difficulty in hiring and training new personnel, to cater for the retirement of skilled staff, imposed considerable challenges in maintaining appropriate technical capacities and resources. Moreover, whatever resources were available in the past, these were utilized in a largely fragmented and localized manner. This is attributed, to some degree, to the difficult cooperation between relevant authorities and the limited complementarity of available technical resources and know-how. Fortunately, this will be addressed by the gradual digital transformation of government authorities and the corresponding adaptation of construction and bridge management companies to the standards of Industry 4.0. Both transformations offer efficient "alternatives" to "compensate" for the lost time and more importantly to better utilize the limited technical and financial resources.

Another limiting factor, at a national level, is the intensified impact of the environment on bridges due to deficient maintenance. This factor has a dual expression. The first relates to the climate crisis. For example, in the aftermath of storm Daniel, the bridge at Paliopyrgos (central Greece) collapsed due to the high volume of water and corrosion of the piers and their foundations. Such extreme weather events, directly related to the climate crisis, were understandably not foreseen during the original design and construction of the bridge. However, the minimal maintenance of bridges, especially those of *"lesser importance"* (note: this bridge connects Paleopyrgos with Alexandrini, two small coastal villages at the Pineios estuary) and their surrounding (e.g. lack of regular cleaning of riverbed) intensified the effects of extreme weather events, leading to failures that could otherwise be avoided or delayed. Many more bridges in Greece have been designed and constructed based on outdated water volumetric flow predictions. This situation was highlighted in the recent storm Daniel which flooded significant areas of central Greece and destroyed much of the infrastructure. In general, the durability and resilience of the national bridge stock is challenged significantly during extreme weather conditions due to the scarce maintenance performed on most of the municipal or prefectural bridges.

The second expression relates to the accumulative impact of protracted lack or minimal maintenance. The interaction between the environment and the bridge is known, expected and designed for. However, this interaction and its mitigation are based on an assumption that regular inspections and maintenance activities take place. If maintenance deviates substantially from its designed frequency, the environmental impact is significantly accelerated, with undesirable results (failures) or higher repair costs. This is noticed particularly in bridges within the urban matrix, such as the road bridges of Kifissos river in Athens. The effects of air pollution (e.g. cement carbonization, rebar corrosion) are intensified by the minimal maintenance activities and the lack of attention to the bridge environment (e.g. non-regular cleaning of the riverbed under the road bridges) which allows for synergistic deteriorating impact of various environmental factors (e.g. air pollution, corrosion of rebars, water/humidity induced weathering, biodecay), beyond the foreseen damage/corrosion rates. The infrequent inspection further complicates this situation, since more than often the impact of the environment is only identified at the terminal stages of the decay phenomena (e.g. detachments of materials, failures of rebars of metal parts).

Arguably, the most important factor in bridge design and construction in Greece is the seismic risk. Historically, construction technology and earthquake protection legislation at national level have evolved over the past decades, reflecting an ever-improving understanding and ability to predict the behavior of structures under seismic loads. However, much of the built environment in Greece, and particularly in Attica, was constructed many decades ago, and is compliant to different legislation than the current stricter one. Moreover, this built environment has been subjected to stresses from various past earthquakes, unfortunately without systematic documentation of the damage sustained or without proper repair works. The accumulation of past earthquake damage and the lack of appropriate documentation on the impact of earthquakes is not unique to the national bridge stock. It is a widespread phenomenon observed for most public buildings and infrastructure. Except for a few new major bridges, which are appropriately designed, regularly inspected and maintained, sustained earthquake damage is systematically under-evaluated, let alone mitigated and addressed. The exploitation of the NRPW and NBR will undoubtedly improve this situation and support prioritization of maintenance efforts. However, a nationwide inspection program focusing specifically on the impact of earthquakes on bridges and the damage already sustained can potentially be a more effective approach for this important natural hazard. Such an inspection program shall be supported by state-of-the-art research and laboratory infrastructure available at national universities, e.g. [26], exploiting the know-how obtained throughout the last decades.

Modern documentation methods, analytical and non-destructive techniques and computational tools can provide information on the current state of preservation of existing structures and infrastructure; however, such information cannot completely compensate for the absence of valuable data from the past. The general lack of information, either at the level of past documentation of the actual bridges (construction/inspection/maintenance records) or at the level of documentation of the past damage due to the impact of the environment, has two main drawbacks: a) it either decreases the accuracy of the prediction models, as they incorporate partial information about the bridges and their environment, or b) requires even more extensive and expensive inspection, maintenance and evaluation efforts to overcome the lack of past data. This situation is even more critical for the Greek bridge stock, where the extent of past information deficiency is larger and the availability of technical and financial resources is limited.

