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STATISTICAL ASSESSMENT OF BRIDGE BEARINGS: A METHODOLOGY FOR ASSET MANAGEMENT, MAINTENANCE AND DESIGN

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Effective management of transportation infrastructure requires structured and data-driven approaches capable of supporting maintenance planning and decision-making. This study presents a data-driven methodology for the organization and analysis of large-scale inspection data, with application to bridge bearing systems. The proposed approach is based on the development of a relational database designed to integrate bearing characteristics, inspection records, and contextual information within a consistent and scalable framework. The adopted data architecture enables the aggregation of heterogeneous information and supports systematic analyses at the network scale. A preliminary application to a dataset of more than 16,000 bearings from the Italian motorway network is presented to demonstrate the analytical capabilities of the methodology. The results highlight differences in damage occurrence across bearing typologies and the prevalence of corrosion-related defects, while also showing that their impact depends on the mechanical configuration of the devices. Overall, the proposed methodology provides a structured basis for the analysis of inspection data and supports the identification of potentially critical components, contributing to more informed maintenance planning. Although applied to bridge bearings, the approach can be extended to other structural components and represents a foundation for future developments, including the integration of environmental data and predictive maintenance strategies.

Keywords: Relational database, Condition rating, Inspection data, Risk prioritization, Maintenance planning, Infrastructure decision support.

1 INTRODUCTION

Bridge bearings are critical components within bridge systems, ensuring the transfer of loads from the superstructure to the substructure while accommodating required rotations and displacements (Lee 1994). Despite their relatively small size, their degradation can significantly affect structural performance and, in severe cases, lead to serviceability or safety issues. Bearings are continuously exposed to environmental actions and repeated traffic-induced load cycles, which contribute to material deterioration, wear, and long-term damage. In large infrastructure networks, such as the Italian motorway system, bearing management represents a significant challenge due to the wide variability in typologies, materials, and installation periods. Although extensive inspection campaigns provide large amounts of condition data, these are often used for localized assessments and are rarely exploited for systematic, network-scale analyses. Traditional inspection-based

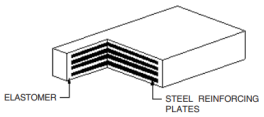
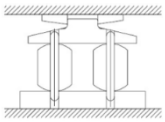
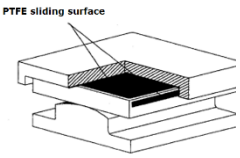
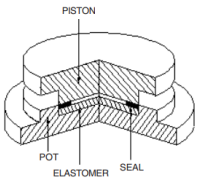
approaches rely on qualitative or semi-quantitative condition ratings assigned during periodic visual surveys. While effective for identifying critical damage, these methods are typically applied at the component level and are often documented in isolated reports, limiting the integration of heterogeneous data sources and the identification of recurring degradation patterns. In this context, data-driven approaches offer significant potential for improving infrastructure management. The systematic organization and analysis of inspection data can provide insights into defect distribution, typology-dependent degradation mechanisms, and condition trends across large asset populations. However, the effective use of such data requires a structured framework capable of integrating technical, temporal, and environmental information within a consistent and scalable architecture. This study proposes a structured data-driven framework for the organization and preliminary analysis of bridge bearing inspection data. The approach is based on the development of a relational database designed to link bearing characteristics, inspection outcomes, and contextual information. The methodology is applied to a large dataset of bridge bearings from the Italian motorway network, with the aim of supporting network-level condition assessment and providing a foundation for future data-driven maintenance strategies.

1.1 Adopted classification of Bridge Bearings

Bridge bearings can be classified based on kinematic characteristics or material and mechanical configuration (Marioni 1983). While kinematic classifications describe the degrees of freedom provided by the devices and are primarily relevant for structural analysis and design, this study adopts a material-based classification, as it better reflects the mechanical behavior of bearings and their characteristic degradation mechanisms and is therefore more suitable for inspection-based data organization and statistical analysis. The bearing categories considered in this study, summarized in Table 1, encompass a wide range of mechanical behaviors and material compositions that are representative of the Italian motorway bridge stock. Elastomeric and Steel-Reinforced elastomeric bearings accommodate movements primarily through shear deformation of elastomeric layers, with the latter providing increased vertical stiffness due to internal steel laminates (UNI Ente Nazionale Italiano di Unificazione 2005). Steel bearings include a range of mechanical devices, such as rocker, roller, and pendulum systems, in which movements are enabled through steel-to-steel interfaces. These devices can accommodate large translations and rotations but are generally more sensitive to corrosion and mechanical seizure (Fan 2014). POT bearings consist of a confined elastomeric pad enclosed within a steel pot, allowing rotations through compression of the elastomer while restraining horizontal movements unless combined with additional sliding or guiding components. PTFE-based bearings rely on low-friction sliding interfaces (Consiglio Nazionale delle Ricerche 1998), typically consisting of polytetrafluoroethylene coupled with stainless steel, to enable controlled horizontal displacements under service loads.

