

# Remaining service life estimation of existing concrete bridges through probabilistic and reliability analyses



Silvia Sarmiento

Structural and Fire Engineering





DOCTORAL THESIS

Remaining service life estimation of existing concrete  
bridges through probabilistic and reliability analyses

SILVIA SARMIENTO

Luleå 2026

Luleå University of Technology  
Department of Civil, Environmental and Natural Resources Engineering  
Division of Structural and Fire Engineering  
SE-971 87 Luleå, Sweden  
[www.ltu.se](http://www.ltu.se)

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**Silvia Sarmiento**

Division of Structural and Fire Engineering

Department of Civil, Environmental and Natural Resources Engineering

Luleå University of Technology

**Academic thesis**

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Opponent: Professor José A. Campos e Matos, Universidade do Minho  
Examining Committee: Dr. Mario Plos, Docent, Trafikverket  
Professor Sylvia Kessler, Helmut Schmidt Universität  
Professor Joan Ramon Casas, Universitat Politècnica de Catalunya

Principal supervisor: Professor Gabriel Sas, Luleå University of Technology  
Assistant supervisors: Senior Lecturer Dr. Jaime González-Libreros, Luleå University of Technology  
Senior Lecturer Dr. Chao Wang, Luleå University of Technology



# Preface

This project was funded by SBUF (construction industry's organization for research and development in Sweden) and by Trafikverket through BBT (Industry program for research and innovation of Construction for the Transport sector). I would like to gratefully acknowledge these institutions for financing this project, thus allowing this research to be possible.

This thesis represents the culmination of five and a half years of research and study, and it is with great pleasure that I present it to you today. The research presented in this explores the role of probabilistic and reliability concepts in determining the remaining life of existing bridges.

Throughout the course of this research, I have had the privilege of working with some truly exceptional individuals. I would like to express my deepest gratitude to my team of supervisors, who provided invaluable guidance and support throughout the entire process. I would like to thank Prof. Gabriel Sas for his exceptional mentorship and support. I also extend my sincere appreciation to Dr. Jaime González-Libreros for his invaluable contributions, as well as for his friendship and encouragement throughout the project. My thanks also go to Dr. Chao for his supervision and meaningful input in this work. In addition, I would like to thank all co-authors of my publications and everyone who has contributed to this research in various ways, their support and collaboration have been greatly appreciated.

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me feel close, regardless of the distance, and my husband, for being here with me, for giving me the courage and standing by me throughout every step of the journey.

Silvia Sarmiento

Luleå, February 2026

## Summary

This thesis aims to assess the remaining useful life of two representative bridge types in Sweden by combining full-scale experimental tests, Finite Element Analysis (FEA), and time-dependent reliability analysis. The combination of these methods seeks to enhance solution accuracy and reduce uncertainties. As the bridge population approaches its intended design life, concerns regarding their current condition start to rise. Recent bridge failures are proof of the need for experts to increase their efforts to accurately assess existing bridges' remaining useful life. However, structural remaining lifetime prediction is a challenging task given the complexity of structural behavior and the various environmental threats the structure faces. Additionally, inherent uncertainties are part of any engineering problem, making an exact solution difficult to achieve. Therefore, introducing probabilistic-based concepts to determine the structure capacity helps account for those uncertainties typically addressed in structural reliability analysis. Time-dependent reliability analysis offers a tool to assess the remaining useful life of a structure, expressed in terms of its time to failure.

The first case study corresponds to a road existing bridge in north Sweden that has been already demolished. The structure is a prestressed box-girder concrete bridge, and it was 66 years old at the time of experimental data collection. The second case is a reinforced concrete (RC) trough railway bridge, which is a representative bridge type in Sweden. The trough bridge was cast at LTU in 2021 as a replica of the design of a decommissioned trough bridge from the Iron Ore Line. The experiments performed, corresponding to residual prestress and fatigue tests, in both case studies are used for two main purposes: the calibration of the Finite Element (FE) models and the update of the probability distributions of the parameters involved in the time-dependent reliability analysis. This will help a better FE model to represent structural behavior and more accurate probabilistic models. Different sensors were implemented during the experimental data collection, such as fiber optic sensors (FOS), traditional strain gauges, and linear variable differential transformers (LVDTs).

Given that the communication between FE and reliability analyses can be computational overwhelming, this thesis proposes an improved metamodel-based reliability algorithm which integrates the advantages of kriging, learning, and copula functions. The proposed algorithm aims to reduce the number of performance function evaluations, so the number of model runs is feasible when using FEA. For the implemented example, the proposed method reduced the number of FE simulations by 67% compared with the LHD-K-U reference algorithm.

The results of this research provide a practical understanding of the stochastic process for resistance deterioration in both case studies. This includes degradation due to prestressing losses for the Kalix bridge and fatigue for the trough bridge. By considering the stochastic process over the years and the random nature of the loads over time, it was possible to calculate the remaining service life both without experimental data and with updated information. For the Kalix bridge, reliability estimates increased by 201% and 264%, using two different testing methods, while for the trough bridge by 172%. These findings have direct implications for the maintenance and management of similar structures, providing valuable insights for the field of civil engineering and structural reliability analysis.

**Keywords:** Existing bridges, reliability, remaining useful life, metamodel, Finite Element Modeling, full-scale tests.

# Sammanfattning

Syftet med denna avhandling är att bedöma den återstående livslängden för två representativa brotyper i Sverige genom att kombinera fullskaliga experimentella tester, finita elementanalyser (FEA) och tidsberoende tillförlitlighetsanalys. Kombinationen av dessa metoder syftar till att förbättra noggrannheten i resultaten och minska osäkerheterna. I takt med att brobeståndet närmar sig sin avsedda livslängd ökar oron kring broarnas aktuella skick. Nyliga brohaverier visar tydligt behovet av att experter intensifierar sina insatser för att korrekt bedöma befintliga broars återstående livslängd. Att förutsäga en konstruktions återstående livslängd är dock en utmanande uppgift, med tanke på det komplexa strukturella beteendet och de olika miljöpåfrestningar som konstruktionen utsätts för. Dessutom är inneboende osäkerheter en del av alla ingenjörspenningar, vilket gör det svårt att nå en exakt lösning. Därför bidrar sannolikhetsbaserade metoder till att bättre beskriva bärförmågan genom att inkludera dessa osäkerheter, vilket är centralt inom strukturell tillförlitlighetsanalys. Tidsberoende tillförlitlighetsanalys erbjuder ett verktyg för att uppskatta en konstruktions återstående nyttjandetid, uttryckt som tiden till brott.

Den första fallstudien avser en vägbro i norra Sverige som redan rivits. Konstruktionen är en förspänd lådbalksbro i betong och var 66 år gammal vid tiden för datainsamlingen. Den andra fallstudien avser en armerad betongtråg-bro för järnväg, vilken är en vanlig brotyp i Sverige. Trågbron göts vid LTU år 2021 som en kopia av en utrangerad tråg-bro från Malmbanan. De experiment som genomfördes, motsvarande restspännings- och utmattningstester, användes för två huvudsyften: kalibrering av FE-modellerna samt uppdatering av sannolikhetsfördelningarna för de parametrar som ingår i den tidsberoende tillförlitlighetsanalysen. Detta bidrar till mer representativa FE-modeller och mer tillförlitliga sannolikhetsmodeller. Under försöken installerades flera typer av sensorer, såsom fiberoptiska sensorer (FOS), traditionella töjningsgivare och LVDT-givare.

Eftersom kopplingen mellan FE-analyser och tillförlitlighetsanalyser kan vara beräkningsmässigt krävande, föreslås i denna avhandling en förbättrad metamodelbaserad tillförlitlighetsalgorithm som integrerar fördelarna med kriging (gaussisk process-baserad interpolering), aktiv inlärning och kopulafunktioner. Den föreslagna algoritmen syftar till att minska antalet utvärderingar av prestandafunktionen, så att antalet modellkörningar blir hanterbart även vid användning av FE-modeller. I det implementerade exemplet reducerade den föreslagna metoden antalet FE-simuleringar med 67 % jämfört med referensalgoritmen LHD-K-U.

Resultaten från denna forskning ger en praktisk förståelse för den stokastiska nedbrytningsprocessen för bärförmåga i båda fallstudierna. Detta omfattar nedbrytning till följd av förlust av förspänning för Kalixbron och utmattning för trågbron. Genom att

beakta den stokastiska processen över tid och lastens slumpmässiga variationer var det möjligt att beräkna den återstående livslängden både utan experimentella data och med uppdaterad information. För Kalixbron ökade tillförlitlighetsuppskattningarna med 201 % respektive 264 % beroende på testmetod, medan trågbron uppvisade en ökning på 172 %. Dessa resultat har direkta konsekvenser för underhåll och förvaltning av liknande konstruktioner och erbjuder värdefulla insikter för civilingenjörssområdet och strukturell tillförlitlighetsanalys.

**Nyckelord:** Befintliga broar, tillförlitlighet, återstående nyttjandetid, metamodel, finita element-modellering, fullskaliga tester.

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# List of Abbreviations

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<b>Abbreviation</b>	<b>Description</b>
AE	Acoustic Emission
AK	Adaptive Kriging
ANN	Artificial Neural Network
DFOS	Distributed Fiber Optic Sensor
DS	Directional Sampling
DT	Destructive Test
ED	Experimental Design
EFF	Expected Feasibility Function
EGO	Efficient Global Optimization
EOLE	Expansion Optimal Linear Estimation
EP	Experimental Points
FBG	Fiber Bragg-Gitter
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Modelling
FORM	First Order Reliability Method
FOS	Fiber Optic Sensor
GEV	General Extreme Value
HL	Hassofer-Lind
IG	Inverse Gaussian
IS	Importance Sampling
JCSS	Joint Committee of Structural Safety
K-L	Karhunen-Loève
LF	Learning Function
LHD	Latin Hypercube Design
LHS	Latin Hypercube Sampling
LSF	Limit State Function
LTU	Luleå University of Technology
LVDT	Linear Variable Differential Transformers
MCS	Monte Carlo Simulations
ML	Machine Learning
MPP	Most Probable Point
NDT	Non-destructive tests
NERS	Nested Extreme Response Surface
NLFEA	Nonlinear Finite Element Analysis

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PC	Prestressed Concrete
PCE	Polynomial Chaos Expansion
PDEM	Probability Density Evolution Method
PDF	Probability Density Function
P-M	Palmgren-Miner
RC	Reinforced Concrete
RS	Response Surface
RSL	Remaining Service Life
RSM	Response Surface Method
SDM	Stochastic Damage Mechanism
SHM	Structural Health Monitoring
S-N	Stress-range vs Number-of-cycles-to-Failure
SORM	Second Order Reliability Method
SRA	Structural Reliability Analysis
SRM	Spectral Representation Method
SRT	Structural Reliability Theory
SS	Subset Simulation
SVM	Support Vector Machin
TdR	Time-dependent Reliability
TRARS	Time-dependent Reliability with Response Surface

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## 1. Introduction

This chapter outlines the hypothesis, purpose, aim, objectives, and research questions of the thesis, and describes the scientific methodology adopted to address them. It also introduces the appended scientific publications, briefly discussing their contribution to the development and application of reliability analysis for assessing the remaining service life of existing bridges.

### 1.1 Purpose, Aim and Scope

#### **Purpose**

The primary purpose of this thesis is to contribute to a more reliable and realistic assessment of the remaining service life (RSL) of existing concrete bridges, addressing a critical need in infrastructure management as bridge population continues to age worldwide. Traditional evaluation methods, often based on deterministic or code-based approaches, provide limited insight into the true structural condition and degradation mechanisms that develop over time. This research seeks to bridge this gap by integrating probabilistic, numerical, and experimental approaches into a unified framework that reflects the actual behavior of deteriorating bridge structures and validates its applicability through representative case studies. By improving the accuracy of RSL estimations, this work supports safer, more cost-effective, and sustainable decision-making for the maintenance and operation of existing bridge assets.

#### **Aim**

The aim is to develop, apply and evaluate an integrated methodology combining monitoring, Finite Element (FE) modeling, and efficient time-dependent reliability analysis to estimate the real capacity and RSL of existing bridges, thus improving structural safety assessment and management strategies.

#### **Scope**

This research focuses on the application of the proposed methodology to two representative cases of existing bridge structures: a prestressed concrete (PC) roadway

bridge, analyzed with respect to long-term prestress losses, and a reinforced concrete (RC) trough railway bridge, evaluated under fatigue loading.

The first case, the PC bridge, was part of a big experimental campaign including on-site measurements of residual prestress, material testing, and proof loading. These experimental data were used to determine long-term prestress losses and to calibrate a linear elastic numerical model. The present study extends this work by integrating experimental results and numerical models with reliability analysis, incorporating degradation models such as the Gamma process, Bayesian updating, and metamodel-based reliability methods.

In the second case, a full-scale laboratory RC trough bridge was subjected to long-term cyclic loading and monitored for strains and displacements. An FE model was developed and calibrated against the experimental data to replicate and forecast fatigue damage. The analyses combined FE modelling with time-dependent reliability methods using degradation processes derived from S–N curves, along with metamodel-based reliability algorithms to achieve efficient and accurate estimation of failure probabilities.

The proposed framework is intended for the structural safety and serviceability assessment of existing bridges with available monitoring or testing data. Broader aspects of bridge management, such as life-cycle cost analysis, environmental impact evaluation, network-level reliability optimization, and maintenance planning, are beyond the scope of this work but are recognized as valuable directions for future research. The methodology and case studies presented herein are particularly relevant for ageing bridge infrastructure under normal operating conditions.

## **1.2 Hypothesis and Objectives**

### **Hypothesis**

The remaining life of existing bridges can be more accurately assessed by integrating full-scale experimental data, calibrated FE models, and time-dependent reliability analysis.

### **Objectives**

The objectives of the thesis are to:

- (i) Perform full-scale tests on representative bridge types, employing detailed instrumentation and monitoring systems to capture structural response, current condition and degradation processes.
- (ii) Calibrate FE models using monitoring and testing results to represent the current condition of the structure and integrate with time-dependent reliability analysis.

- (iii) Propose and implement an improved metamodel-based reliability algorithm to efficiently evaluate failure probabilities with reduced computational effort when using FE modelling.
- (iv) Develop a framework for estimating the real capacity and RSL of existing bridges incorporating monitoring and testing data, degradation mechanisms, FE models, and uncertainties.
- (v) Quantify the impact of data-informed reliability updating on RSL predictions and use the updated reliability to estimate maximum allowable load.

### **1.3 Research Questions**

The following research questions are addressed in this thesis:

- (i) How can existing reliability methods be enhanced to improve the efficiency of failure probability ( $P_f$ ) estimation when integrated with FE modeling, while avoiding added analytical complexity?
- (ii) To what extent can an integrated framework enhance the reliability and practical applicability of RSL assessments for existing bridges?
- (iii) What is the impact of destructive and non-destructive testing for residual prestress measurement on the evaluation of the RSL and reliability levels of PC bridges?
- (iv) What are the degradation and reliability levels of typical railway RC bridges after completion of their design fatigue cycles?

### **1.4 Scientific Approach**

A scientific approach was adopted to fulfill the research objectives of this thesis, which is illustrated in Figure 1. First, a literature review, presented in [Chapter 2](#), was conducted on time-dependent reliability analysis, metamodel-based reliability methods, and structural resistance degradation models. The objective of this review was to establish a solid foundation and ensure a clear understanding of the background and current state of research in these areas. The literature review on time-dependent structural reliability ([Section 2.2](#)) highlighted how this approach can be applied to determine the RSL of aging structures over a defined period, as well as the key aspects that must be considered in such assessments, including the resistance degradation models ([Section 2.3](#)). Additionally, it was identified in [Section 2.4](#) that metamodel-based methodologies have been demonstrated to be an excellent alternative to integrate FE modeling and reliability analysis. However, drawbacks from existing metamodel-based algorithms were also found, which can affect the efficient convergence of the algorithm.

Building on the findings from the literature, [Chapter 3](#) introduces the proposed framework, which integrates concepts from the reviewed scientific areas and outlines their main aspects and sequential steps. This methodology was first applied to a generic

case of a prestressed I-girder concrete bridge, presented in the first appended paper ([Paper I](#)), where redundancy, robustness and importance were employed as indicators of damage. This example revealed both the limitations of redundancy and robustness as damage indicators and provided insights into the efficiency of reliability methods.

Addressing the drawbacks identified in existing metamodel-based algorithms, the second appended paper ([Paper II](#)) presents the proposal for an improved metamodel-based reliability methodology, developed to enhance convergence and efficiency when FE modelling is used for capacity evaluation. Additionally, [Chapter 3](#) describes how this method is integrated into the proposed framework.