Another national-limiting factor is the implementation of ineffective and/or incompatible interventions. This is a more acute problem for non-major bridges, mostly at municipal levels, where any repair interventions are conducted on an ad-hoc basis. This can be attributed to a) the general lack of legislative framework, until recently [4-7]; b) the shortage of skilled personnel at the corresponding technical departments of municipalities, prefectures, or even at Ministries, that could develop technical studies of adequate detail and prepare contract calls with strict specifications; c) the shortage of technical contractors with specialized personnel and equipment suited to bridge repair; d) the general lack of effective quality control by the responsible or the supervising authorities of the implemented works, due to the main focus being the compliance with the financial terms and conditions only; e) the very limited budgets, which largely allowed for basic evaluation analyses and implementation of limited repairs only. The implementation of ineffective and/or incompatible interventions, in turn, makes the bridge more vulnerable to environmental factors, since their impact is preferentially concentrated on the repaired parts or the nearby areas instead. The use of inappropriate restoration (replacement, reinforcement, protection) materials that are mechanically and physico-chemically incompatible with the original materials can dramatically increase the susceptibility to damage and deterioration of the repaired bridge. A typical example is the rebar repair of concrete bridges, when such works are performed by non-qualified contractors or without strict compliance to pertaining norms and standards. As a result, more than often, the repairs fail after a short period of time or – even worse – intensify the deterioration of nearby bridge parts due to incompatibility issues. In addition, the use of technologies that extensively alter the original structural system of the bridge and/or rely on technical solutions that are reliable for other structures or for environments vastly different than the one examined, can also cause significant damage if they are applied to the examined bridge without proper analysis and prior validation to similar types and environments.

4 Key drivers towards an enhanced inspection, evaluation and maintenance methodology

In the current socio-economic environment of Greece, the limited technical, human and financial resources available for the inspection, assessment of condition and evaluation of the safety and resilience of the national bridge stock requires a more efficient, “smart” utilization of these resources. Such an integrated methodology, which exploits the capacities created by the NRPW, K.E.SY.GE., NBR, Smart Brides and SBN, must fulfil certain requirements:

- Provides reliable and cost/time/resource-effective assessment of the state of preservation and performance of bridges
- Enables an expanded assessment of their safety margin and remaining lifetime

- Evaluates the durability of materials and the vulnerability of bridges under the influence of varying, current and projected environmental loads, natural disasters or human-induced factors
- Supports the planning of routine, special and preventive maintenance and repair interventions, to improve the resilience of these structures

Such a methodology is also useful for other countries that face similar challenges as Greece and required a better utilization of limited resources.

4.1 Expanded preliminary inspection of the bridge and its environment

The first step in all international legislation and guidelines regards a preliminary inspection of the bridge. However, such a preliminary inspection is usually conducted under the responsibility of the bridge management authority [BA] – through its corresponding department - without substantial involvement of 'external' participants, other than cooperating with contractors to implement the inspections if in-house resources are not available. Instead, if the preliminary inspection is expanded in scope and if it involves more teams, early on, it can cover a wider range of issues and direct the otherwise limited resources to the more imminent risks and hazards. An expanded preliminary inspection aims to bring all involved teams of stakeholders, officials, engineers, and scientists to a common initial level of knowledge of the current state, main problems and challenges faced by the examined bridge.

Such an approach is not without shortcomings. The most important one regards the challenge of organizing a diverse group of teams. Therefore, it is important that a coherent group of involved teams is formed, with a clear understanding of everyone's role and responsibilities. This group should include representatives from:

- the official body responsible for the management of the bridge [BA] (e.g. Ministry of Infrastructure and Transportation, Prefecture, Municipality, Private Company)
- the end-users of the bridge (note: which may be different from the above)
- the BA's department or the external technical company that will conduct the inspection and evaluation [BIEA]
- the BA's department or the external technical company that will perform the maintenance of the bridge [BMTA]
- the initial construction company (if feasible)
- the Technical Chamber of Greece, as the official adviser of the State and as manager of the NRPW and SBN platforms
- the Bridge Administrative Authority [BAA], in an advisory role only
- Experts from the scientific and technical communities (selected ad hoc, depending on the "importance" and size of the bridge) in the fields of bridge technology, railway infrastructure engineering, materials science and engineering, structural analysis and antiseismic research, earthquake engineering, surveying, photogrammetry and computer vision, building/architectural technology, non-destructive testing and evaluation, environmental planning and impact assessment, geotechnical engineering, hydrography, spatial planning and urban

planning, transportation planning and engineering, building information modeling, information technology, sensors technology and others

It is recommended that a Bridge Steering Committee (BrSC) is formed by the official body responsible for the management of the bridge, as the advisory body to oversee the overall activities. The composition of the BrSC should reflect the importance of the bridge and include representatives (in-house or external) from the applicable scientific/technical fields. The management, organization and implementation of inspection, evaluation and maintenance works will obviously remain the responsibility of the BA, through the BIEA and BMTA. Regular meetings of the teams, either plenary or per working groups, should be organized, as well as in-situ visits to the examined bridge.

