Summary

Infrastructure assets, such as bridges and tunnels, are crucial for a Country's economic and social development. In Western countries, much of this infrastructure was developed post-World War II and has now reached or exceeded its design life. Due to degradation and design or construction deficiencies usual at the time of construction, the safety and functionality of these assets are now at risk.

Currently, the primary needs regarding these infrastructures involve assessing their safety and interpreting their structural behaviour using Structural Health Monitoring (SHM) systems. For safety assessments, increasingly sophisticated numerical models are required. For interpreting structural behaviour, either purely data-driven or model-driven methodologies can be employed, often involving the creation of digital twin models. These models are particularly essential for complex structures.

This thesis fits into the previously discussed context by investigating, through real case studies, the potential of non-standard approaches for the safety assessment and interpretation of the structural behaviour of existing bridges and viaducts.

It first focuses on the safety assessment of existing bridge decks, specifically three girder decks made of prestressed reinforced concrete, which are a common typology in existing infrastructures.

The assessment is conducted using different methods: Courbon theory, linear elastic finite element (FE) analysis, and nonlinear FE analysis (NLFEA) according to three global safety formats.

The decks are initially modelled using Courbon's theory and then with a linear elastic FE model composed of beam elements only.

In both cases, safety is evaluated by comparing design resistant and acting moments in the sections of interest, using partial safety factors for local approaches.

Subsequently, nonlinear 3D FE models are applied, implementing global safety formats that yield varying safety margins compared to local methods.

The first two local approaches employed in safety assessments are notably conservative, leading to a reduced safety margin. In contrast, global approaches—relying on global safety formats—tend to yield higher safety margins. However, the extent of this improvement depends significantly on the specific global safety format adopted.

Moreover, the safety level is evaluated in relation to structural damage through global nonlinear 3D numerical analyses, considering various damage scenarios. These numerical studies assess the structural performance of the deck under ultimate limit state conditions for each scenario, establishing a correlation between safety loss and the extent of damage. Based on this, a threshold-

based approach is proposed, in which specific static parameters are used to monitor the progression of damage within the structure.

Several key considerations emerge from this first aspect—namely, the safety assessment of existing bridge decks. Chief among them is that increasing the complexity of analysis and modelling generally leads to improved safety margins. Certain modelling aspects, such as the accurate representation of boundary conditions and constraint stiffness, are critical to the final safety assessment. Finally, while structural damage does reduce load-bearing capacity, the resulting loss in strength typically exceeds the corresponding reduction in stiffness. This discrepancy suggests that static parameters are not well-suited for reliable damage detection.

The second focus of the thesis is the interpretation of the structural behaviour of existing bridges and viaducts through the analysis of Structural Health Monitoring (SHM) data, with a specific emphasis on dynamic behaviour.

The dynamic behaviour of the structures under investigation is determined using Operational Modal Analysis (OMA) methods. Over the past decade, rapid technological advancements and the reduction in sensor costs have enabled the monitoring of increasingly complex structures. In this context, the development of finite element models (FEM) has become essential for interpreting monitoring data and understanding structural behaviour. These models also play a crucial role in verifying the safety of the monitored structures.

In the second part of the thesis, three viaducts—each representing a different structural typology—are examined. A digital twin is developed for each structure, and model updating is carried out using a range of approaches, from fully manual calibration to optimization techniques based on genetic algorithms. This process highlights both common and structure-specific modelling challenges, which must be carefully addressed to ensure that the numerical models reliably represent the actual behaviour of the structures.

Several key considerations emerge from this second aspect—namely, the interpretation of structural behaviour through the analysis of Structural Health Monitoring (SHM) data and the subsequent model updating of digital twins. The most critical point is that structural models used for interpreting SHM data differ significantly from those developed for design purposes, owing to their distinct objectives. Key divergences between design models and simulation models include the characterization of bearing friction and deformability, the global deformability of the soil-structure system, the estimation of permanent loads, and the specification of material properties. Among these, certain factors—such as bearing behaviour or global system deformability—tend to play a dominant role across multiple structural types, while others are more relevant to specific configurations.