The framework was subsequently applied to two representative bridge types:

1. a prestressed concrete box-girder bridge and,
2. a reinforced concrete trough railway bridge.

The general details of the applications are presented in [Chapter 4](#), meanwhile the main analyses and findings are presented in appended [Papers III–V](#).

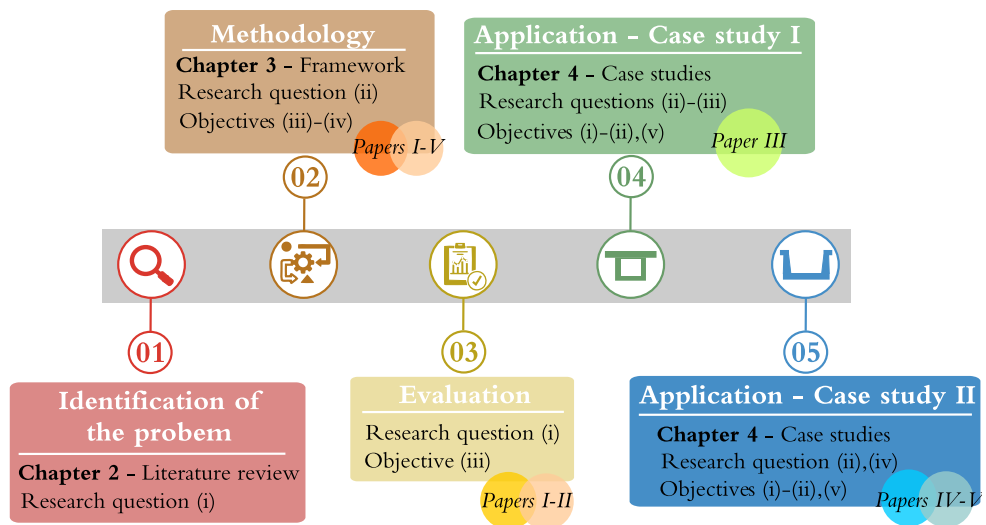


Figure 1. Scientific approach.

## 1.5 Limitations

This section describes the main limitations of this research. The literature review focused exclusively on articles published in peer-reviewed journals indexed in major international databases such as Scopus, Web of Science, and Google Scholar. Consequently, relevant publications outside these sources may have been unintentionally overlooked. In addition, given the large variety of metamodel-based reliability methods available, it was

not feasible to test and compare all alternatives. Instead, the methods selected for this work were based on previous reviews (e.g., Teixeira et al., 2021b) and recent studies (Xiong and Sampath, 2021; Yu Zhang et al., 2023) that demonstrated high accuracy and efficiency.

From a methodological point of view, the time-dependent reliability analyses relied on specific degradation models, such as the Gamma process and bi-linear S–N curves. While these models are widely accepted, alternative formulations could lead to different results. Furthermore, the calibration of the FE models was based on experimental datasets of strains and displacements obtained under controlled conditions, which may not fully capture the variability of real service environments. The proposed methodology demonstrates strong potential where detailed structural monitoring data are available; however, its generalizability to structures without such data remains limited.

Practical limitations were also encountered during the experimental campaigns. These included restrictions related to the available laboratory infrastructure and data acquisition systems, time constraints caused by delays in delivery of equipment and materials, and scheduling conflicts such as the demolition timeline of one of the studies.

Finally, the scope of this thesis was deliberately restricted to structural safety expressed in terms of failure probability. Broader aspects that are critical for comprehensive bridge management, including life-cycle costs, environmental impacts, and maintenance optimization strategies, were not considered within this research.

## **1.6 Outline of the Thesis**

This is a compilation thesis, composed of an extended summary followed by appended research papers. This summary consists of six chapters, briefly described as follows:

**Chapter 1 – Introduction** provides the background and motivation for the research, outlines the objectives and research questions, and presents the scientific approach adopted to address them. The chapter also highlights the limitations of the study and introduces the structure of the thesis, including the appended papers.

**Chapter 2 – Literature review** summarizes the state of the art in the key research areas addressed in this thesis: time-dependent reliability analysis, metamodel-based reliability methods, and resistance degradation models. The review identifies existing challenges and research gaps, which form the foundation for methodological development.

**Chapter 3 – Framework for RSL of existing bridges** presents the integrated framework developed in this thesis, detailing the main research components, methodological steps, and how different scientific areas are combined. The framework

provides the basis for applying time-dependent reliability methods, metamodel-based approaches, and FE model calibration to real bridge problems.

**Chapter 4 – Application of the framework for RSL evaluation of existing bridges** demonstrate the application of the proposed methodology to representative bridge types, including prestressed concrete and reinforced concrete bridges. The chapter describes the data used, the calibration of finite element models, the reliability analyses performed, and the main findings from each case study.

**Chapter 5 – Conclusions** summarize the main contributions of the research, providing answers to the research questions and reflecting on the validity of the initial hypotheses.

**Chapter 6 – Future research** proposes how this research can be continued based on its conclusions and limitations.

## 1.7 Appended Papers

The core of this thesis consists of five papers: Four published journal papers, and one submitted journal paper. The appended papers are briefly presented in this session, including my contribution to each of them.

### **PAPER I**

**Sarmiento, S.**, Thöns, S., Björnsson, I., González-Libreros, J. & Sas G. (2024). Comparison and joint evaluation of importance, redundancy and robustness indicators applied to aging prestressed concrete bridges. *Nordic Concrete Research* 70(1), 147-171. <https://doi.org/10.2478/ncr-2024-0008>

This paper contains a comprehensive comparison between relevant importance, redundancy, and robustness indicators found in literature with different levels of complexity. The indicators under analysis have been used separately in various studies; however, they have never been addressed together. Therefore, this study presents a joint evaluation of deterministic, reliability- and risk-based indicators to evaluate the differences in interpretation and information provided by the indicators. The approach is exemplified by analyzing a prestressed concrete bridge subjected to continuous degradation due to chloride ingress.

My contribution includes the development of the methodology, development of FE model, computation of structural indicators, interpretation of the results, and preparation of the manuscript.

**PAPER II**

**Sarmiento, S.**, O'Connor, A., González-Libreros, J. & Sas, G. (2025). An Improved Metamodel-Based Algorithm Using Copula Theory for Assessing Reliability Analysis of Structures using FEM. *Structural Engineering International (SEI)*, 1–14. <https://doi.org/10.1080/10168664.2025.2517059>

This paper presents a new metamodel-based methodology to assess structural reliability. The method is aimed at problems in which FEM is implemented, and a low computational cost is desired. The methodology integrates learning functions, copula concepts, and kriging regression. Analytical functions are used to validate the methodology, which is finally applied to a reinforced trough bridge case study.

My contribution includes programming, development, exemplification and validation of the algorithm, FE modeling, interpretation of the results and preparation of manuscript.

**PAPER III**

**Sarmiento, S.**, Agredo, A., Thiery, F., González-Libreros, J., Wang, C. & Sas, G. (2025). Time-dependent reliability of a prestressed concrete bridge incorporating residual prestress and material properties updates for SLS assessment. *Structure and Infrastructure Engineering*. <https://doi.org/10.1080/15732479.2025.2571887>

This paper presents a time-dependent reliability assessment of a 66-year-old prestressed concrete box-girder bridge by integrating experimental data with Bayesian updates. Non-destructive and destructive tests provided refined estimates of material properties and residual prestress. Results showed that updating these parameters significantly increased the reliability index, demonstrating the value of on-site measurements in improving serviceability assessments of aging bridges.

My contribution includes the development of the time-dependent reliability methodology, the execution of the reliability analyses, the interpretation of the results, and the preparation of the manuscript.

**PAPER IV**

**Sarmiento, S.**, González-Libreros, J., Wang, C., Elfgrén, L., Enoksson, O., Højsten, T., Andersson, L-O. & Sas, G. (2025). Experimental and reliability analyses for fatigue induced damage in reinforced concrete through bridges. *Case studies in Construction Materials* 322, 126480. <https://doi.org/10.1016/j.conbuildmat.2022.126480>

This study experimentally investigates the fatigue behavior of a full-scale reinforced concrete trough bridge, representative of structures on Sweden's Iron Ore Line,

tested under laboratory conditions. Progressive cyclic loading was applied to evaluate stiffness loss, as well as the evolution of strains and displacements, while fatigue checks and reliability analyses were performed according to Eurocode and *fib* Model Code 2020. After 10 million cycles, equivalent to 48 years of service, the bridge maintained functional capacity, though code-based reliability checks suggested conservative reinforcement safety margins.

My contribution includes the planning and execution of the instrumentation and experimental campaign, code verification and reliability analyses, interpretation of the results, and preparation of the manuscript.

### **PAPER V**

**Sarmiento S.**, González-Libreros, J., Wang, C., Elfgren, L., Enoksson, O., Højsten, T., Andersson, L-O. & Sas, G. (2025). Multi-level fatigue reliability assessment of reinforced concrete railway bridges. *Structural Concrete*. [submitted]

This paper presents a multi-level reliability framework for evaluating fatigue life and allowable axle loads of reinforced concrete trough bridges under cyclic loading. By integrating probabilistic S–N curves, monitoring data, nonlinear FE modeling, and survival information, the framework enhances prediction accuracy. Its application to a full-scale bridge highlights its effectiveness for assessing remaining service life and load capacity.

My contribution includes the development of the methodology, FE model calibration, execution of the reliability analyses, interpretation of the results, and preparation of the manuscript.

## **1.8 Additional Publications**

Apart from the research papers appended to this thesis, a Licentiate thesis and conference papers have been published by the author as well. These publications are listed in this section but not appended to this thesis.

### **Licentiate Thesis**

**Sarmiento, S.** (2023). Redundancy and Robustness Quantification of Bridge Systems based on Reliability and Risk Approaches (Licentiate dissertation). Luleå University of Technology. Retrieved from: <https://urn.kb.se/resolve?urn=urn:nbn:se:ltu:diva-96316>

## Conference Papers

### **ESREL Conference, Angers 2021**

**Sarmiento S**, Gustafsson J, Åkergren D, González-Libreros J, Sas G & Elfgren L. (2021). Pressure Distribution Patterns Between the Ballast and the Concrete Slab in Railway Trough Bridges. *31st European Safety and Reliability Conference (ESREL 2021)*. Angers, France, pp. 1093–1100.

This paper presents an overview of various models used to assess stress patterns on ballasted concrete bridge slabs. Subsequently, a simplified finite element model of a concrete trough bridge is employed in a parametric analysis to investigate how the pressure distribution patterns, as identified earlier, impact the structural performance of such bridges. Lastly, a probabilistic reliability analysis is conducted to study the effect of specific parameters on bridge safety. The reliability index is calculated through the polynomial response surface method, and the obtained values are compared across various boundary condition scenarios.

### **EUROSTRUCT Conference, Padova 2021**

**Sarmiento S**, González-Libreros J, Sas G, Elfgren L, Coric I & Enoksson O. (2021). Metamodel-based Reliability Assessment of Reinforced Concrete Beams Under Fatigue Loads. *1st European Conference of the European Association on Quality Control of Bridges and Structures (EUROSTRUCT 2021)*. Padova, Italy.

This paper investigates how uncertainties in fatigue models for reinforced concrete structures influence reliability and identifies critical parameters in fatigue damage. A metamodel-based method is applied to calculate failure probability and reliability index values in a case study. By coupling reliability analysis with nonlinear finite element simulations, the approach significantly reduces computational cost while maintaining high accuracy, offering an efficient alternative to traditional simulation methods.

### **IABSE Conference, Ghent 2021**

**Sarmiento SJ**, Gonzalez-Libreros J, Sas G, Sanabria Díaz RA, Texeira da Silva MC & Trautwein LM. (2021). Response Surface Method strategies coupled with NLFEA for structural reliability analysis of prestressed bridges. *IABSE Congress 2021: Structural Engineering for Future Societal Needs*. Ghent, Belgium, pp. 1813–1822.

This paper aims to evaluate different methods for enhancing the conventional Response Surface Method (RSM) without compromising its precision. Initially, each method is applied to assess the safety of an explicit limit state function, known for its high nonlinearity. Based on the outcomes obtained, the most effective strategy is

chosen and subsequently implemented to conduct a prestressed concrete bridge reliability analysis. The analysis considers the nonlinear behavior of materials via NLFEA simulation. The resulting value of  $\beta$  is then compared against the ULS target value prescribed in Eurocode.

#### **IABSE Conference, Prague 2022**

**Sarmiento, S.**, Åkergren D, Gustafsson J, Gonzalez J, Sas G, Elfgrén L, Coric I, & Enoksson O. (2022). A Parametric Study of an old Concrete Trough Bridge using non-linear Finite Element analysis. *IABSE Symposium Prague 2022: Challenges for Existing and Oncoming Structures*. Prague, Czech Republic, pp. 1652–1659.

This paper examines the Bridge and Tunnel Management database (BaTMan) of railway infrastructure in Sweden to gain insights into the present condition of Swedish railway bridges, particularly trough bridges. Subsequently, a non-linear finite element model is calibrated utilizing the experimental findings from a former test conducted on a decommissioned trough bridge. The calibrated model is then applied in a parametric study to evaluate the impact of significant mechanical parameters on the capacity of trough bridges.

#### **IABMAS Conference, Barcelona 2022**

**Sarmiento S**, Gonzalez-Libreros JH, Sas G, Thöns S, Björnsson I, & Díaz RS. (2022). A risk-based robustness evaluation of a prestressed concrete bridge. *IABMAS 2022, Bridge Safety, Maintenance, Management, Lifecycle, Resilience and Sustainability*. Barcelona, Spain, pp. 2045–2052.

This paper proposes a preliminary framework for evaluating the robustness of concrete bridges. The framework comprises a metamodel-based reliability analysis and risk concepts to assess the level of robustness of concrete bridges by factoring in failure probabilities and consequences. A case study of a prestressed multi-beam concrete bridge is conducted to validate and illustrate the methodology. The capacity of each element and the intact and damaged structural system is determined using finite element modeling (FEM).

#### **Fib symposium, Istanbul 2023**

**Sarmiento S**, González-Libreros J, Elfgrén L, Andersson E, Petersson & Sas G. (2023). Validation of an experimental methodology for measuring concrete fracture energy in existing structures. *fib Symposium Istanbul 2023*. Istanbul, Turkey.

This paper validates an experimental methodology to estimate the fracture energy of existing concrete structures, addressing uncertainties in finite element capacity predictions. Tensile tests on notched specimens and cores were compared with

three-point bending tests and FEM results, showing the method's potential and highlighting the influence of notch depth on fracture energy values.

#### **IALCCE Conference, Milan 2023**

**Sarmiento S**, González-Libreros J, Sas G, Björnsson I & Thöns S. (2023). Validation of an experimental methodology for measuring concrete fracture energy in existing structures. *Fib Symposium Istanbul 2023*. Istanbul, Turkey.

This paper proposes a novel framework linking reliability- and risk-based robustness, redundancy, and importance indicators for bridge safety assessment. Applied to a prestressed concrete bridge under overloading and chloride attack scenarios, the approach highlights interrelations among performance indicators, supporting more comprehensive risk and robustness analyses for critical infrastructure.

#### **IABMAS Conference, Copenhagen 2024**

**Sarmiento S**, González-Libreros J, Sas G, Enoksson O & Højsten T. (2024). Experimental determination of trough bridges pressure distribution. *IABMAS 2022, Bridge Safety, Maintenance, Management, Lifecycle, Resilience and Sustainability*. Copenhagen, Denmark.

This paper investigates load distribution in a full-scale reinforced concrete trough bridge on Sweden's Iron Ore Line through laboratory tests using load cells on slab and beam surfaces. Results from static and cyclic loading highlight how traffic loads are shared among sleepers and distributed longitudinally and transversally, providing key insights for assessing axle load effects on aging trough bridges.



## 2. Literature review

### 2.1 Background

Ensuring the safety of bridge infrastructure has consistently been a priority for society, owing to the substantial economic and social repercussions of structural failures. In practice, this translates into two pressing challenges that bridge engineers must address in the evaluation of existing infrastructure: 1. guaranteeing public safety under uncertainty, and 2. ensuring the economic sustainability of maintenance strategies for aging infrastructure.

The importance of addressing these challenges is underscored by several notable bridge failures, where inadequate assessment or deterioration led to catastrophic consequences. Well-known cases such as the collapse the Silver Bridge in Point Pleasant in 1967 (Lichtenstein, 1993), the Polcevera (Morandi) bridge in Italy (Galik and Calvi, 2024), the Carola Bridge in Germany (Marx, 2024), as well as other recent failures of road bridges in Italy (Bazzucchi et al., 2018), demonstrated the consequences of insufficient monitoring, long-term deterioration, and inadequate safety assessment.