The preliminary inspection of the bridge and its environment regards the collection and organization of all available documentation of the bridge. The NRPW and NBR will act as the core elements of such archiving and management of information, but the effort should not be limited to what is available in these depositories only. The information retrieved should include as much feasible from the following types:

- Original documentation (plans and reports), regarding the construction phases, the progress of works and any past interventions or modifications
- Past and current detailed plans (ideally originally digital or digitized afterwards)
- Detailed information of critical bridge elements (bearings, cables, vibration suppression devices, absorbers, safety equipment etc.)
- Information about the bridge deck, its equipment (e.g. road pavement, rail superstructure) and its connection to and interaction with the bridge
- Detailed information about the materials used, both structural (e.g. concrete, steel, stone, mortars) or non-structural (coatings, plasters, paints etc.) as originally used or as modified subsequently, including data about the vulnerability of the materials against the designed environment (e.g. corrosion or weathering behavior)
- Static and dynamic studies of the bridge, as originally built or as modified
- Studies relevant to the bridge’s environment, such as spatial, urban, urban planning and town planning; this type of information is arguably the most difficult to collect. The NBR requests such studies, however, the BrSC and BA group of experts will probably request far wider information, especially as the inspections of the bridge and its environment proceed
- Multimedia: photos and videos of the bridge and its surroundings. Special effort should be made to retrieve as much past photographic evidence as possible, to support the assessment of the bridge’s current state and rate of deterioration. The multimedia library will be supplemented with in-situ visits of the interdisciplinary group, paying special attention to details of the bridge (as indicated by experts) and obtaining images and videos of the bridge from ground and aerial positions
- Inspection records: Results, date and comments; evaluation information
- Maintenance records: Reports from regular or non-scheduled maintenance and dates of completion; specifications; sheets; instructions; restoration instructions
- Preliminary analysis of monitoring data from the SBN

The above retrieved information is administered by the BA (through BIEA and BMTA) and will be at the disposal of the BAA. Due to its size and extent in technical and thematic areas, the above information - in its entirety – may not be mandatory for submission to the NBR; the later will be updated with new data and any missing studies if retrieved during the above effort. The rationale is based on the understanding that the full array of such information is considered "raw" data at this preliminary stage.

Based on the above findings, the interdisciplinary group will organize meetings and in-situ field visits a) to identify critical areas and record observed damage and deterioration on existing plans; b) compare the current (preliminary assessed) state of the bridge with the one described in the retrieved documentation, and accordingly organize activities and surveys to update it; and c) prioritize – at a preliminary level - the various inspection and evaluation activities.

The outcome of this stage is a technical report on the preliminary inspection of the bridge and its environment, accompanied by photographic documentation of the locations where wear/damage and critical issues have been identified. This report is submitted by the interdisciplinary group to the body responsible for the management of the bridge, and it is uploaded to the NBR.

4.2 Advances in the assessment of the state of preservation of the bridge

The findings from the preliminary inspection of the bridge and its environment will, subsequently, guide the application of on-site and laboratory tests and measurements to document the bridge's geometry, materials, damage and deterioration in the context of assessing its state of preservation. Typical tests and measurements on bridge structure, surfaces and materials are described in the relevant legislation, and several standards are applicable for most of them. The following regard scientific/technical fields where the recent advancements present potential to further improve the quality of the information obtained and allow an enhanced integration and fusion of different types of information.

4.2.1 Geometric documentation

In general, many bridges in Greece, except for the road and railway bridges forming part of the national highway system (which are mostly recent constructions), were constructed prior to the recent CAD and BIM technological advancements, and most of their plans are in paper form. The responsible authorities (Ministry of Infrastructure and Transportation, Prefectures, Hellenic Railways Organization) are making significant efforts to retrieve, organize and manage old archives, either as part of their obligations for the NBR or to utilize them for inspection and maintenance activities. Digitization of these archives is a vital stage, but it is often realized only as a conversion of plans into digital form (e.g. scanning) rather than a full conversion into truly digital plans (e.g. by recreation in CAD environments). This situation is reasonable for many reasons. First, the original plans are often dispersed at many authorities and construction and technical companies, and a great effort is required to locate and retrieve them; even then, often the retrieved material is seldom a full collection of plans to describe the bridge in all its details. Second, the full digitization of documents or the digital transformation of the inspection, monitoring and maintenance processes [27] are resource-intensive efforts, which can be applied by the responsible authorities only for the most important bridges from the national bridge stock; for the rest, scanning of original plans and documents is often considered adequate.