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Table 1. Material classification of bearings.

Elastomer	Steel Reinforced Elastomer	Steel	PTFE	POT
				

1.2 Inspection Procedures and Condition Rating System

The condition of bridge bearings is assessed through periodic inspection campaigns conducted as part of routine infrastructure management activities. These inspections typically involve visual surveys aimed at identifying visible defects, documenting their characteristics, and assigning condition ratings that reflect the overall state of the component (Brighenti *et al.* 2024). The frequency and level of detail of inspections may vary depending on regulatory requirements, asset criticality, and maintenance strategies, but they generally follow standardized procedures to ensure consistency across the network. Inspection reports usually include structured information on the inspected structure, such as location, identification codes, inspection date, and inspection type, followed by a systematic assessment of individual structural components (Consiglio Superiore dei Lavori Pubblici 2022). For bearings, inspectors record the presence of defects using predefined defect codes and assign severity levels or condition ratings based on qualitative or semi-quantitative criteria. These inspection data constitute the primary input for the database and form the basis for the subsequent analysis.

2 DATABASE STRUCTURE

2.1 Relational Structure and Information Levels

The database is implemented as a structured relational system organized into hierarchical information levels, describing a specific aspect of bridges and their bearing systems within the road network. Fig. 1 provides a schematic overview of the database architecture and of the logical relationships among its main components. The database is structured into three main levels:

- **bridge level**, including general information on the structure and intervention history;
- **bearing level**, including type, installation year, and constraint scheme of individual devices;
- **inspection level**, including defect codes, condition ratings, and temporal records derived from periodic inspections.

These levels are interconnected through relational links, enabling the integration of geometric, technical, and condition-related data. This structure allows consistent aggregation and querying of inspection records, as well as the tracking of damage evolution over time at the level of individual bearing devices. Overall, the proposed organization provides a coherent and scalable framework for managing large volumes of heterogeneous inspection data and supports reproducible analyses at the network scale. Although developed for bridge bearing systems, the same relational structure can be extended to other structural components, enabling the systematic analysis of inspection data across different asset types. This approach allows the identification of recurring defect patterns in

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relation to structural typology, environmental exposure, and network-scale conditions, providing a consistent basis for comparative assessments and maintenance planning.

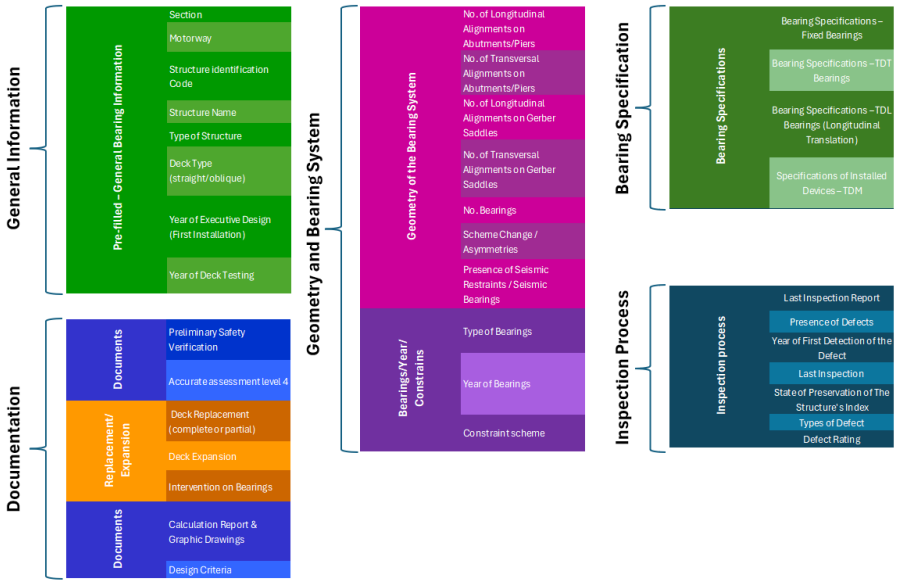


Fig. 1. Database structure.