Beyond the immediate concern for public safety, a second major challenge relates to the economic sustainability of maintenance and rehabilitation strategies. As bridges age and deteriorate, they impose substantial financial demands on owners and operators, particularly across large infrastructure networks (Biondini and Frangopol, 2016). Inefficient approaches often lead to unnecessary expenditure of resources or premature replacement of infrastructure. In Europe, structural assets represent nearly 50% of national wealth, and approximately half of all construction expenditure is already devoted to repair, maintenance, and remediation (Long et al., 2001; Plos et al., 2016). Additionally, Europe's bridge network is extensive, comprising about one million bridges with a combined replacement cost exceeding 400 billion euros (Sýkora et al., 2013). Similar concerns can be encountered worldwide, with a growing share of the bridge stock reaching or surpassing its design service life.

Over the years, researchers have developed a variety of approaches and frameworks aimed at establishing robust methodologies to address the challenges outlined above. These

approaches include both deterministic and probabilistic methods, with the latter generally being more suitable when evaluating structural safety (Šomodíková et al., 2016; Wang, 2021a; Yaotian Zhang et al., 2023). Probabilistic methods explicitly account for uncertainties and a range of possible scenarios, rather than relying on a single deterministic outcome (Wang et al., 2021; Yaotian Zhang et al., 2023). Within this context, time-dependent reliability methods have proven particularly valuable, as they incorporate the evolution of resistance and/or loading over time (Ang and Tang, 2007). This enables not only the evaluation of current safety levels but also the projection of future performance and the estimation of the RSL of structures (Wang et al., 2021; Alam et al., 2022).

Despite their advantages, the accuracy of probabilistic-based reliability analysis strongly depends on the quality of assumptions regarding key parameters and their probability distributions (Chen and Omenzetter, 2013). If these assumptions are poorly defined, reliability estimates can deviate significantly from reality, especially in cases where inspection and monitoring data are scarce (Chen and Omenzetter, 2013; Alam et al., 2022). To mitigate this risk, structural health monitoring (SHM), together with destructive (DT) and non-destructive testing (NDT) methods, has become increasingly important for obtaining timely and continuous information to support damage assessment (Sanayei et al., 2015). SHM has thus become a key tool for assessing aging infrastructure, enabling the early detection of structural problems and helping to ensure public safety (Casas and Cruz, 2003). Today, a wide range of SHM strategies and sensing technologies are available, including Fiber Optic Sensors (FOS), wireless sensor technology, weight-in-motion systems, Acoustic Emission (AE) systems, among others, offering detailed measurements that enhance the reliability of assessments.

However, the growing availability of rich monitoring data introduces the challenge of effectively incorporating this information into reliability analyses. To address this, Bayesian updating frameworks have been proposed as a powerful tool to integrate monitoring and test data with reliability analyses (Keßler et al., 2014; Chen et al., 2025), by consistently combining prior knowledge with new evidence to reduce uncertainties (Chen and Omenzetter, 2013; Chen et al., 2025). Yet, most applications remain confined to academic case studies or numerical examples, typically involving simplified geometries, idealized material models, or controlled laboratory conditions (Tonelli et al., 2023). This shows a need for extending such methods to complex, real-world structures.

In addition to monitoring, numerical modeling serves as a tool for predicting future structural performance. As an example, FE modeling allows for detailed simulation of structural responses under varying load magnitudes and progressive degradation scenarios (Cervenka, 2013) and together with nonlinear FE analysis (NLFEA) a more realistic estimation of the structural response is obtained (Matos et al., 2016; Plos et al., 2016). When calibrated with SHM data, FE models can be employed to project the long-term

behavior of bridges and estimate their RSL. This integration of monitoring and modeling therefore strengthens the basis for probabilistic reliability analysis, ensuring that assessments are both data-informed and representative of realistic structural behavior.

Nevertheless, the integration of detailed FE modeling into probabilistic reliability analyses is frequently constrained by the significant computational demands. Considering uncertainties requires the evaluation of a large number of scenarios and repeated simulations, which quickly becomes computationally unfeasible (Zhou and Li, 2023). Recognizing this challenge, numerous studies have aimed to develop more efficient methodologies without compromising the quality of results (e.g., Au and Beck, 1999; Bichon et al., 2008; Echard et al., 2011; Gong and Frangopol, 2019; Guimarães et al., 2018; Teixeira et al., 2021a). In this regard, surrogate or metamodel-based reliability methods have been increasingly developed and proven to reduce computational cost while maintaining accuracy. However, many metamodel-based methods remain validated primarily on simplified or academic examples, with limited application to full-scale bridges and realistic monitoring data (Neves et al., 2006). This creates a gap between theoretical advances and practical decision-making in bridge management.

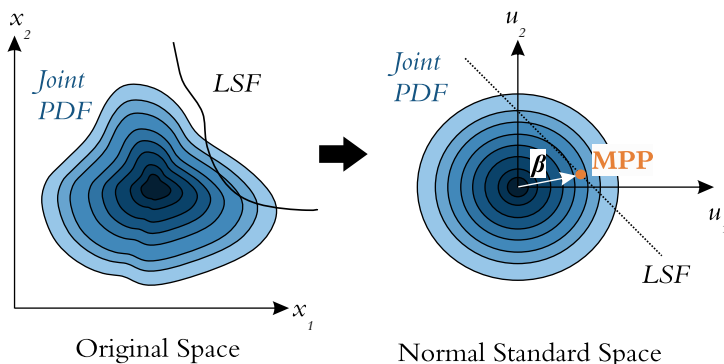
Building on the aspects discussed above, this thesis develops a comprehensive framework to enhance the assessment of RSL, and allowable axle loads by integrating reliability-based approaches with SHM data and FE modeling. Furthermore, an improved metamodel-based methodology for failure probability estimation is proposed and validated, offering more efficient yet reliable results. The proposed framework is first demonstrated on a generic prestressed concrete I-girder bridge, with a focus on resistance deterioration due to corrosion. In this initial study, redundancy, robustness, and importance indicators are employed as measures of damage. The framework is then adapted and applied to two representative and significant bridge types in Sweden: (1) a PC box-girder road bridge and (2) a RC trough railway bridge. In the first case, resistance degradation is modeled through prestressing losses, and Bayesian updating is employed to incorporate site-specific monitoring data. In the second case, monitoring is integrated through an accelerated laboratory fatigue test, where multiple sensors were installed to track the structural response from an undamaged state up to the design number of cycles representative of the Iron Ore Line in Northern Sweden. Nonlinear FE analysis is employed to predict further damage and assess structural capacity, thereby enabling the estimation of both the RSL and the allowable axle load.

## 2.2 Time-dependent reliability

### Fundamentals

In structural engineering, safety primarily concerns preventing structures from causing harm or danger to people (Pugsley, 1951). To achieve acceptable safety standards while accounting for risks and uncertainties, Structural Reliability Theory (SRT) was developed. The core of SRT lies in applying statistical methods and probability theory to establish a formal mathematical framework for structural safety. Therefore, from a SRT perspective, the reliability of a structure can be expressed as the “probability of a system or component to perform its intended functions under specified operating conditions for a specified period of time” (Rackwitz, 2001).

Mayer (1926), Wierzbicki (1936) and Streletskii (1947) are recognized as the pioneers in formulating the mathematical problem of structural safety (Nowak and Collins, 2000). They were the first to acknowledge that load and resistance factors are stochastic variables, and consequently each structure has a finite probability of failure. This idea was later expanded by Freudenthal (1956) during the 1950s. However, it was not until the development of Cornell and Lind's work in the late 1960s and early 1970s that practical applications of reliability analysis were feasible. Cornell (1969) proposed a second moment reliability index and later Hasofer and Lind (1974) introduced a new index denominated the Hasofer-Lind (HL) reliability index. The HL index, known as  $\beta$ , can be defined as the smallest distance from the origin of the standard normal space to the Most Probable Point (MPP), i.e., the point on the failure surface with highest probability (Figure 2).



**Figure 2.** Representation of classical reliability analysis and illustration of reliability index and MPP.

Conceptually, the structural resistance and load effect, denoted by  $R$  and  $S$ , respectively, depend on many parameters such as geometry, material properties, among others. Letting  $X = \{x_1, x_2, \dots, x_n\}$  be a vector of these random parameters,  $R$  and  $S$  would be functions of  $X$ . In classical STR,  $R$  and  $S$  are time-invariant, where the structural reliability,  $L$ , is

defined as the probability that  $S$  does not exceed  $R$  (Equation 1). The corresponding probability of failure,  $P_f$ , is given by Equation 2.

$$L = P[R > S] = \int_{Z(X) > 0} f_X(x) dx \quad 1$$

$$P_f = 1 - L = P[R \leq S] = \int_{Z(X) \leq 0} f_X(x) dx \quad 2$$

where  $P[\cdot]$  is the probability of the event in brackets,  $f_X(x)$  is the joint probability density function (PDF) of the random variables  $X$ , and  $Z(X)$  is the limit-state function (LSF) which is given by Equation 3:

$$Z(X) = R - S \quad 3$$

The LSF defines the structural safety condition, where  $Z(X) = 0$  represents the boundary between safe and failure domains;  $Z(X) > 0$  indicates safety, while  $Z(X) < 0$  corresponds to failure.

In contrast with classical SRT, time-dependent reliability (TdR) considers the resistance degradation and/or the changes and fluctuations of the demand through time for a more accurate reliability assessment. Thus, in this approach  $R$  and  $S$  become dependent on time  $t$ ,  $R(t)$  and  $S(t)$ . Figure 3a illustrates conceptually the time-invariant reliability problem (classical reliability) meanwhile Figure 3b-f presents the different scenarios in a TdR approach.

Figure 3b shows the situation where resistance is modeled as a non-stationary process to reflect degradation, while the load or demand is assumed stationary. Figure 3c, 3e, and 3f represent cases where resistance and demand are modeled as stochastic processes: with monotonically increasing loading (Figure 3c), a random continuous process (Figure 3e) and a random discrete process (Figure 3f). Finally, Figure 3d illustrates the case where the demand is a nonstationary process representing progressive degradation, while resistance is defined as an allowable damage threshold.

For TdR problems the limit state function is re-formulated as:

$$Z(X, t) = R(t) - S(t) \quad 4$$

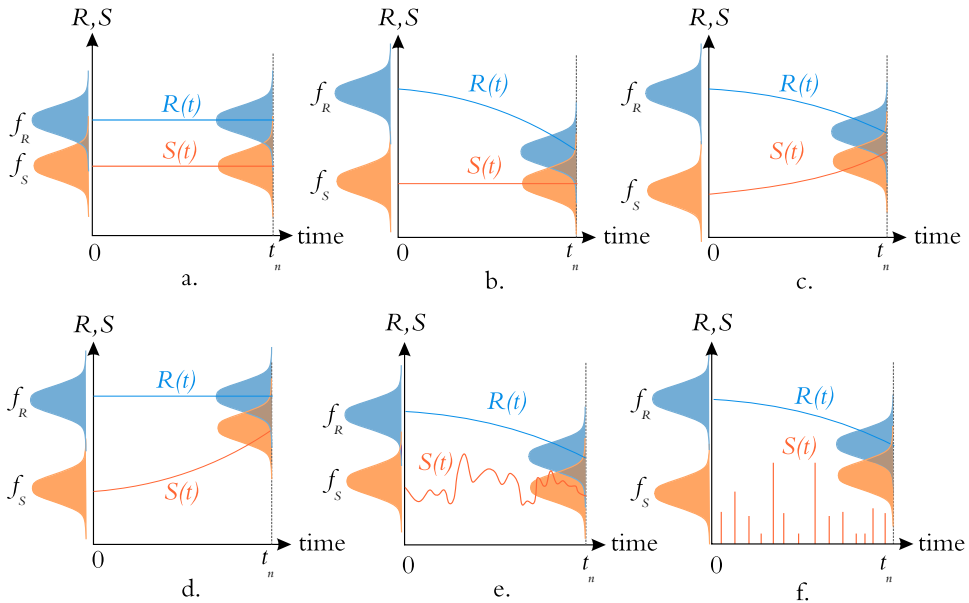
Under the assumption that  $R(t)$  and  $S(t)$  are statistically independent, the instantaneous probability of failure  $P_f(t)$  is given in Equation 5:

$$P_f(t) = P[R(t) \leq S(t)] = \int_0^{\infty} F_R(s, t) f_S(s, t) ds \quad 5$$

where  $F_R(\cdot, t)$  is the cumulative density function (CDF) of  $R(t)$  and  $f_S(\cdot, t)$  is the PDF of  $S(t)$ .

However, in the evaluation of the RSL of a structure, it is more important to look at the failure probability in the entire period  $[0, T]$  than only the instantaneous reliability at  $t$ , then the  $P_f(t)$  is given by:

$$P_f(0, T) = P\{\exists t \in [0, T]: R(t) \leq S(t)\} \quad 6$$



**Figure 3.** Illustration of reliability problems for a. time-independent and time-dependent with b. non-stationary monotonic resistance and stationary load c. non-stationary monotonic resistance and load d. stationary resistance and non-stationary monotonic load e. non-stationary monotonic load and non-stationary continuous load and f. non-stationary monotonic resistance and non-stationary discrete load.

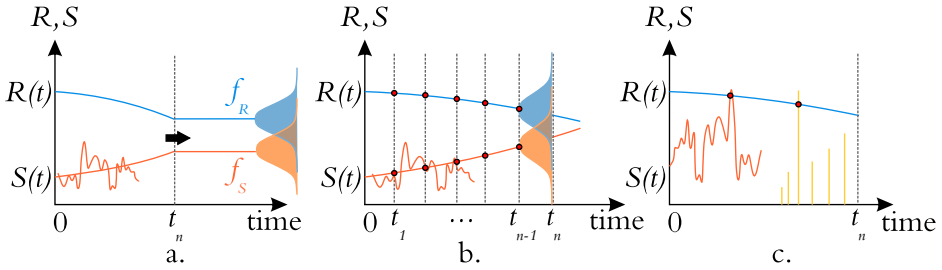
## Methods

TdR methods to solve Equation 6 can be classified as time-integrated (Wen and Chen, 1987), time-discretization (Melchers, 1999) and first-passage (Vanmarcke, 1975) approaches. Each approach addresses the problem differently, as conceptually illustrated in Figure 4. Together, these approaches form the foundation of TdR theory, offering trade-offs between accuracy, computational efficiency, and applicability to different types of load and resistance processes.

Within the time-integrated category (Figure 4a), a widely used simplification is to reformulate the problem in terms of the extreme value of the load process. When resistance decreases monotonically over time and loads are stationary or monotonically

increasing (Figure 3b–c), or when demand grows with degradation while resistance is treated as a stationary threshold (Figure 3d), the reliability problem can be expressed using the maximum load effect,  $S_{max} = \max(S(t))$ . In this way, TdR reduces to an equivalent time-invariant problem, where classical SRT methods can be applied. This formulation is particularly practical when combined with FE modeling, as it facilitates integration with metamodel-based reliability methods and has been demonstrated effective for bridges in past studies (Carneiro et al., 2023; Fan et al., 2023; Kim and Song, 2021; Mankar et al., 2019). However, it is unsuitable for random load processes, where outcrossing may occur only at specific load events, requiring explicit modeling of event sequences (Wang et al., 2019b). The value of  $P_f$  in this approach can be calculated as:

$$P_f(t_n) = P[R - S_{max} \leq 0] = \int_{-\infty}^{\infty} F_R(x) f_{S_{max}}(x) dx \quad 7$$



**Figure 4.** Methods for Time-dependent reliability a). time-integrated b). time-discretization and c). first-passage approaches. adapted from Petryna and Krätzig (2005)

The time-discretization approach (Figure 4b) is similar to the time-integrated method. This approach, as the name suggests, divides the reference period into a sequence of discrete time intervals and evaluates the instantaneous reliability at each interval, treating the overall problem as a system reliability analysis of correlated events. This formulation has been adopted in recent works (e.g., Liu and Frangopol, 2005; Gong and Frangopol, 2019; Zhao et al., 2024), as it transforms the TdR problem into a well-established system of time-invariant reliability problem. Nevertheless, when many time steps are required, the approach can become computationally intensive and may lead to conservative estimates if temporal correlations are not properly captured. The value of  $P_f$  in this approach can be calculated as:

$$P_f(t_n) = \int_0^{\infty} [1 - P(S_1 < x) \cdot P(S_2 < x), \dots, P(S_{N_t} < x)] f_R(x) dx \quad 8$$

In contrast, first-passage approaches (Figure 4c) directly model the probability of the load process crossing the resistance threshold for the first time, providing a rigorous

representation of failure occurrence but requiring more complex stochastic process modeling. First-passage approaches can be broadly divided into analytical and simulation-based approaches, with hybrid formulations aiming to improve computational efficiency. Analytical methods include outcrossing-based approaches (e.g., Rice's formula) and parallel system models, each providing closed-form or approximate solutions under specific assumptions. Simulation-based methods, on the other hand, are built on Monte Carlo simulation (MCS) and its advanced variants, which are more flexible but computationally demanding.