The general deficiency in original plans in digital form (compatible with the latest software and BIM applications) can be addressed, to some extent, by the creation of 3D models of the bridge through state-of-the-art geometric documentation methods and instrumentation. Such models cannot entirely replace true digital plans (construction and detail) of the bridge, as they are created by compiling records of the visible parts of the bridge only, in its current form and state. Extensive editing and processing are required to create products (plans, sections, etc.) that can be used in analogous roles as the original digital plans. State-of-the-art laser scanning and photogrammetric techniques and unmanned aerial vehicles (UAV) [28, 29], drones [30, 31] and microdrones can be utilized complementary to fully document geometrically the bridge, even at difficult to access areas.

The development of 3D geometric models of bridges is important for Greece and other similar countries, where the challenges of limited original documentation hinder the implementation of systematic maintenance activities. Such 3D geometric models can be utilized in BIM applications, for the mapping of materials/damage/weathering, as input into Finite Element Modelling (FEM) applications and structural analyses, as well as for the generation of cross-sections at required parts of the bridge to aid the corresponding analyses and complement any available plans. These digital models allow for the early identification and calculation of observed deformations (e.g. bending arrows, deviations from the vertical,) in specific cross-sections and parts of the bridge. A network of fixed points needs to be established in the wider area to record deformations, suitably adjusted to provide the required accuracy. The 3D models can also function as an accurate, standardized, inclusive base upon which all inspection and maintenance activities can be reported on. An accuracy of the model in the order of 1cm is deemed adequate, whereas the density of the point cloud should be at least 5mm, to ensure the quality of subsequent analytical and modelling processes.

In some cases, 3D models of the original bridge can be created through crowdsourced imagery and correlation with previous geodetic data or other information (Fig. 2), to improve the accuracy, scale and detail of the model [32, 33]. Such information is crucial for comparison after failures.

Fig. 2. Left. Orthophoto of the traditional stone bridge at Plaka, prior to its collapse, reconstructed through crowdsourced imagery. Right. 3D models of the surviving abutments of the Plaka bridge after its collapse, produced with photogrammetric techniques [32, 33]

4.2.2 Survey of the internal structure of the bridge

The preceding geometric documentation provides a detailed description of the bridge, in terms of its exterior form, geometry and features, however, it cannot generally provide information regarding the bridge's internal structure. Although such crucial information may be found in plans and drawings, if available, a detailed survey of the current state is required to ensure high quality modelling and assessment.

An important non-destructive evaluation (NDE) technique for bridge inspection [34] is ground penetrating radar (GPR), a well-established geophysical technique [28, 35, 36]. The most efficient GPRs for bridge inspection are multi-channel systems (Fig. 3), connected to GPS to enable georeferencing findings in 3D environment. Specialized software is used for the acquisition of raw data and their post-processing and analysis. Artificial Intelligence (AI) is progressively employed nowadays to aid in the interpretation of findings [37, 38], while the increasing application of GPR on bridges creates valuable expertise and databases for effective analysis. GPR can be used to inspect the internal structure of bridge parts, such as the arch/beam structure, columns/piers, towers, and decks, as well as other bridge supporting elements, such as pier foundations, embankment/abutments/revetments etc. The main drawback of the technique is the need to contact surveyed surfaces; thus, accessibility is an important issue.

Various ultrasonic testing (UT) techniques [39, 40] are applied to bridge inspection, mainly for the identification of defects at concrete, steel or stone parts of the bridge. The most common UT technique is pulse-echo. However, the typically high scattering and attenuation of the transmitted pulses due to the very heterogeneous nature of concrete or stone masonries decreases the effective depth to which defects and interfaces can be detected. Pulse-echo UT is a well-standardized and widely employed NDE technique for both metal and concrete structures defects detection. Recent advancements in UT focus on ultrasonic tomography [41-43] with the use of multiple arrays of probes. Through capturing a series of 2-D sections a specialized software assembles them into a 3-D image, that can aid in the identification of internal defects or discontinuities in the examined volume. Nonetheless, UT requires coupling of the transducers with the measured surface, thus, it is subjected to the same accessibility limitations as other contact or near-contact techniques (e.g. GPR, rebound test, hardness). Electromagnetic acoustic transducers (EMAT) for non-contact acoustic wave generation and reception in conducting materials can offer non-contact probing, however, they are limited to metal surfaces and are mostly used for inspection of welds.