2.2 Dataset Composition and Coverage

The database developed for this study includes more than 16,000 bearing records from bridges belonging to the Italian motorway network, covering bearing devices installed over several decades. Fig. 2 summarizes the geographical distribution of bearing included in the dataset.



Fig. 2. Geographical distribution of the bridges included in the database.

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The dataset includes bearings installed over several decades, with the majority of records corresponding to the period between the 1960s and the early 2000s, consistent with the main expansion phases of the Italian motorway network. This temporal distribution provides a suitable basis for investigating age-related degradation trends and long-term behavior.

3 RESULTS AND PRELIMINARY ANALYSIS

The analysis of the inspection dataset provides an overview of the current condition of bridge bearings at the network scale, enabling a first quantitative and qualitative interpretation of degradation phenomena across different bearing typologies. The proportion of damaged bearings varies significantly across typologies, ranging from approximately 7% for elastomeric bearings to about 37% for steel bearings, with intermediate values for PTFE (28%), POT (22%), and reinforced elastomeric bearings (12%). The results indicate that a non-negligible proportion of the inspected bearing stock exhibits observable deterioration, confirming the relevance of degradation processes for these critical structural components. When the analysis is disaggregated by bearing type, differences emerge in the proportion of damaged elements across the categories defined in Table 1. This comparison suggests that certain bearing typologies are more frequently associated with deterioration phenomena, highlighting the influence of material characteristics, mechanical behavior, and exposure conditions on long-term performance, and providing a first indication of those typologies that may require more frequent monitoring and maintenance attention.

Building on the quantitative assessment of damage occurrence, a further level of analysis was carried out to characterize the nature of the observed deterioration through the distribution of defect categories across bearing types. The results confirm that corrosion and oxidation-related defects represent the most frequent damage mechanisms across all bearing typologies. However, their effects differ significantly depending on the operating principles of the bearing systems.

For **elastomeric and steel-reinforced elastomeric bearings**, corrosion mainly affects external steel components, such as connection plates, and is generally not critical unless it leads to severe loss of connection. In these systems, the most frequent and relevant deterioration mechanisms are associated with the elastomer itself, including neoprene aging, crushing or extrusion, and excessive horizontal deformation. These defects indicate that the bearing may have exceeded its design limits and can lead to increased stiffness and altered structural behavior. **Steel bearings** exhibit a markedly different behavior, as their functionality relies on steel-to-steel contact surfaces. In this case, corrosion plays a critical role, as it promotes the formation of debris and surface irregularities that can reduce sliding capacity. This often results in mechanical issues such as locking or seizure, which are among the most relevant observed defects. Additional defects, including permanent misalignment (e.g. out-of-plumb pendulums) and incorrect pre-adjustment, further contribute to altered load transfer mechanisms and reduced performance. For **PTFE-based bearings**, corrosion is again the most frequently observed defect, while degradation of the sliding interface is more difficult to detect through visual inspection. External corrosion may reduce load-bearing capacity, whereas internal deterioration, although not directly observable, can compromise the low-friction behavior of the PTFE-steel interface and lead to progressive loss of functionality. For **POT bearings**, corrosion is also commonly observed but generally has a less direct impact on performance. More frequent and critical defects are associated with excessive horizontal deformation of the confined elastomer, indicating that the bearing has experienced forces beyond its design capacity.

Overall, the analysis shows that steel bearings exhibit the highest proportion of damage and therefore deserve particular attention within maintenance and inspection planning. While corrosion represents a common degradation mechanism across all typologies, its impact varies significantly

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depending on the bearing configuration, with more severe consequences for steel systems and predominantly material-related deterioration in elastomeric devices.

4 CONCLUDING REMARKS AND PERSPECTIVES

This study presented a structured, data-driven framework for the organization and preliminary analysis of inspection data related to bridge bearing systems. By integrating heterogeneous information within a relational database architecture, the proposed approach enables consistent data aggregation, improved traceability of inspection records, and scalable analysis at the network level. The exploratory results demonstrate the potential of the database to support the identification of recurring degradation patterns and to provide objective insights into the condition of bearing systems across different typologies. In particular, the combined analysis of damage occurrence and defect distribution highlights both common degradation mechanisms and typology-specific behaviors, offering a meaningful basis for maintenance prioritization. Although limited to a preliminary investigation, the proposed framework establishes a robust foundation for future developments. Overall, the study confirms that structured data architectures combined with systematic analytical procedures can enhance infrastructure management processes and support more informed, data-driven decision-making.

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