Rice formula-based methods are among the classical foundations of TdR. They evaluate the rate at which a stochastic process  $X(t)$  crosses a safety boundary, expressed as up-crossing rates (for threshold limits) or outcrossing rates (for enclosed safe domains). Originally derived by Rice (1945), where methods have been developed for only for Gaussian process both stationary (e.g., Lindgren, 1980) and non-stationary (e.g., Li and Melchers, 1993). More recently, Li et al. (2016) developed the first analytical solution applicable to non-stationary and non-Gaussian processes, which is the still the only analytical solution to Rice's formula beyond Gaussian assumptions.

Parallel system model-based methods extend the concept of up-crossing estimation through system reliability formulations. A representative example is the PHI2+ method introduced by Sudret (2008), which uses FORM/SORM to approximate up-crossing probabilities, building on earlier work by Andrieu-Renaud et al. (2004). Later refinements, such as the PHI2 method combined with moment-based transformations Zhang et al. (2021), improved efficiency but remain sensitive to strong non-stationarity or non-Gaussian behavior, highlighting the limitations of FORM/SORM in accurately determining design points under complex stochastic conditions.

Simulation-based methods have emerged as the most widely applied in practice, especially for complex bridge systems and correlated multivariate processes. MCS forms the basis, with enhanced techniques such as the Expansion Optimal Linear Estimation (EOLE) (Li and Der Kiureghian, 1993), Spectral Representation Method (SRM) (Grigoriu, 1984), and Karhunen-Loève (K-L) expansion (Huang et al., 2001) developed to improve efficiency in simulating stochastic processes. Despite their flexibility, simulation-based methods remain computationally demanding, particularly when modeling nonstationary and non-Gaussian processes, motivating the growing reliance on surrogate modeling and variance reduction techniques.

In addition to the approaches discussed above, a widely used class of methods is the extreme value-based approach. Unlike time-integrated formulations that operate on the maximum or minimum values of the load and resistance processes, the extreme value approach directly characterizes the distribution of the maximum (or minimum) response itself, i.e.,  $Z(x,t)$ . The main challenge lies in characterizing the probability distribution of

the extreme value, which is generally nonlinear and computationally demanding. Several approaches have been developed to address this. Early efforts relied on surrogate modeling and optimization techniques, such as the Efficient Global Optimization (EGO) method (Jones et al., 1998) and its extensions (Hu and Du, 2015, 2013), which coupled adaptive kriging with Monte Carlo simulation. Other methods, including the nested extreme response surface (NERS) method (Wang and Wang, 2013) and its improvements (Wang and Chen, 2016), introduced surrogate models to approximate extreme responses, though efficiency remained sensitive to time discretization. Alternative formulations, such as the probability density evolution method (Li et al., 2007), sought to estimate the extreme value distribution through auxiliary stochastic processes, though their applicability was limited to cases with explicitly known process evolution. More recent studies (e.g., Ping et al., 2019) have explored series of expansion approaches, but these remain restricted to Gaussian processes. The value of  $P_f$  in this approach can be calculated as:

$$P_f(t_n) = P[G_{Ex}(t_n) \leq 0] \quad 9$$

where  $G_{EX}$  is the extreme response of the LSF defined by:

$$G_{Ex}(t_n) = \min_{t \in [0, t_n]} Z(X, t) \quad 10$$

When resistance and load processes can be expressed with simplified models, closed-form hazard function methods provide explicit solutions for TdR. The hazard function,  $h(t)$ , represents the probability of failure at time  $t$  conditional on survival up to  $t$ , offering semi-analytical efficiency. These methods are particularly appealing when Gaussian or simplified assumptions hold, though accuracy diminishes for strongly nonlinear or non-Gaussian processes. Different formulations of  $h(t)$  can be found in Wang (2021b).

Recent research continues to refine TdR methods to improve realism and efficiency. For instance, Zhang et al. (2017) introduced a TdR analysis with response surface (TRARS), combining surrogate modeling, iterative sampling, and FORM to efficiently estimate reliability indices. Gong and Frangopol (2019) reformulated TdR as a large-scale series system, avoiding outcrossing computations and achieving high efficiency through advanced integration schemes. Wang (2021a) developed explicit solutions for aging structures by modeling loads as a Markov process and resistance deterioration via a gamma process, capturing correlations between load and degradation. More recently, Zhan et al. (2024) and Zhao et al. (2024) developed surrogate-based approaches combining kriging with parallel or importance sampling, respectively.

Comprehensive reviews of TdR methods and their applications are provided in (Wang et al., 2021; Zhang et al., 2024), and their details and examples can be found in Li and

Yang (2022). Table 1 presents a comparison among the discussed TdR methods, highlighting their key idea, main advantages and their limitations.

**Table 1.** Comparison of TdR methods.

<b>Method</b>	<b>Key idea</b>	<b>Main advantages</b>	<b>Limitations</b>
Time-integration	Use of extreme values (e.g., $S_{max}$ , $R_{min}$ ) when processes are stationary or monotonic, reducing the TdR problem to a time-invariant case	Simple and computationally efficient	Inaccurate for random non-monotonic or strongly correlated loads and cannot capture event-based outcrossing.
Time-discretization	Discretize time into intervals and evaluate failure at each step, treating overall TdR as a series-system reliability problem.	Handles correlation and nonstationary processes; widely applicable	Can be conservative and computationally expensive
First-passage	Modeling the stochastic process to determine the probability of first up-crossing of the limit state	Rigorous, physically realistic and directly aligned with true TdR definition	Requires complex stochastic process modeling; limited analytical solutions
Simulation-based	Use Monte Carlo or advanced sampling methods to simulate full load-resistance histories and evaluate failure.	Flexible, suitable for arbitrary processes and real data	Very computational expensive, especially for low failure probabilities
Extreme value-based	Use extreme value theory to model the distribution of the maximum/minimum of the response $Z(t)$ over a time interval.	Handles nonstationary or highly variable loads effectively	Requires accurate modeling of extreme response and needs large datasets

As research progressed, it was recognized that early approaches often oversimplified real-world conditions by treating deterioration as fully correlated and loads as stationary. To

address this, Li et al. (2015) introduced a methodology incorporating non-stationary load processes to account for increasing traffic intensity and frequency over time, though their model still assumed fully correlated deterioration. Extending this direction, Yuan et al. (2019) developed a procedure for existing concrete bridges that combined non-stationary traffic loads modeled by Generalized Extreme Value (GEV) distributions with resistance deterioration represented by a Gamma process, offering a more realistic prediction of reliability evolution. Similarly, Wang et al. (2015, 2017) highlighted the importance of autocorrelation in resistance degradation, while Wang and Zhang (2018) demonstrated the significant influence of temporal correlation in load processes. Together, these studies contributed to the advancement of TdR towards more realistic bridge reliability estimation.

At the same time, deterioration mechanisms became a focus of investigation. For instance, Zhu and Frangopol (2016) introduced a cumulative-time failure probability approach to capture the full history of load and degradation. Zhu et al. (2017) developed probabilistic models of chloride-induced corrosion in RC bridge columns to evaluate residual capacity and rehabilitation effects. More recently, Yang et al. (2022) introduced a spatio-temporal modeling framework for resistance degradation, while Das and Sil (2022) applied a modified TdR model to RC bridges, combining time-variant and time-invariant loads to identify critical periods of resistance loss. These contributions highlighted the importance of mechanistic deterioration models for predicting service life.

Applications to real and representative bridge systems have further demonstrated the practical value of TdR. Tu et al. (2019) evaluated the time-dependent reliability and redundancy of prestressed multi-girder bridges at multiple levels (material, component, system), capturing corrosion effects through nonlinear FE analysis. Luo et al. (2021) analyzed the fatigue reliability of aging prestressed concrete bridges by incorporating stochastic traffic loading and resistance degradation with realistic fatigue stress spectra. Kim and Song (2021) applied a TdR and updating framework to PC box girder bridges, incorporating environmental categories for corrosion, and validated their approach on a full-scale cable-stayed bridge. Similarly, Al-Mosawe et al. (2022) performed a case-specific TdR assessment of a post-tensioned bridge in the UK, illustrating the role of tendon corrosion in failure. These applications showed the potential of TdR to address system-level complexity and validate predictions with real structures.

More recently, Bayesian updating has become increasingly important for reducing uncertainty in TdR assessments. Xu and Azhari (2021) used inspection and nondestructive testing data to update corrosion-driven deterioration and load models for prestressed concrete highway bridges, demonstrating improved prediction of remaining service life. Vries et al. (2024) extended this to proof load testing, showing how Bayesian updating with different information sources can refine reliability estimates before, during,

and after testing. More recently, Chen et al. (2025) proposed a Gaussian process-based Bayesian updating framework for bridges with sparse inspection data, enabling robust reliability predictions under uncertainty.

New research also continues to expand TdR applications to deterioration-load interactions. El Hajj Chehade et al. (2022) investigated serviceability-based TdR for RC T-beam bridges under realistic WIM-derived traffic, including creep and shrinkage effects. Chen et al. (2023) analyzed PC box-girder bridges under cyclic creep induced by traffic, employing efficient FE modeling and Importance Sampling (IS). Celati et al. (2025) incorporated spatial and temporal reliability for post-tensioned decks, combining system-level modeling with corrosion. Zemed et al. (2025) moved further toward predictive maintenance by integrating surrogate modeling and active learning for RC bridges, explicitly accounting for material degradation and traffic growth.

Overall, these studies demonstrate that TdR has evolved from early conceptual models to sophisticated frameworks incorporating deterioration mechanisms, non-stationary loads, surrogate modeling, and Bayesian updating. Such evolution is summarized in Table 2. Applications to real bridges confirm its value for predicting RSL and guiding maintenance strategies, although challenges remain in scaling methods to complex systems with limited monitoring data.

**Table 2.** Summary of TdR analysis evolution for existing concrete bridges.

<b>Year</b>	<b>Authors</b>	<b>Contribution Summary</b>	<b>Deterioration</b>	<b>Loads</b>
1993	Mori & Ellingwood	First probability-based TdR model	Basic degradation functions (deterministic $g(t)$ )	Non-stationary (Poisson pulse load process)
1997	Ellingwood & Mori	Extended model to optimize maintenance	Basic stochastic (deterministic $g(t)$ )	Non-stationary (Poisson pulse with hazard-based modelling)
1998	Enright & Frangopol	Application to RC bridges under corrosion, T-beam example	Semi-mechanistic stochastic (chloride, cracking)	Stationary (random variables)
1998	Stewart & Rosowsky	Interaction of cracking, chloride diffusion, and corrosion modelling for RC slab decks	Mechanistic stochastic (Fick's law + corrosion loss)	Stationary (random variables)
2015	Li et al.	Combination of non-stationary live loads with corrosion in a closed-form reliability solution of RC structures.	Stochastic time-dependent (empirical corrosion loss)	Non-stationary (Poisson load with increasing rate)

<b>Year</b>	<b>Authors</b>	<b>Contribution Summary</b>	<b>Deterioration</b>	<b>Loads</b>
2015	Wang et al.	Resistance autocorrelation modelling	Gamma process with temporal autocorrelation	Non-stationary (Poisson occurrence of loads)
2016	Zhu & Frangopol	Introduced cumulative-time failure probability for lane-closure risk assessment under traffic and scour	Mechanistic: corrosion (girders), scour (piers)	Non-stationary: time-varying traffic & flood loads
2017	Zhu et al.	Probabilistic modelling of chloride-induced corrosion and repair effects on RC bridge columns	Mechanistic–stochastic: chloride ingress via Fick’s law + corrosion propagation	Non-stationary: truck weight and traffic volume increase over time
2018	Wang & Zhang	Temporal correlation in loads and its coupling with resistance shocks via copulas	Hybrid (gradual + shock); shock depends on load via copulas	Non-stationary with temporal correlation (lognormal)
2019	Yuan et al.	Combined non-stationary GEV-modelled traffic with Gamma resistance degradation	Gamma process (corrosion)	Non-stationary (GEV traffic model)
2019	Tu et al.	Reliability and redundancy at material, component, and system level using nonlinear FE under corrosion.	Mechanistic (material loss in FE)	Stationary
2021	Luo et al.	Long-term monitoring data, integration of cracks, and 3-stage traffic growth of aging PC bridges.	Mechanistic (corrosion & cracks)	Stochastic traffic
2021	Kim & Song	TdR of PT box girder bridges with Bayesian updating using inspection data and environment categories.	Mechanistic (corrosion by ISO 9224) + Bayesian updating	Time-varying
2021	Xu & Azhari	Bayesian updating of load and corrosion models using inspection and NDT for RSL prediction	Stochastic corrosion + Bayesian updating	Non-stationary (updated from field/NDT data)
2022	Al-Mosawe et al.	Field-data-driven TdR of UK PT bridge; assessed system-level tendon degradation	Mechanistic + scenario-based (tendon corrosion)	Stationary (traffic)

Year	Authors	Contribution Summary	Deterioration	Loads
2022	Cehade et al.	Apply multi-mechanism deterioration to serviceability limit under realistic traffic for RC T-beam bridges	Mechanistic: creep, shrinkage, corrosion	Non-stationary (WIM-based + copulas)
2023	Chen et al.	Include cyclic creep in TdR of PC bridges under stochastic traffic + FEM	Mechanistic (cyclic creep via FE)	Non-stationary (traffic-induced creep)
2024	Vries et al.	Bayesian updating of reliability using proof load testing at different knowledge stages	Probabilistic resistance degradation	Stationary
2025	Chen et al.	Bayesian updating of reliability using Gaussian process regression and sparse inspection data	Stochastic degradation (GPR-based)	Non-stationary (correlated traffic model via copulas)
2025	Celati et al.	Spatio-temporal system-level TdR of post-tensioned decks with corrosion	Mechanistic + spatial correlation (tendon corrosion)	Time-varied
2025	Zemed et al.	Predictive TdR using surrogate modelling and active learning for predictive maintenance of RC bridges with traffic growth	Deterministic (deflection limit)	Deflection increases due to creep, shrinkage and growing traffic

### Reliability-based service life prediction

TdR can be implemented to predict the service life of aging structures. By comparing evolving reliability over time with prescribed target reliability levels, engineers can determine the point at which a structure no longer meets safety requirements. This approach enables not only the prediction of structural service life but also the assessment of maintenance and repair strategies within the context of life-cycle cost optimization, resource allocation across multiple assets, and resilience analysis of infrastructure systems (Wang et al., 2021).

The end of service life is commonly defined as the time when structural reliability falls below the minimum acceptable safety threshold. In practice, once the probability of failure  $P_f(t)$  exceeds a maximum tolerable risk, the structure is considered unsafe or unserviceable. This allows the service life to be expressed as the inverse function of reliability, i.e.,  $P_f^{-1}(p)$ , where  $p$  denotes the acceptable failure probability (Cheung and Kyle, 1996). Such estimates provide a rational basis for asset owners to schedule interventions and extend service life through timely maintenance.

Target reliability indices  $\beta t$ , which correspond to acceptable failure probabilities through the relationship  $p=\Phi(-\beta t)$ , have been established for new structures via code calibration. However, for existing structures, the appropriate choice of  $\beta t$  is less straightforward, as uncertainties, degradation effects, and socio-economic considerations often need adjustments to the target reliability level (Stewart, 2001).

### 2.3 Structural resistance degradation models

This section reviews probabilistic degradation models for concrete structures, with particular emphasis on bridges. As mentioned in Section 2.2, structural resistance deteriorates over time due to several degradation agents. In concrete structures, multiple interacting mechanisms contribute to this deterioration, making it essential to adopt models that capture both the current state of damage and its future evolution.

The main degradation mechanisms include corrosion of reinforcement, freeze-thaw cycles, alkali-aggregate reaction, internal and external sulphate attack, erosion, leaching of alkalinity, and fatigue (Val et al., 2024). Among these, reinforcement corrosion is the most critical for RC bridges and has been the focus of extensive research (Frangopol et al., 1997, 2003). While deterministic models exist for each mechanism, this section focuses on probabilistic-based and stochastic modeling of structural resistance deterioration.