4.2.3 Assessment of the thermohygric behavior of the bridge

The assessment of the bridge's thermo-hydraulic behavior and its correlation with areas of damage and deterioration is largely based on data from permanent and non-permanent environmental monitoring sensors (temperature, humidity, precipitation, wind) and findings from systematic surveys with infrared thermography (IRT). IRT evaluation (Fig. 3) is performed over all exterior parts of the bridge on macro- and meso-scales. It aims to identify and document damaged areas [28, 44-48] that exhibit differential thermal performance due to surface or near-subsurface damage (e.g. cracks, delamination of layers), material deterioration (e.g. corrosion, salt decay, crusts) or water and humidity transport phenomena (e.g. rising damp, localized accumulation of atmospheric precipitation, leaks) as compared to undamaged or non-affected parts of the bridge.

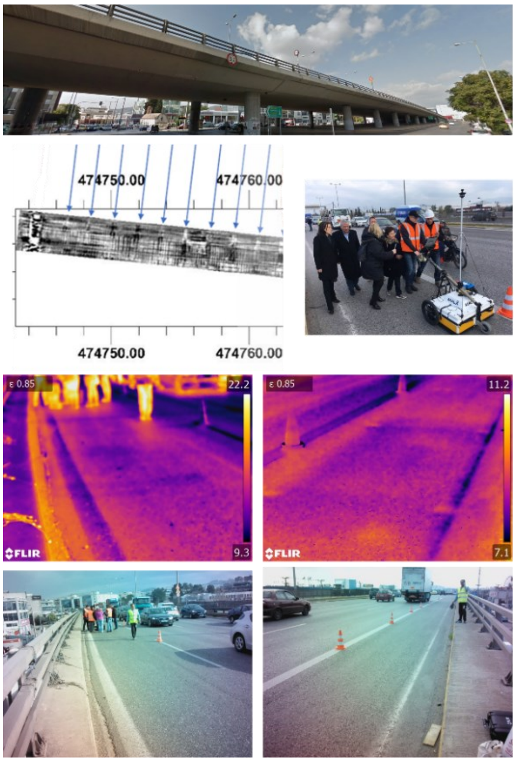

Fig. 3. Top: Utilization of non-destructive testing and evaluation methods on the Kifissos / Konstantinoupoleos road bridge in Athens. Middle: Utilization of the Guideline GEO GPR MALÅ 3D Imaging Radar Array (MIRA) 16-channel system for the 3D prospection of the internal structure of the bridge deck. Lower: Use of Infrared thermographic survey of the bridge deck, other structural and non-structural elements of the same bridge

The portable nature of the IRT equipment allows it to be installed on drones to document difficult to reach areas of the bridge or at viewing angles that cannot be achieved from surface or deck level positions. Alternatively, telescopic boom truck cranes with baskets or scaffolding can provide complementary positions for IRT surveying, especially in cases of local assessment of damage and deterioration. IRT can also be employed to survey the bridge's surroundings, such as riverbanks, pier foundations, embankment/abutments/revetments and reveal local variations of water/humidity transport phenomena that can influence the susceptibility of the bridge to environmental loads.

4.2.4 Assessment of the foundation environment with non-destructive methods

The foundation environment of a bridge is crucial to its stability and dynamic behavior and must be regularly evaluated, especially when the bridge spans rivers, large water volumes, or gorges. In the case of bridges in urban areas, the assessment must focus on the overall influence of the surrounding built environment on the foundation environment of the bridge. Variations in water transport phenomena imposed either from the surrounding built environment or climate change may modify the soil moisture content and adversely alter the physicochemical and mechanical properties of the ground environment over which the bridge is constructed. The typical geophysical and geotechnical methods employed can assess the properties and behavior of soil and rock substrate, as described in the relevant codes, standards and technical specifications.

The continuous development of non-destructive methods such as the electrical resistivity tomography (ERT) and the advancements in 3D signal analysis have improved their effectiveness and applicability. ERT is a geophysical technique for imaging subsurface structures by recording the resistivity and induced polarization (IP) data from the surface (with electrodes bored on the soil) or by suspended probes within boreholes (for deeper measurements). It can detect voids and identify subsurface hazards and features that pose risks to the integrity and static and dynamic performance of the bridge piers and embankments. It can also provide information to support the assessment of the load-bearing capacity of the foundation environment. ERT is conducted either. Accessibility is an important issue, especially at difficult to reach areas, like sloped riverbanks. Permanent installation of electrodes or use of predrilled boreholes can expand the monitoring capabilities of the technique over extended timeframes.

4.2.5 Real-time Structural Health Monitoring (SHM)

As described above (sections 2.2.1 and 2.7), Structural Health Monitoring (SHM) regards the management of an array of permanent and non-permanent sensors that record specific information from the bridge structure, surfaces and environment that can be used for the evaluation of its condition and the impact of the environment [49, 50]. SHM regards three levels: a) monitoring specific data of the bridge through sensors; b) identification and extraction of damage features and c) analysis of the revealed damage to evaluate the condition of the monitored bridge. The challenges faced by current and future SHM systems are significant and must be addressed efficiently.

The first challenge regards the representativeness of the monitored data. SHM equipment can incur a significant cost, both for its initial acquisition as well as for its operation and maintenance. The selection of the most appropriate sensors and their location needs to be the result of careful planning. In this framework, the implementation of a comprehensive preliminary analysis of the current condition of the bridge, as described above, is beneficial to allow the efficient design and installation of a finite number and specific types of sensors. Built-in or permanent sensors may be preferred, however, in the long term they may not be as adaptable and representative as compared to portable/repositionable sensors that follow the evolution of damage/decay or weathering. The recent developments in wireless technology and IoT “release” sensors from the constraints of wiring and permanent connections to central monitoring systems.

The second challenge regards data interpretation for identification and extraction of damage, deformations, or wear. Modern sensors, load cells and strain gauges record data of high resolution and frequency. These sizeable data, in turn, necessitate the availability of large databases, specialized software for signal analysis and advanced platforms for their management and representation. Limitations of computational ability and data analysis methods at the levels of the BA (BIEA, BMTA), as well as the deficiency in clear correlations between the various types of information, create significant challenges in SHM data interpretation. Big data (BD) computing and artificial intelligence (AI) techniques can aid significantly [51-53]. BD analysis, as currently utilized in bridge SHM, emphasizes more on processing time series rather than categorical data as in typical commercial big data applications. This is justified by the finite number of sensors installed and used and the finite types of parameters monitored. However, as the interaction between the bridge and its environment will be more extensively assessed, i.e. by expanding this interaction in temporal, spatial and spectral terms, BD analysis in SHM of bridges needs to shift towards processing of categorical data. AI techniques that are increasingly used for pattern recognition and identification of defects or damage, require appropriate training stages, which in turn, require comprehensive experience, know-how and measurable results. In the end, the role of experienced engineers and scientists is more than critical for the broader and more efficient utilization of techniques exploiting BD computing and AI.

Similarly, the third challenge regards the fusion of multispectral, massive information gained by SHM systems into the overall, holistic assessment of the bridge, especially in the context of the bridge's interactions with its environment. From the scientific perspective, the systematic definition of indicators and threshold levels is important to avoid false alarms, inefficient evaluations or loss of crucial information. Again, the role of engineers and scientists, especially the close cooperation among the various disciplines, is the fundamental lever for an efficient and representative fusion of information; despite their virtues, BD computing and AI may miss critical information if the original data are limited in nature [54], their interrelation is not clear and the location and number of sensors is not optimal.

4.2.6 Assessment of the static, dynamic and seismic behavior of the bridge

It should be realized that most bridges were designed and constructed using previous norms, standards and legislation. For example, design loads were specified according to DIN 1072, dimensioning and construction according to DIN 1075, the concrete specified according to DIN 1045, etc. The unification of standards and norms under the EN framework and Eurocodes, effectively necessitates the assessment according to the current standards and norms to ensure that the bridge conforms to the current requirements.

The dynamic characteristics of the bridge (e.g. eigenperiods, eigenmodes, damping,) need to be analyzed to ensure that the bridge conforms to the desired limit states. These can be measured through a variety of methods, including the microvibration method and the forced oscillations from the passage of vehicles.

It is important to measure the vertical displacements of the bridge deck, as it is subject to traffic loads. The accumulation of damage and wear, and especially its differential occurrence along the bridge structure may alter significantly the rigidity/elasticity of the bridge parts and displacements distribution along the deck. Permanent sensors and gauges can offer continuous monitoring capabilities, however, it is often more effective to measure such parameters under forced loading from a heavy vehicle (truck or railway vehicle).

Due to the high seismic risk, all elements of the bridge must be evaluated regarding their seismic durability. This evaluation should be implemented over two timeframes: the original design earthquake (original construction period), and the earthquake specified under current legislation and norms. The assessment is carried out both by elastic analysis using spectral analysis, and by non-linear analysis and performance levels for the both earthquake cases, to investigate what limit state the bridge will reach. The measured dynamic characteristics of the bridge are then utilized in accurate 3D models, which can be further verified against the measurements of the actual vertical displacements, under real time operation of forced loading.