The degraded time-dependent resistance of a structure or element is commonly expressed as the product of the initial resistance,  $R_0$ , and the deterioration function,  $g(t)$ , as follows:

$$R(t) = R_0 \cdot g(t) \quad 11$$

where  $g(t)$  is a monotonically non-increasing stochastic process, without considering maintenance or rehabilitation measures. A simple form of  $g(t)$  is:

$$g(t) = 1 - a \cdot t^\theta \quad 12$$

where  $a$  represents the deterioration rate,  $t$  is time, and  $\theta$  is a parameter representing the dominant deterioration mechanism. The deterioration process can be modeled as linear, parabolic or square root behavior, corresponding to  $\theta = 1, 2$  and  $0.5$ , respectively.

This formulation was first introduced by Mori and Ellingwood (1993) for corrosion degradation and later extended to a two-parameter function by Enright and Frangopol (1998) and Enright and Frangopol (1999) as follows:

$$g(t) = 1 - a_1 \cdot t + a_2 \cdot t^2 \quad 13$$

For stochastic modeling in time domain with independent increments, three processes are commonly used: the Gamma, Wiener (or Brownian motion) and inverse Gaussian (IG) processes (Dong and Cui, 2019; Ling et al., 2019). Among these, the Gamma process is generally preferred for resistance degradation and has been extensively used to model structural resistance deterioration (van Noortwijk et al., 2007; Li et al., 2015; Wang et al., 2015). Its popularity rises from the fact that it describes a continuous stochastic process with non-decreasing trajectories, with a lot of applications in bridges, e.g., Strauss et al., 2017; Wang et al., 2019a; Wang, 2020; Yaotian Zhang et al., 2023. The Wiener process, although widely used, is less suited for strictly monotonic degradation, whereas the IG process is less common in structural reliability due to its less intuitive physical interpretation (Ye and Chen, 2014).

The degradation function can be also expressed in terms of the increments,  $D_i$ :

$$g(t) = 1 - \sum D_i \quad 14$$

where  $D_i$  follows a stochastic distribution.

Despite Gamma distribution advantages, it has some limitations: (i) the variance of  $g(t)$  is tied to the mean; and (ii) the autocorrelation between two different times is uniquely determined once the mean values of  $g(t)$  at the two times are known, reducing modeling flexibility.

Extension to the models mentioned above also account for sudden shock events (such as earthquakes) alongside gradual deterioration, to better represent real bridge environments. In these frameworks, both resistance and load demand evolve stochastically over time. Examples include Kumar et al. (2015) and Sanchez-Silva et al. (2011), who extended classical stochastic degradation models to capture the joint effect of gradual deterioration and extreme events.

Figure 5 summarizes the most known stochastic degradation processes in TdR with their main features, advantages and limitations.

A brief overview of corrosion-induced, prestress force loss and fatigue-induced degradation models is presented below, which are the focus of [Paper I](#), [Paper III](#) and [Paper V](#), respectively. For other types of deterioration mechanisms, see Val et al. (2024).

#### *Corrosion-induced models*

Corrosion-induced degradation of RC structures has been extensively studied, and probabilistic models have been developed for both chloride- and carbonation-induced corrosion, commonly referred to as pitting and uniform corrosion, respectively.

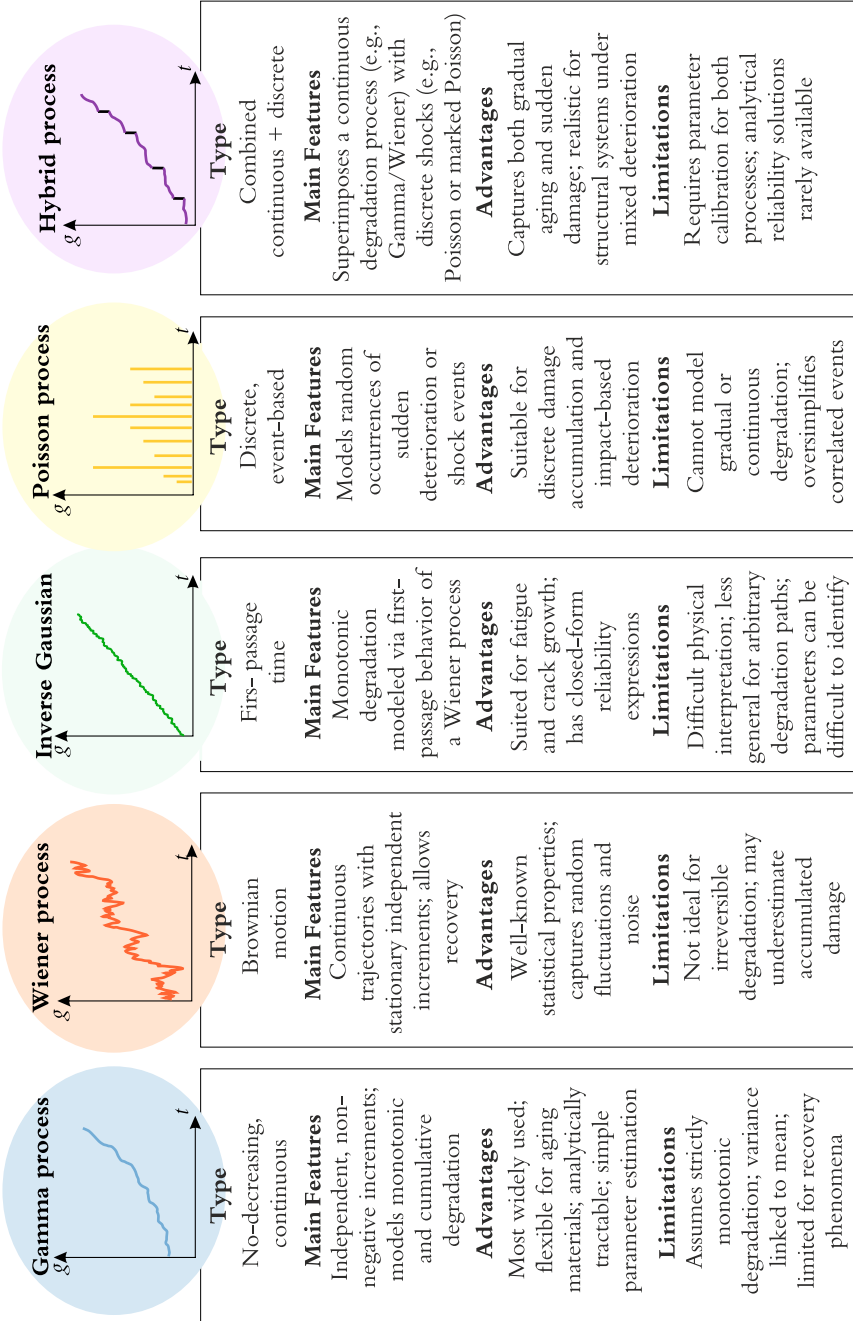


Figure 5. Summary of common resistance degradation process.

The effects of corrosion include the loss of reinforcement cross-sectional area, reductions in yield and ultimate strength, and the development of stress concentrations, all of which lead to a decrease in structural resistance.

For chloride-induced corrosion, the most widely used approach is based on Fick's second law of diffusion (Equation 15), with its solution given by Equation 16.

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} \quad 15$$

$$C(x, t) = C_0 + (C_s - C_0) \left[ 1 - \operatorname{erf} \left( \frac{x}{2\sqrt{D \cdot t}} \right) \right] \quad 16$$

where  $C(x, t)$  is the chloride concentration at depth  $x$  and time  $t$ ,  $C_0$  is the initial chloride content,  $C_s$  is the chloride concentration at the surface,  $D$  is chloride diffusion coefficient, and  $\operatorname{erf}(\cdot)$  is the error function.

Improvements of Equation 16 rely on the accuracy on modeling the chloride diffusion coefficient  $D$ . To turn this model into probabilistic terms, the main parameters are treated as random variables (Biondini et al., 2014). Alternative formulations include the resistance degradation models, such as those by Mori and Ellingwood (1993) and Enright and Frangopol (1998), which calibrates the parameters in Equations 12–13 based on Equation 14 results.

Among the earliest corrosion models applied to RC bridges are those by Enright and Frangopol (1998) and Stewart and Rosowsky (1998), who explicitly used Fick's law to model the time to corrosion initiation. In their approaches, chloride diffusion through concrete is treated as a stochastic process governed by material properties and exposure conditions. In contrast, Val and Melchers (1997) did not directly use Fick's Law; instead, they adopt a more empirical, mechanism-based deterioration model that distinguishes between general and localized corrosion, integrated with nonlinear FE modeling. Additionally, they propose a geometrical model for reinforcement area loss. Similarly, Frangopol et al. (1997) employed parametric deterioration models (e.g., time-dependent cross-sectional steel loss rates) without explicit diffusion modeling, focusing instead on probabilistic simulation of capacity loss.

For carbonation-induced corrosion, the process is typically modeled as a diffusion-controlled penetration of the carbonation front, with depth given by:

$$x_c(t) = k_c \sqrt{t} \quad 17$$

where  $x_c(t)$  is the carbonation depth at time  $t$ , and  $k_c$  is the carbonation coefficient/rate. In probabilistic models,  $k_c$  is treated as a random variable depending on material properties, humidity, temperature, and  $\text{CO}_2$  concentration.

More recent developments include the adoption of stochastic process models, such as Gamma process for corrosion progression (Wang et al., 2019a; Z. Zhang et al., 2021) or Poisson process for number of pits (Nguyen et al., 2013), as well as hybrid approaches combining probabilistic models with fuzzy logic (Tran et al., 2024). Significant research has also addressed spatial variability in chloride-induced corrosion, modeled through random fields (Stewart, 2004; Stewart and Mullard, 2007; Darmawan and Stewart, 2007; Marsh and Frangopol, 2008; Shafei and Alipour, 2015; Pedrosa and Andrade, 2021; Celati et al., 2025). Additionally, combined deterioration mechanisms such as corrosion-fatigue interaction (Zhang and Yuan, 2014; Zhang et al., 2016) have received increasing attention, particularly for bridges, along with the emerging impact of climate changes on corrosion rates and durability (Bastidas-Arteaga et al., 2010; Nava et al., 2023).

For PC bridges, similar approaches to those used for RC bridges have been adopted. When tendons are in direct contact with concrete (no ducts), Fick's law can be applied to calculate the time to corrosion initiation, with the model proposed by Val and Melchers (1997) for estimation of area loss (Tu et al., 2019). However, for post-tensioned elements with metal ducts, the initiation phase is more complex, since the initiation of corrosion depends on chloride diffusion not only through the concrete cover but also through the grout and finally to the tendons (Guo et al., 2011). A review on PC models for corrosion-induced degradation is given by Vereecken et al. (2021).

#### *Fatigue-induced deterioration models*

Fatigue degradation refers to the progressive deterioration of materials under cyclic loading, where repeated stress cycles lead to the initiation and growth of cracks that can ultimately result in failure. Thus, for structures that are constantly subjected to repetitive loads, such as railway and road bridges, fatigue is a critical concern.

Fatigue probabilistic models are normally given in terms of the traditional stress-range versus number-of-cycles-to-failure (S-N) curves (Equation 18) combined with the Palmgren-Miner (P-M) rule (Equation 19), often denominated S-N-P.

$$N_f S^m = C \quad 18$$

where  $S$  is the stress range,  $m$  is the slope of the S-N curve, and  $C$  is a material-dependent constant representing fatigue strength.

$$D = \sum_{i=1}^j n_i / N_i \leq 1 \quad 19$$

where  $n_i$  is the number of applied cycles at stress level  $i$ , and  $N_i$  is the fatigue life at that stress level.

A second approach is based on fracture mechanics which focuses on fatigue crack initiation and propagation using laws like Paris' law (Equation 20 for steel bars) (Sain and Chandra Kishen, 2008; Rocha and Brühwiler, 2012; Wang et al., 2013).

$$\frac{da}{dN} = C \cdot \Delta K^m \quad 20$$

$$\Delta K = Y \cdot \Delta \sigma \cdot \sqrt{\pi \cdot a} \quad 21$$

where  $C$  and  $m$  are material constants,  $\Delta K$  is the stress intensity factor range,  $\Delta \sigma$  is the stress range,  $a$  is the crack size and  $Y$  is a shape factor which depends on the element and crack geometry.

Both S-N- and fracture mechanics-based approaches are recommended by the Joint Committee of Structural Safety (JCSS) probabilistic code (JCSS, 2001).

A third approach is stochastic damage mechanics (SDM), a probabilistic extension of continuum damage mechanics, which has been widely applied to model fatigue in concrete structures. In recent years, SDM has often been combined with the probability density evolution method (PDEM) to capture the stochastic evolution of fatigue damage under cyclic load, e.g., Liang et al., 2017; Gao et al., 2019; Li and Gao, 2019. This approach has shown to be more complex, and it is used mainly for fatigue deterioration of concrete.

### *Prestress force deterioration models*

Prestressed concrete bridges are particularly vulnerable to deterioration caused by time-dependent prestress losses, whose contributing factors (such as concrete creep, shrinkage, and steel relaxation) are interdependent and nonlinear, making it difficult to accurately predict the state of a prestressed concrete member at any given time.

Predictive models for short- and long-term losses remain largely theoretical due to the difficulty of directly measuring effective prestress. To address this, advanced probabilistic methods, such as Bayesian inference combined with global sensitivity analysis, have been employed to manage uncertainties and refine residual prestress predictions using monitoring data (Biswal and Ramaswamy, 2017; Dias-da-Costa et al., 2019; Botte et al., 2021; Moravčík and Kral'ovanec, 2022; Tonelli et al., 2023)

The probabilistic modeling of prestress losses has progressed significantly since the 1990s. Early studies (Steinberg, 1995; Casas and Crespo-Minguillon, 1998) modeled creep, shrinkage, and relaxation losses as random variables. Subsequent work (Yang, 2005; Podroužek et al., 2014) introduced updating procedures and system-level reliability concepts. Overall, prestress losses are increasingly treated as time-dependent stochastic variables, supporting more realistic life-cycle reliability evaluations of prestressed and post-tensioned structures.

The variability of the mechanical properties of prestressing steel as well as the prestress force and its losses can be found in the JCSS probabilistic code (JCSS, 2001).

## 2.4 Metamodel-based reliability methods

Over the years, significant research efforts have been dedicated to developing accurate and efficient methods for calculating structural failure probability ( $P_f$ ), especially given the typically small magnitude of  $P_f$ , the mathematical complexity of reliability problems, and the large number of possible random variables involved. As discussed in Section 2.2, in the context of TdR analysis, a common practice is to transform the problem into a time-independent one using time-integration or time-discretization techniques. This transformation allows for the application of classical SRT methods. The present study adopts this approach, as it offers sufficiently accurate estimates while remaining simple and practical for real-world engineering applications. Accordingly, this section presents an overview of metamodel-based methods developed within the framework of classical SRT.

Classical reliability methods are commonly grouped into three categories: (1) approximation, (2) simulation, and (3) metamodel-based methods (Guimarães et al., 2018). Approximation methods, also known as gradient-based or Taylor expansion-based methods, include the well-known First- and Second-Order Reliability Methods (FORM and SORM). These techniques have been introductory in reliability analysis and are well-documented in classical literature such as Madsen et al. (1989). Simulation-based methods, on the other hand, rely on random sampling to explore potential outcomes of uncertain systems. Common examples include Monte Carlo Simulation (MCS), Latin Hypercube Sampling (LHS) (Mckay et al., 1979), Importance Sampling (IS) (Harbitz, 1986), Subset Simulation (SS) (Au and Beck, 1999).

Metamodel-based methods offer a powerful alternative by replacing the original LSF with a surrogate model that approximates its behavior. This substitution reduces the computational effort, particularly when the LSF is costly to evaluate. This approach is often combined with approximation or simulation techniques to obtain  $P_f$ . In the literature, metamodel-based methods are also referred to as Response Surface Methods (RSM) or Machine Learning-based (ML-based) reliability methods, depending on the surrogate type. For example, polynomial surrogate functions are commonly used in RSM, whereas advanced models such as Support Vector Machines (SVMs) and Artificial Neural Networks (ANNs) are denominated as ML-based reliability approaches.

The application of metamodel-based methods to structural reliability analysis (SRA) began in the 1990s with the introduction of RSM. This approach was originally proposed by Box and Wilson (1992) and later adapted to SRA by Bucher and Bourgund (1990),

with subsequent refinements in later studies, e.g., Kim and Na, 1997; Romero et al., 2004; Allaix and Carbone, 2011; Roussouly et al., 2013; Guimarães et al., 2018. Over the past few decades, a wide range of surrogate models have been integrated into the SRT framework, including SVM, Kriging (Gaussian process regression), Polynomial Chaos Expansion (PCE), and ANN. Comprehensive reviews on metamodel-based approaches in SRA are provided by Teixeira et al. (2021b) and Afshari et al. (2022), while more focused surveys on SVM and ANN can be found in Xu and Saleh, 2020; Afshari et al., 2022; Roy and Chakraborty, 2023. More recently, Afshari et al. (2023) reviewed the emergence of deep learning (DL) methods, which build upon the foundations of ML-based techniques.

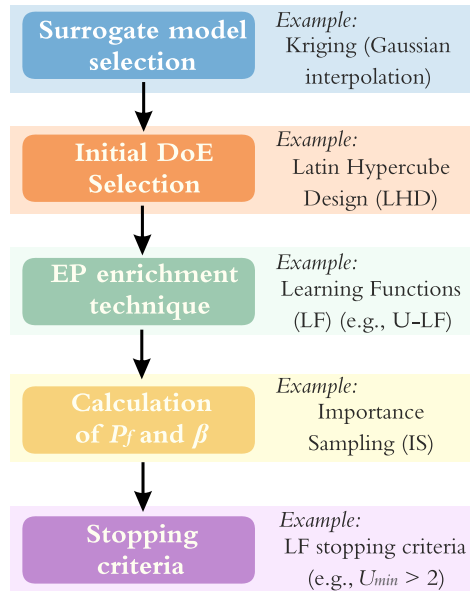
Despite the wide range of existing surrogate models, kriging, first introduced by Matheron (1973), have gained particularly popularity due to their exact interpolation nature and ability to quantify prediction uncertainty (Yu Zhang et al., 2023; Zhou and Li, 2023). Their application to SRA was initiated by Romero et al. (2004) and expanded by Kaymaz (2005), who examined kriging in the context of FORM and SORM. Subsequent research on kriging-based SRA has focused on improving four key aspects: the initial experimental design (ED), the enrichment strategy and stopping criteria, the ED size and domain, and the metamodel hyperparameters (Teixeira et al., 2021b).

For kriging-based SRA, several learning functions (LFs) have been proposed to enhance the selection of new experimental points (EP). A LF is a convenient mathematical function that weighs the metamodel properties to identify the most suitable candidate for enhancing the EP. Bichon et al. (2008) introduced the Efficient Global Reliability Analysis (EGRA) and proposed the Expected Feasibility Function (EFF) to enrich the EP, which is a well-known active LF. Later, Echard et al. (2011) proposed the U LF, which selects points by considering the wrong classification probability, and the H function presented by Lv et al. (2015) based on the information entropy. Among these, U-function remains widely used due to its simplicity and the fact that it enables easy identification of the point with the highest probability of misclassification (Yu Zhang et al., 2023). Further developments were developed by Wang et al. (2024), who proposed an adaptive LF allocation strategy that automatically selects the most suitable LF from a portfolio, and Zhang et al. (2023), who introduced a distance-based subdomain approach to select candidate points near the limit state surface, reducing computational effort during the active learning process.

Many developed algorithms have combined kriging surrogate models with simulation techniques, building on the AK-MCS framework proposed by Echard et al. (2011). Variants such as AK-IS (Cadini et al., 2014), AK-SS (Huang et al., 2016), AK-MCSi (Lelièvre et al., 2018), AKEE-SS (Zhang et al., 2019), ALK-DIS (Guo et al., 2020) and AK-ARBIS (Yun et al., 2020), integrate adaptive kriging with different sampling

approaches to improve efficiency. More recently, Zhou and Li (2023) proposed the IE-AK algorithm, which enhances kriging model training through a LF based on information entropy theory. Also, Peng et al. (2024) introduced the AK-SEUR method, which employs a new LF designed to minimize the expected failure probability bound for the new samples highlighting the need to better incorporate the location and probability density of random input parameters.

Figure 6 illustrates the main steps involved in constructing a metamodel within the framework of structural reliability analysis (SRA), along with an example corresponding to each step.



**Figure 6.** Metamodeling procedure for SRA.

Another growing area of development in metamodel-based reliability analysis involves the use of copula functions to model complex dependencies among input variables. Traditionally, independent variables are assumed independent or rely on simplistic correlation models, which can lead to inaccuracies. Copula-based approaches address this limitation by capturing nonlinear and asymmetric dependencies, examples in this area include those by Jiang et al., 2015 and Amini et al., 2021. Additionally, existing kriging methods have also been successfully extended to time-dependent reliability problems, as demonstrated in recent works by Zhan et al., 2024 and Zhao et al., 2024, thus expanding the applicability of metamodel-based techniques.

In summary, metamodel-based reliability methods have evolved from simple polynomial approximations into a rich and diverse field that integrates advanced ML techniques,

active learning strategies, hybrid simulation approaches, and dependency modelling via copulas. These methods provide a flexible and computationally efficient framework for SRA, especially in high-dimensional, time-dependent, and complex correlated systems. While substantial progress has been made, challenges remain in areas such as optimal ED, and integration of information from the joint PDF. Addressing these challenges is crucial for further advancing the practical implementation of metamodel-based reliability analysis in modern engineering applications.

## 3. Framework for remaining service life (RSL) of existing bridges

### 3.1 Existing framework for bridges condition assessment

Condition assessment frameworks and bridge rating systems are fundamental tools for evaluating the performance and safety of existing bridges. These frameworks assess a bridge's as-designed, as-built, and current condition to characterize its mechanical properties, identify deterioration mechanisms, and estimate the RSL of the asset (Agredo, 2025). In recent years, several national and international guidelines (e.g., DIN, 2010; Setra, 2010; SIA, 2011; RVS, 2011; CS465, 2020; MIT, 2020; CEREMA et al, 2023) have expanded these frameworks by incorporating multi-risk and probabilistic approaches. Such developments allow infrastructure managers to account for the likelihood and consequences of adverse events when prioritizing maintenance and rehabilitation interventions, promoting a more risk-informed and reliability-based management strategy (Agredo et al., 2024).

Recent national initiatives, such as the BAST (2024) *Guideline on the Strategic Implementation of Monitoring for Engineering Structures*, represent important progress towards the systematic incorporation of SHM into bridge management. These documents provide structured guidance on the planning, execution, and evaluation of monitoring systems and emphasize their potential role in probabilistic and reliability-based assessments. However, they remain guidelines rather than formal standards, and the integration of SHM data into codified condition assessment and rating frameworks is still under development. Consequently, continuous monitoring in practice remains optional, unstandardized, and largely research-driven, rather than systematically embedded in asset management processes (Del Grosso, 2014).

Several international standards address the assessment of existing structures, but they differ in depth, scope, and integration compared with the methodology developed in this thesis. The AASHTO - Manual for Bridge Evaluation (MBE) (AASHTO, 2018) for example, focuses on condition ratings and load assessments based on deterministic methods,

without incorporating probabilistic or time-dependent reliability concepts. ACI 562 (ACI, 2019) supports performance-based evaluation and the use of in-situ data but lacks detailed guidance on reliability modeling or degradation analysis. ISO 13822 (ISO, 2010) provides a global framework for reliability-based assessment but does not prescribe specific tools or data integration methods. In contrast, the fib Model Code 2020 (MC2020) (fib, 2023) offers the most advanced framework. It recognizes the value of data-informed assessment by promoting the integration of structural monitoring, inspection data, and performance requirements into a holistic decision-making process (Strauss et al., 2023). Nevertheless, despite supporting advanced reliability-based approaches, MC2020 intentionally avoids prescribing specific computational methods, leaving their selection to the engineer’s discretion.

Despite these advances, the integration of on-site inspection and monitoring data within probabilistic condition assessment frameworks remains limited. Most established methodologies still rely on deterministic evaluations derived from periodic inspection snapshots, providing only discrete representations of structural condition. To capture the inherent uncertainty in deterioration processes, more probabilistic deterioration models should be calibrated and validated using real-world, on-site data. Such models can quantify uncertainties associated with material degradation, environmental exposure, and loading conditions, leading to better predictions of structural reliability over time.

Addressing these gaps, this thesis proposes and validates an integrated methodology that combines experimental monitoring, FE modelling, and efficient TdR analysis to estimate the actual capacity and RSL of existing bridges, thereby enhancing structural safety assessment and supporting informed decision-making. The developed framework unifies these three key scientific areas offering a structured pathway for data-informed, reliability-based decision-making. The conceptual structure of this framework, including its inputs, outputs, and interactions, is illustrated in Figure 7.

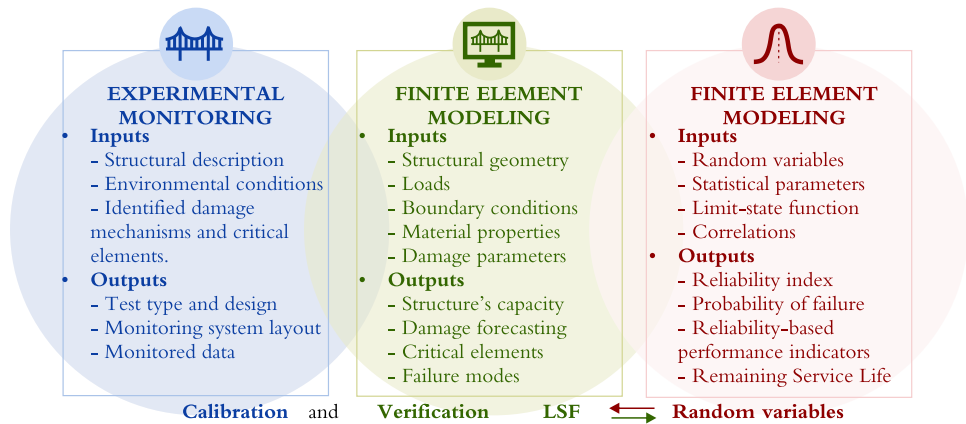


Figure 7. Framework main areas inputs and outputs.

In addition to integrating these three key scientific areas, the proposed framework offers a more detailed exploration of efficient reliability methods suitable when using FE modeling and monitoring data. The overall methodology is organized into five main steps, as illustrated in Figure 8, with a detailed description of each step provided below.

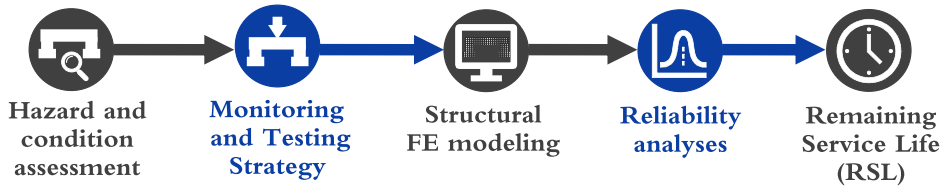


Figure 8. Framework main steps.

### 3.2 Proposed framework

#### Step 1 – Hazard and condition assessment

The first step consists of identifying all exposures (or hazards) to which the structure has been or may be subjected. An exposure or hazard can be defined as a threat capable of causing harm (Ellingwood, 2008), such as causing degradation of the structure’s capacity. In the case of bridges, these typically include environmental and operational factors such as those discussed in Section 2.3, along with accidental events like overloading, explosions, or vehicle impacts.

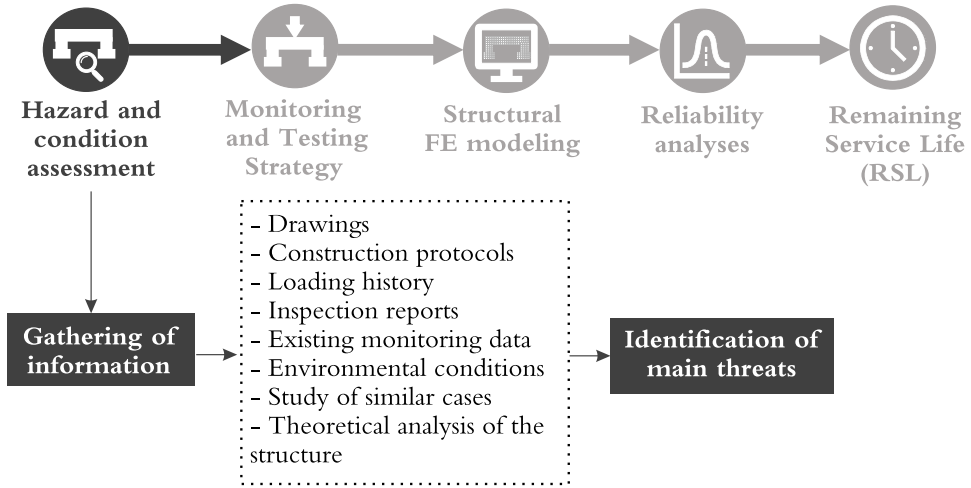
In this step, it is essential to gather and document all available information related to the bridge’s construction, maintenance, inspection, and monitoring history, since these data help reduce epistemic uncertainties in the subsequent analysis. Sources of information include inspection reports, sensor data, laboratory testing, and observed structural responses. Also, it can be given in terms of observations like accidents or events of natural hazards (JCSS, 2008). When direct measurements are not available, insights from similar structures or previous studies may be used as references, while the associated uncertainties should be explicitly modeled. The damage identification process is depicted in Figure 9.

Because damage often results from the combined effects of multiple mechanisms acting simultaneously, it is crucial to consider their interaction. For example, the co-occurrence of live, dead, and environmental loads together with deterioration due to chloride-induced corrosion.

This step results in a comprehensive understanding of the structure’s condition and the key degradation mechanisms influencing its residual capacity, forming the basis for the subsequent steps.

## Step 2 – Monitoring and testing strategy

The second step involves defining how structural response and evidence of damage is collected. This includes selecting appropriate testing and monitoring methods capable of capturing relevant information about the structure's behavior and condition. NDTs and SHM techniques are generally preferred because they do not affect structural integrity while providing continuous and reliable information. An overview of different components that should be considered for the experimental work within the proposed framework is presented in Figure 10.



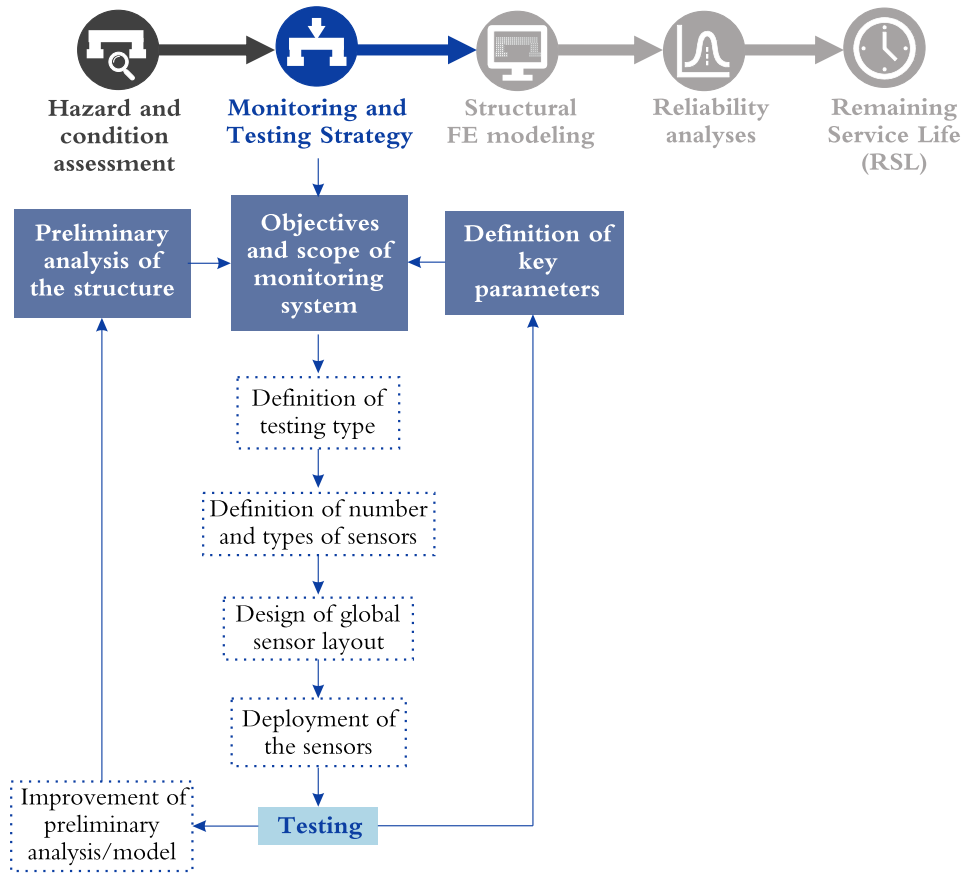
**Figure 9.** Damage identification process.

The design of the monitoring system is an important step, involving selection of the testing approach, sensor types, sensor placement, load configurations, and duration of data collection. Preliminary analyses, such as simplified calculations or non-calibrated FE models, can guide sensor placement by identifying critical components and sections of the structure. Although several theoretical approaches have been developed to support the design and optimization of monitoring systems, the selection of the required number and deployment of sensors generally depends on the engineer's experience and understanding of the relevant physical, chemical, and mechanical processes, as well as on the available monitoring budget (Frangopol et al., 2008).