4.2.7 The microbial 'footprint' of the bridge, in relation to the bridge's thermohygric behaviour and the observed deterioration and pathology

The environment impacts the bridge through various phenomena of mechanical (e.g. cracks, deformations, displacements, wear), chemical (e.g. corrosion, deterioration, carbonization), electrochemical (e.g. corrosion) and biological (e.g. crusts, deterioration) nature or combination thereof (e.g. fatigue of materials). The biological aspects of a bridge may at first be considered as minor; a large infrastructure may not be considered as prone to actions of microorganisms! However, what is of interest in inspection, evaluation and even maintenance activities, is the microbial 'footprint' of the bridge. Many deteriorating mechanisms, especially those that involve water transport phenomena, infer alterations to the microflora of the bridge ecosystem. Although the microflora itself is not directly involved in most of the damage, wear or deterioration mechanisms (except biodeterioration of some building materials), in effect it can function as a trace of underlining damage phenomena. By monitoring the microflora on specific critical bridge elements (e.g. piers, abutments, stone arches) one can indirectly monitor the temporal variation of environmental impact on the examined areas, without necessarily documenting, directly, the complex mechanisms involved.

Specific deterioration phenomena, such as crust formation on concrete or stone masonries, can be correlated with the thermohygric behavior of the bridge, which in turn affects directly the microbial environment over the affected areas of the bridge. Documentation of this microbial environment, thus, can provide indications for underlying (non-documented) phenomena, which may not be detectable through conventional SHM or inspection techniques.

The bridge microflora is a complex ecosystem, due to the large size of the bridge. New technologies such as next-generation sequencing (NGS) are applied for the metagenomic analysis of microbial ecology. DNA analyses of microbial communities can be carried out on samples without prior need for cultivation. Therefore, by revealing the composition of the taxonomic groups of microbial communities and the way microbial populations interact with each other and the environment, a deeper understanding of the biodegradation processes occurring in bridge areas can be gained that can be correlated with other observed damage, wear or failures. Such a correlation can either be applied at the level of observed results (data from inspections, NDE, SHM) or at the level of environmental impact analyses.

4.3 The evolution from Building Information Modeling (BIM) to Bridge Information Modeling (BrIM)

Building Information Modeling (BIM) has emerged as a valuable tool for engineers and construction companies that offers an improved design environment and effective management of information, allows users to achieve higher levels of collaboration and advance and streamline project implementation [55]. The BIM methodology utilizes a digital representation of the examined asset to optimize the design, construction, and operation processes, throughout the lifetime of the building. In effect it is composed of two elements [56]. The Project Information Model (PIM) refers to the design and construction phases, whereas the Asset Information Model (AIM) regards the operational (and thus, the relevant inspection, evaluation and maintenance) phase.

Bridge Information Modeling (BrIM) is gradually being developed as a BIM customized to suit bridge projects. It aims to provide a complete representation of the physical and functional characteristics of a bridge, functioning as an information repository for its entire lifecycle. In the case of ongoing construction projects of large bridges, BrIM improves the quality of design through the availability and management of accurate information, consistent documentation, and improved constructability. In such large-scale applications, BrIM allows for accurate pre-fabrication and just-in-time material deliveries and supports project collaboration across the various disciplines involved. However, in the case of already constructed bridges (especially those constructed in the distant past), the levels of documentation required, and the challenges related to information management are significant, thus, limiting the utilization of BrIM (if available) to only few selected, significant cases.

The key drivers for BIM and BrIM are transparent communication and high-level collaboration, both of which require data standardization. However, information can be managed and utilized efficiently only when introduced into the process in standardized usable formats. In this case, sharing of data - regardless of what software is being used - enables high level collaboration. The advancement of BIM/BrIM capabilities in the context of creating open, interoperable and repeatable processes is beneficial to all its users and involved stakeholders. To this end, the expansion of Industry Foundation Classes (IFC) standards [21] must encompass bridge methodologies (IFC level 4 and beyond), to successfully address the specific needs of bridge construction, inspection and maintenance.

The majority of the bridge stock has been constructed and has been operating prior to the advent of modern IT-based systems. Accordingly, a significant effort is required to transform relevant information (if available!) into digital formats exploitable by BIM. At national level, the main priority regards the digitization of available records of existing bridges and to a lesser degree the digitalization of bridge design, construction and management processes; digitalization is reserved and employed mainly to the newer large bridge projects.

The continuous development of BIM and BrIM is exploiting modern information technologies, such as big data analysis, augmented reality (AR), virtualization (VR), the Internet of Things (IoT), wireless monitoring, cloud and real-time collaboration.

Understandably, BIM and BrIM transformations are gradually streamlining processes and developing corporate cultures toward model-based practices.

Nevertheless, the success of this transformation is highly dependent on a critical factor, parameterization. It refers to the capacity of the users to express and monitor elements of the building (bridge) through specific parameters and somehow clearly define their interactions. Only through such an approach can a parametric application like BIM allow users and stakeholders to create, collect, store, and share accurate and systematic data and information as part of full life-cycle support processes.