According to Wong et al. (2000), the planning of a monitoring system should follow four key steps: (i) defining the objectives and scope of monitoring, (ii) identifying key structural parameters to monitor, (iii) selecting the appropriate sensor types, and (iv) designing the global sensor layout. The key selection criteria for the proper sensor types should be based on monitoring objectives and practical constraints (Zarate Garnica et al., 2022) such as:

1. The parameters or structural responses to be measured.
2. Preliminary calculations to estimate expected response ranges.
3. Site accessibility and suitable sensor installation points.
4. Environmental conditions, including temperature and humidity variations.
5. Redundancy in critical measurements to mitigate data loss or sensor failure.

The different components of the monitoring system definition or design are presented in Figure 11.

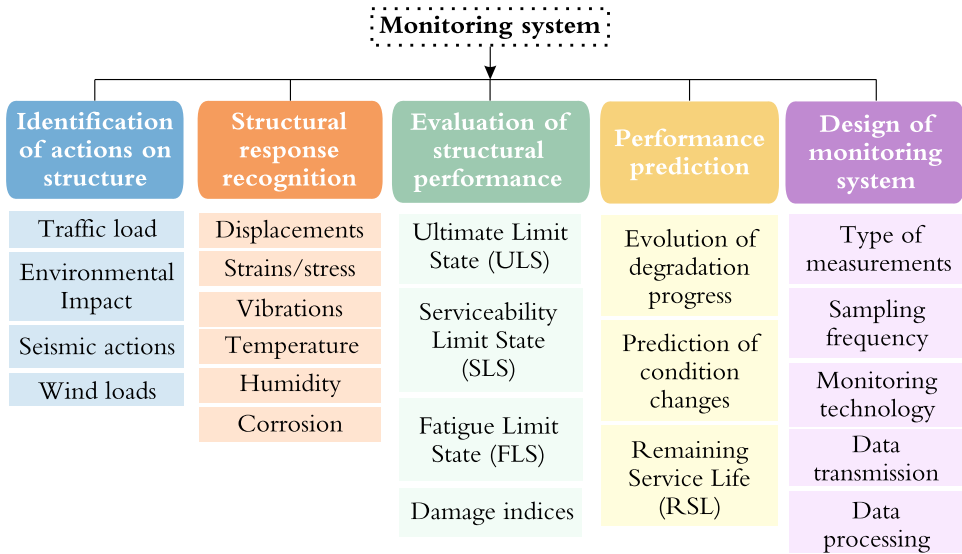


**Figure 10.** Experimental work procedure, based on (Bień et al., 2020).

A wide range of sensors and testing methods are available today to measure parameters related to material degradation, loading, and performance. Comprehensive reviews of various sensor types and their applications can be found, for instance, in Bień et al. (2020) and Zarate Garnica et al. (2022), while summary is presented in Table 3.

After the sensor layout has been designed, the subsequent step involves the deployment of the sensors and the execution of the designated testing program. The data collected

during this phase can be utilized to refine and update the preliminary analysis, thereby enabling a more precise and reliable deterministic assessment of the structural performance.



**Figure 11.** Functional components of a monitoring system based on (Bień et al., 2020).

In addition to monitoring and testing the structure response, it is essential to perform all feasible material tests to complement the assessment of structural condition. Material testing provides direct information on the mechanical and physical properties of structural components, which is crucial for evaluating the current performance and residual capacity of the structure. While extracting core samples from existing bridges can yield valuable data, such methods are often impractical or undesirable for structures that remain in service due to their invasive nature. Therefore, NDT techniques are preferred alternatives. For example, the Schmidt hammer test can be used to estimate the surface hardness and rebound value of concrete, offering an indirect yet reliable measure of its compressive strength. These non-destructive methods enhance the accuracy of structural assessments while minimizing disturbance to the bridge’s integrity and serviceability.

### Step 3 – Structural FE modeling

In this step, a numerical model representative of the structure’s geometry, boundary conditions, material properties, and loading configuration is developed. The model serves as a computational representation of the physical structure, allowing for simulation of structural response, degradation progression, and reliability evaluation under various loading and environmental scenarios.

**Table 3.** Monitored parameters in bridges and examples of sensors.

<b>Monitored parameter</b>	Linear displacement	Angular displacement	Strain/stress	Vibration velocity and acceleration	Crack opening
	Geodetic techniques Mechanical sensors Inductive sensors Vibrating wire sensors				
<b>Sensor example</b>	Capacitive sensors Eddy current sensors Fiber optics sensors Laser techniques Radar techniques Hydraulic sensors Digital image correlation Microwave interferometer radar	Inclinometers Fiber optics sensors Micro-Electro-Mechanical systems (MEMS) sensors	Electrical resistance gauges Fiber optics sensors Vibrating wire sensors MEMS sensors Digital image correlation Microwave interferometer radar Smart Aggregates	Piezoelectric sensors Capacitive sensors Inertia sensors Inductive sensors Radar techniques Laser techniques MEMS sensors Microwave interferometer radar	Mechanical sensors Inductive sensors Fiber optics sensors Vibrating wire sensors Digital image correlation Smart Aggregates
<b>Monitored parameter</b>	Bearing/cable reactions	Degradation processes	Live loads	Strain/stress	Temperature
		Acoustic emission sensors Chloride level sensors			
<b>Sensor example</b>	Electrical resistance gauges Piezoelectric sensors Vibrating wire sensors	Sensors of pH level Corrosion sensors Smart Aggregates	Wheel pressure sensors TV/video cameras Weight-in-motion systems	Thermocouples Thermistors Electrical resistance thermometers MEMS sensors	Hygrometers MEMS sensors

FE modeling is particularly suitable for probabilistic-based analyses, as repeated experimental testing of a real structure is neither economically feasible nor practically possible given the large number of scenarios required to account for uncertainties. In contrast, FE modeling provides a cost-effective numerical prototype that allows for extensive simulations under varying conditions. Furthermore, it enables a detailed representation of the stress–strain behavior and can incorporate material degradation laws, such as time-dependent reductions in stiffness or strength, that correspond to the monitored parameters identified in Step 2.

In this step the calibration of the model is carried out using data obtained from monitoring or testing. This process involves adjusting model parameters so that simulated responses (e.g., displacements, strains, modal frequencies) closely match observed data. Calibrated FE models provide a reliable foundation for predicting future damage progression and serving as an input for probabilistic analyses in subsequent steps.

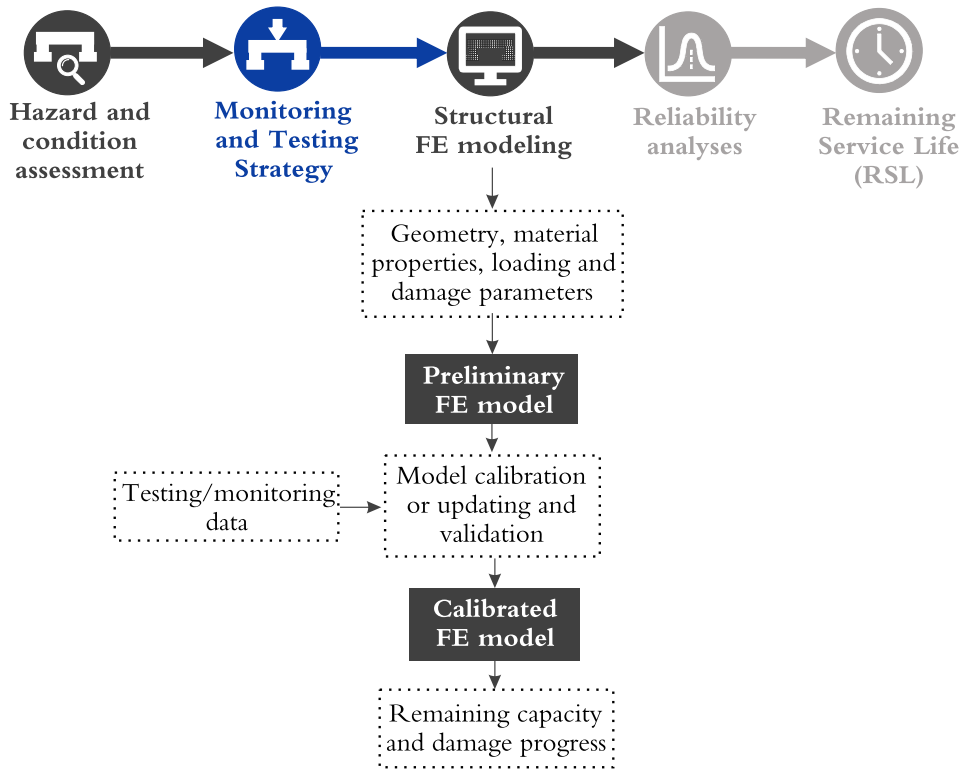


Figure 12. FEM calibration process.

### Step 4 – Reliability analyses

This step involves quantifying the probability of failure ( $P_f$ ) and reliability index ( $\beta$ ) of the structure as a function of time. The proposed methodology applies a time-dependent reliability methodology, accounting for the degradation of structural resistance and variability of loads over the service life.

The reliability estimation can be implemented through a stepwise or multi-level approach, in which the modeling of uncertainties and damage progressively increases in complexity to enhance the accuracy of the analysis. This allows for a systematic integration of information, starting from simplified models and advancing toward fully probabilistic, time-dependent formulations as more data and understanding become available.

The reliability analysis follows the steps illustrated in Figure 13:

1. Formulation of the time-dependent problem, in which the stochastic nature of the random variables is defined.
2. Construction of the LSF, representing the performance criterion of the structure.
3. Selection of the TdR method, which is coupled with the calibrated FE model through a metamodel-based reliability framework.

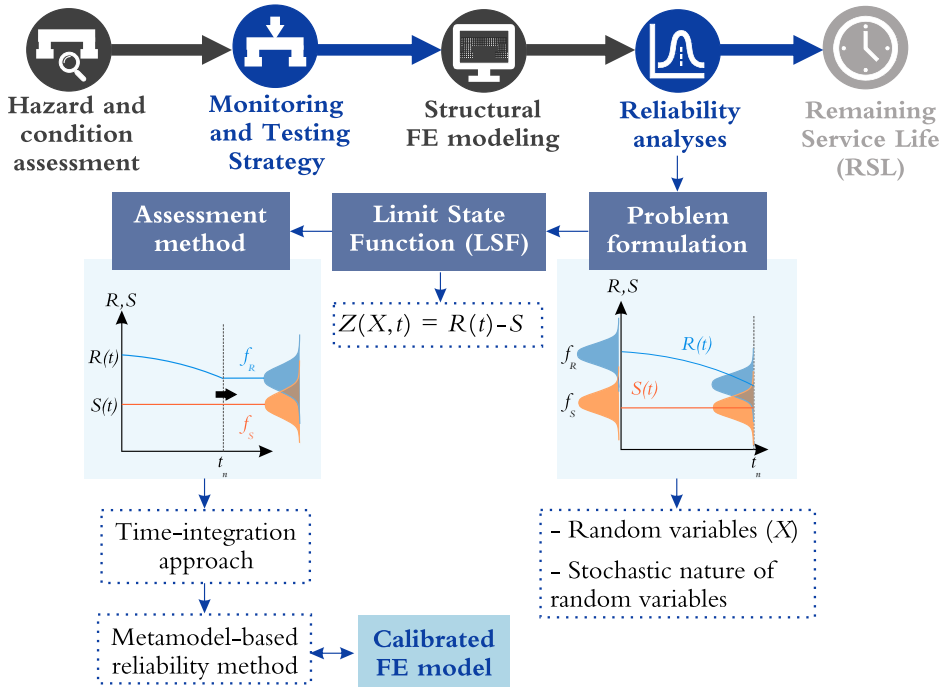


Figure 13. Steps for reliability analysis.

### Step 5 – Remaining Service Life (RSL) calculation

Once the TdR analysis has been completed, the RSL can be defined as the time at which the reliability index or the probability of failure reaches a predefined target safety level. This target is typically based on design codes or agency-specific requirements (e.g.,  $\beta = 3.1$  for serviceability or  $\beta = 3.8$  for ultimate limit states). Estimating the RSL through a reliability-based approach (illustrated in Figure 14) ensures that experimental data and uncertainties are explicitly considered, enabling a more realistic assessment and forecasting of future structural performance. When the deterioration model is stochastic, the RSL can be expressed probabilistically, i.e., as a distribution rather than a single deterministic value, thereby capturing the inherent uncertainty in the prediction.

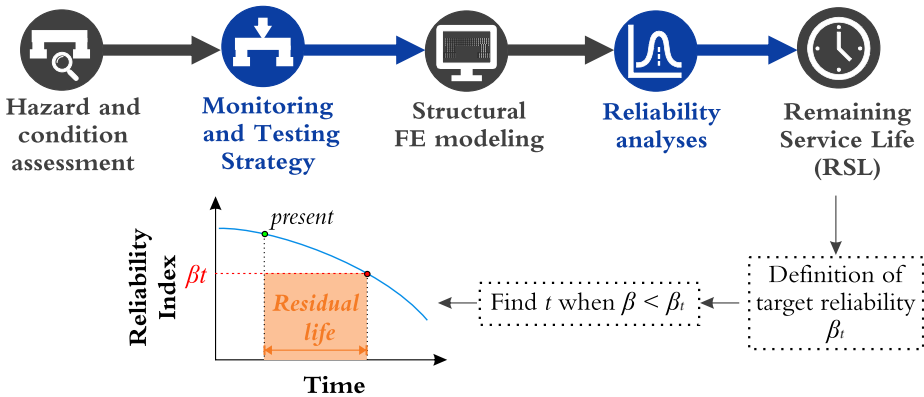


Figure 14. Residual service life illustration.

Although the proposed framework is structured around five main steps (Figure 8), it can be extended with two optional steps, probability updating and performance indicator evaluation, when relevant and more detailed reliability management is required (Figure 15).

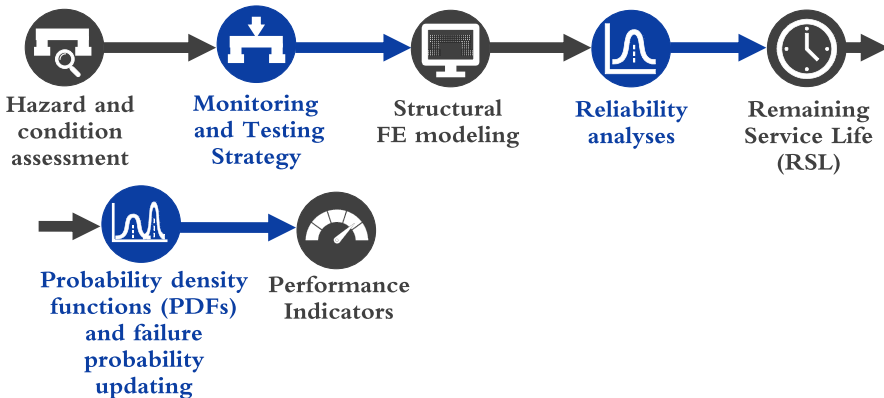


Figure 15. Additional steps for proposed framework.

## Step 6 – Probability density functions (PDFs) and failure probability updating

The framework can be extended by incorporating new monitoring or testing data as it becomes available. In such cases, the probabilistic description of model parameters and failure probabilities should be updated to reflect the evolving state of knowledge about the structure. This updating process can be carried out using Bayesian inference, where prior distributions of model parameters (e.g., material strength, degradation rates) are refined based on observed data to yield posterior distributions. By iteratively updating PDFs and recalculating the reliability index, the assessment becomes more accurate and reflective of the actual structural condition.

Other types of updates can also be performed using additional sources of information. For instance, in proof-loading tests, the PDF of the resistance can be truncated based on the survival of the structure under specific load levels, as demonstrated by Vries et al. (2024). Moreover, for service-proven structures, where it is known that the structure has survived for  $T$  years, the probability of failure can be directly updated. Using the Bayes' theorem, the conditional probability of failure in the subsequent years ( $T'$ ) is expressed as:

$$P_f(T'|T) = \frac{P_f(0, T + T')}{P_f(0, T)} \quad 22$$

where  $P_f(0, T + T')$  and  $P_f(0, T)$  denote the cumulative failure probabilities from the initial time up to  $T + T'$  and  $T$ , respectively.