The level of BIM/BrIM analysis relies on the following general constraining aspects:

1. The desirable extent of the structure to be described and thus parameterized
2. The feasible extent of the structure to be described and monitored, especially when it regards its past state
3. The extent of the environment which imparts a measurable effect on the structure

The first constraining aspect refers to the multitude of factors pertaining to the diminishing of performance or failure of a complex structure (bridges in particular) as opposed to the minimum information (and corresponding parameters and indicators) required to support a reasonable assessment (in engineering terms) of the structural integrity, performance and safety of the examined asset. It is a contradictory challenge in the context of eligibility (compliance with existing legislation), feasibility (too many parameters require significant resources), and scientific excellence (too few parameters may reduce the precision of the analysis and assessments and subsequently endanger the effectiveness of any proposed measures and interventions).

The second constraining aspect is a pragmatic challenge and refers to the temporal nature of the overall assessment and monitoring processes. Whatever elements of the structure will be evaluated and whatever parameters are selected as indicative of their state and performance, these should extend in the past. On one hand, the sufficient recording of past values of any selected parameters and indicators will permit an improved analysis of their variation patterns, allowing for early detection of potential failures. The same applies to the frequency, continuity and resolution of the information obtained by monitoring, as it directly affects the accuracy of the developed (structural or environmental) models. On the other hand, knowledge of past states of the examined asset and past events imparting damage or failure may expose latent information that has not been considered in the current modeling of the examined structure. This is a common challenge in historic buildings and structures where limited documentation of their decay and damage pathology and especially past events and interventions result in the creation of Finite Element Models (FEM) and analytical models of reduced representation, consequently leading to less effective assessments, evaluations and intervention/repair proposals.

The third constraining aspect regards the interaction between the bridge and its environment. The challenge lies in assessing the extent to which the impact of the surrounding environment should be considered. Typically, analyses consider the immediate environment of the bridge, such as the water volume (if the bridge is constructed over a river or in the sea), and the geotechnical environment of its foundations. The benefits of availability of central databases such as the NRPW or NBR are clear, as they constitute the basic sources of relevant information (e.g. environmental studies, geotechnical studies). In the case of seismic risks, the parameters involved are clearly defined in relevant legislation (e.g. EAK 2000 [14]). However, the interaction between the bridge and its environment is neither oligo-parametric nor continuous and consistent in temporal terms. This is emphasized by the growing global concern on climate crisis that forces the scientific and technical communities to consider changes at the macroscale. In the last decades, scientific knowledge regarding the impact of various environments on materials has progressed significantly, and much of this know-how has been introduced in the design, construction and maintenance of new bridges. This know-how, nonetheless, must be adapted to the challenges posed by climate crisis. Such an adaptation, in turn, expands the level of analyses required to better describe the performance, resilience and sustainability of bridges, within this framework of increased and variable risks and hazards. Similarly, by increasing the extent to which the environmental influence is introduced into assessments and evaluations, one could identify indirect interactions between environmental factors that detrimentally intensify the environmental impact on the examined bridge. A typical example is urban pollution and its correlation with acid rain and decay of building materials.

Overall, the evolution from BIM to BrIM is obviously the way forward. However, such an evolution should take into account the specific characteristics, constraints and challenges relevant to bridges.

5 Conclusions

Bridge inspection, evaluation and maintenance are key factors for the safe operation, efficient management and improved resilience of historic and contemporary bridges. The interactions between the bridge, its environment and the road/railway traffic are complex in nature, multiparametric and largely not known or documentable to their full levels. Within such a complicated scientific and engineering field, authorities responsible for the inspection, evaluation and maintenance of bridges are required to apply relevant legislation, regulations and methodologies which at least tackle with the most important priority, i.e. safety.

At national level, the (delayed) development of bridge-specific and the establishment of relevant authorities (NRPW, NBR, BAA), along with the implementation of essential projects like “Smart Bridges” have set the ground for efficient bridge inspection and evaluation processes. Nonetheless, the large number of bridges, their large variety, and the general shortage of past inspections, evaluations and maintenance for most of the bridge stock pose significant restrictions onto the application of the current legislative framework and undermine significantly its effectiveness.

To overcome this, an enhanced preliminary inspection (as described above) is deemed beneficial, as it may compensate for the deficiencies in past documentations and assessments. Ongoing developments on the geometric documentation technologies and non-destructive evaluation methods, in conjunction with the advanced capabilities of modern SHM systems and platforms can offer the necessary enablers for an improved inspection, evaluation and maintenance framework that develops beyond the current priorities and capabilities.

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