## Step 7 – Performance indicators

An additional step can include more specific structural performance indicators (PIs), which complement the reliability analysis by describing the structural system's ability to withstand and adapt to damage. Two key structural PIs are:

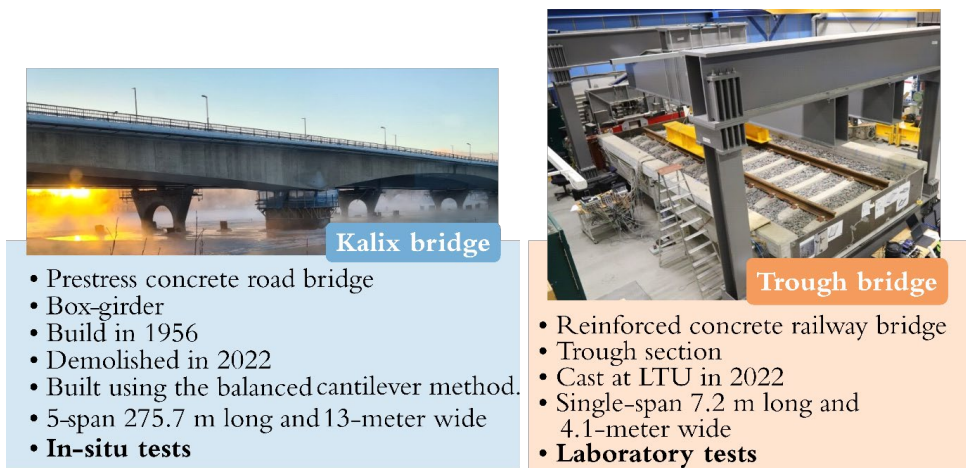
- Redundancy, defined as the capacity of an initially intact structural system to maintain its load-carrying function following the failure of one or more components (Miao and Ghosn, 2016). By including redundant components, a structure can continue to function even if some parts fail.
- Robustness, defined as the ability of a structure to sustain a certain level of damage without experiencing consequences that are disproportionate to the initiating cause (Biondini et al., 2008). A robust structure is less likely to fail under extreme loads, such as those caused by natural disasters like earthquakes, hurricanes, or floods.

Both indicators can be evaluated using the calibrated FE model and reliability results, often through system reliability approaches or progressive failure simulations. These PIs help to minimize the potential for damage propagation, as well as to reduce the risk of disproportionate failure events and progressive collapse (Ellingwood, 2006).

In literature several mathematical definitions of redundancy and robustness can be found, and a joint comparison of these existing measures can be found in [Paper I](#).

## 4. Application of the framework for RSL evaluation of existing bridges

The framework described in [Chapter 3](#) is applied first to a theoretical case, followed by two applications to real structures. The first real case corresponds to the Kalix Bridge, which was demolished in 2022, and the second to a full-scale replica of a decommissioned RC trough bridge. An overview of the cases is presented in [Figure 16](#).



**Figure 16.** Overview of case studies.

### 4.1 Illustrative case

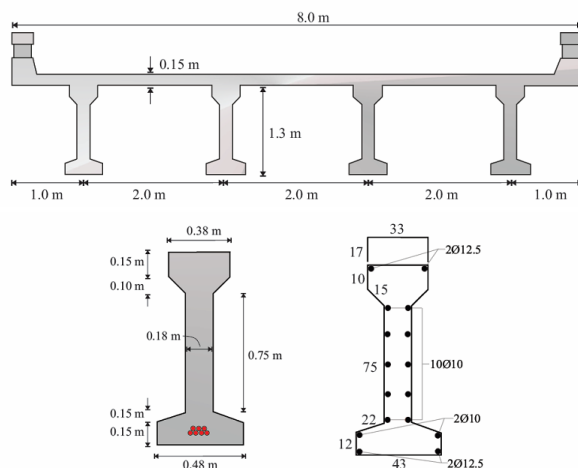
This section presents an illustrative application of the proposed framework. The example, originally developed in [Paper I](#), demonstrates the methodology's implementation to assess structural redundancy and robustness using reliability- and risk-based approaches. The case study consists of a PC I-girder bridge.

### Step 1 - Hazard and condition assessment

As this case represents a theoretical example rather than a monitored structure, the analysis is based on limited information, which includes:

- Structural geometry, reinforcement, and prestressing layouts.
- Design loads.
- Location and corresponding environmental exposure conditions.

This information was taken from available design drawings of an existing bridge in Colombia. The superstructure geometry is displayed in Figure 17. Given the available data and considering that among the most common deterioration mechanisms for RC and PC structures (without steel ducts) is the steel corrosion; thus, the corrosion of prestressing tendons was identified as the primary threat to structural performance.



**Figure 17.** Structural geometry of the example. (taken from Sarmiento et al., 2024)

The failure scenarios were modeled considering two main exposure mechanisms: traffic loading and chloride ingress. Preliminary analysis identified bending failure as the governing failure mode. While corrosion was assumed to progress uniformly across the beams, the tendons located at the critical flexural section of the external girder were found to be more vulnerable due to higher stress levels from traffic loads and greater exposure to chloride ingress. Specifically, four of the seven tendons in this section are positioned near the external surface, leading to earlier corrosion initiation and increased likelihood of failure.

### Step 2 - Monitoring and testing strategy

As this is a theoretical example, no experimental or monitoring data were available. Instead, theoretical corrosion parameters were adopted to represent deterioration, based on typical values reported in the literature for similar environmental conditions. These

parameters were used to simulate the progression of corrosion in the prestressing tendons and its influence on structural performance.

*Step 3 - Structural FE modeling*

A FE model was developed to represent bridge geometry, material properties, and loading conditions, and NLFEA were carried out to determine the structural capacity. Traffic loading was considered the primary action, and the corresponding design load was applied in the analysis. The model included corrosion-induced deterioration due to chloride ingress in the external beam and accounted for both prestressing losses and reinforcement corrosion. Prestress losses were estimated following the AASHTO LRFD provisions, while corrosion effects were incorporated through time-dependent degradation of material properties, governed by environmental exposure and diffusion processes.

*Step 4 - Reliability analysis*

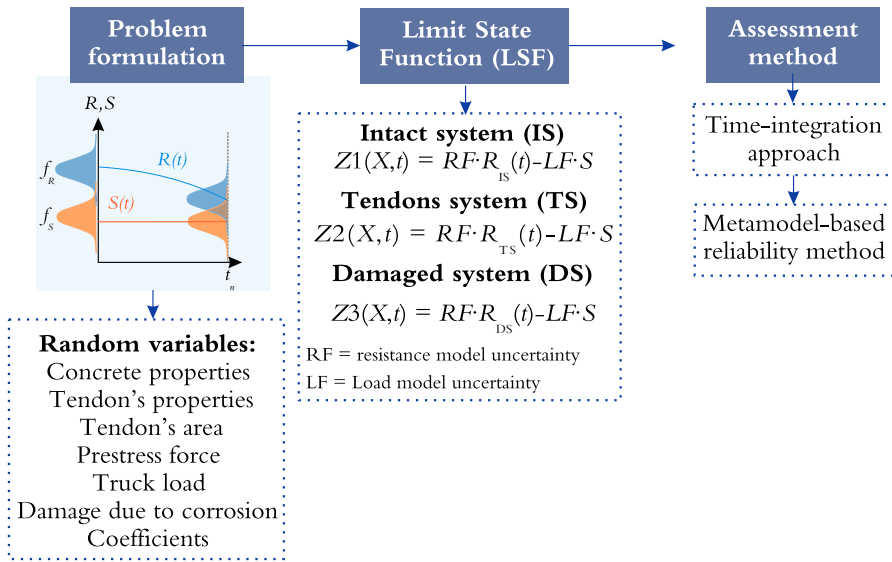
The reliability analysis process for this example is depicted in Figure 18. Resistance degradation is considered and derived from the FE model, where several LSFs were formulated necessary to obtain the redundancy and robustness indicators. Several important parameters were defined as random variables, all listed in [Paper I](#). A metamodel-based TdR analysis was performed to evaluate the bridge performance over time. The instantaneous probability of failure was estimated at three points in time (5, 25, and 50 years), representing different stages of deterioration.

To assess redundancy and robustness, the analysis was conducted in three stages:

1. Intact system reliability, where all structural elements were included and no damage was considered, corresponding to  $t = 0$  years.
2. Component reliability, evaluating the failure probability of the most vulnerable tendons identified in Step 1.
3. Damaged system reliability, in which the critical elements (4 tendons) of the external girder were removed from the model to simulate their failure and evaluate the structural performance.

*Step 5 - Remaining Service Life (RSL) calculation*

The RSL of the structure can be estimated by comparing the obtained reliability at different points in time with a target value. Since the structure was evaluated for ULS, a target reliability index of  $\beta_t = 3.8$  can be adopted. Based on this criterion, the tendons system reaches the target threshold slightly after 25 years, which is below the intended design life of 50 years. Moreover, the damaged bridge system exhibits reliability values below the target at all evaluated time points, indicating that the sudden loss of the critical tendons leads to a consistent violation of the required reliability levels.



**Figure 18.** Reliability analysis process for example application.

*Step 6 - Probability density functions (PDFs) and failure probability updating*

Not applicable, as no monitoring or inspection data were available for updating the probabilistic models. However, this step can be easily integrated into the analysis if such data becomes available.

*Step 7 - Performance indicators*

Reliability-based redundancy and robustness indicators were calculated for the analyzed structure using several available measures and mathematical definitions found in the literature. These included deterministic, reliability-based, and risk-based formulations for comparative evaluation. The results showed that the magnitude and interpretation of the indicators can vary significantly depending on the adopted definition, emphasizing the importance of clearly understanding their formulation and purpose. It was also observed that some measures commonly used as robustness indicators are more accurately characterized as redundancy indicators, suggesting the need for continued research to achieve consistent and interpretable definitions.

This step allows for a broader interpretation of structural performance, as it incorporates criteria beyond reliability levels alone. In addition to evaluating reliability, the assessment of redundancy and robustness provides complementary indicators that may have different target thresholds. These additional measures can reveal that a structure satisfies performance requirements even when its reliability index falls below conventional targets, offering a more targeted evaluation of structural safety.

## 4.2 Kalix bridge

The first real case, presented in [Paper III](#), concerns a PC bridge located over the Kalix River in northern Sweden (see [Figure 19](#)). The bridge was constructed in 1956 and demolished in 2022. It had a single-cell box girder cross-section with five spans of varying dimensions and was built using the balanced cantilever method, cast in 40 stages. The total bridge length was 275.7 m, with a section 13 m wide and heights ranging from 2.2 m to 5.3 m. The structure contained 226 prestressing cables at the section with the highest cable density.



**Figure 19.** Kalix bridge picture.

The demolition was undertaken because previous calculations indicated that the bridge no longer met current service requirements, and a new structure was needed to accommodate increased traffic loads ([Begström, 2015](#)). Before demolition, the bridge was used as research test-bed, allowing several experimental tests to be carried out (see [Figure 20](#)).

The application of the framework presented in [Chapter 3](#) to this case study is illustrated in [Figure 20](#), which outlines the main steps and highlights the key aspects of each. A brief description of each step, along with the main results and findings from the case study, is provided below.

### *Step 1 – Hazard and condition assessment*

This step consists of identifying critical aspects of the structure that should be monitored and understanding the potential damage scenarios based on the available information, which should carefully be studied. From this case the available data was:

- Technical drawings: geometry, reinforcement layout, materials, applied prestress force, construction stages.
- Bridge assessment: ULS, SLS assessment, among others.
- Inspection reports.

- Design notes and calculations.

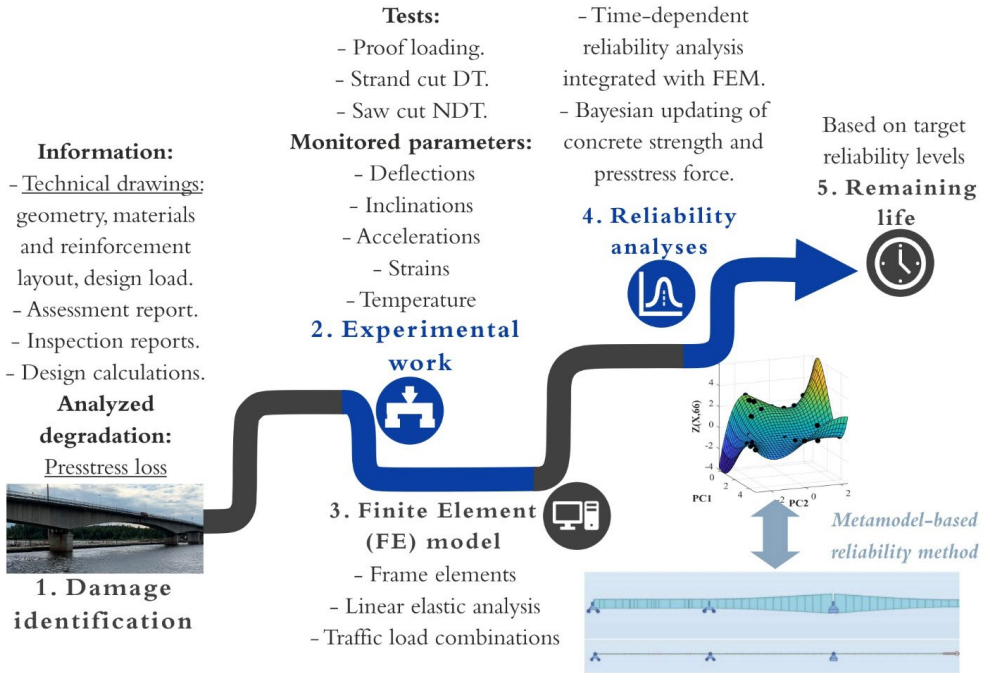
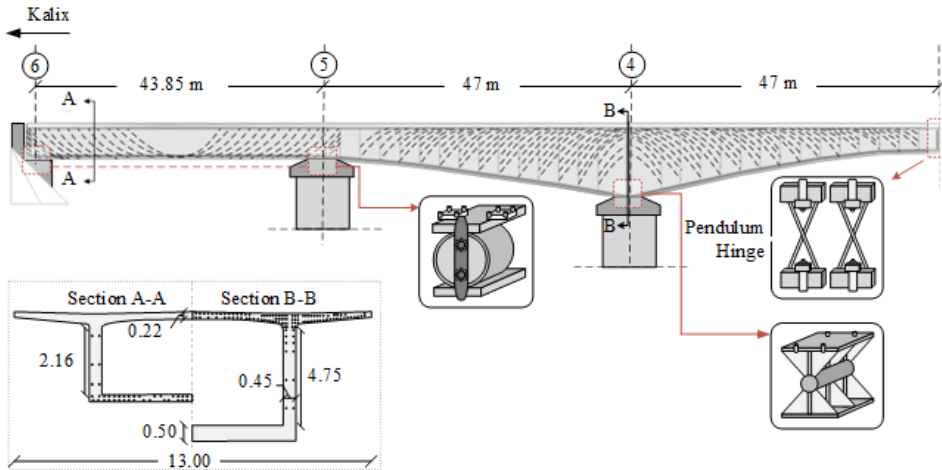


Figure 20. Framework applied to the case of Kalix bridge.

Most of the information gathered is reported by Sas et al. (2024). The geometry of the bridge and the prestress layout is presented in Figure 21, together with the boundary conditions taken from the technical drawings. In this figure, two transversal sections (A-A) and (B-B) are detailed, which were found to be the sections with the largest negative and positive bending moments. Section A-A, at 13.8 m from the support, had an accessible location; therefore, it was selected as a primary measurement point of investigation for monitoring and further calculations of residual prestress. The prestressing system consisted of Dywidag high-strength ribbed steel bars, arranged both longitudinally and transversely, comprising 26 mm diameter rods grouted within 31 mm diameter ducts.

From the bridge assessment, presented by Begström (2015), it was concluded that the calculated service limit and fatigue performance were critically low. The report highlighted that the bridge no longer satisfied the requirements for crack resistance and tensile stress as specified in Sections 4.3.1 and 4.4.1 of the governing standard TDOK 2013:0267 (Trafikverket, 2013). These deficiencies were primarily attributed to the limited concrete cover of the prestressing system (< 50 mm) and the absence of hydro-membrane insulation. Thus, it was identified in this step that the key structural concern relates to parameters affecting serviceability limit state performance, particularly the

potential for crack initiation at critical sections. This underscored the importance of monitoring the residual prestressing forces.



**Figure 21.** Kalix bridge details (taken from Sarmiento et al. (2025))

### Step 2 – Monitoring and testing strategy

Based on the available information, the objectives of the tests and monitoring systems were defined. The main objective of this experimental campaign was to evaluate the overall integrity of the structure and gather as much information as possible before its demolition. A secondary objective was to determine the residual prestress force in the critical section of the bridge, identified as section A-A in Figure 21, which was selected due to its accessibility.

The main test consisted of proof loading, where different points and structural responses were measured during three load cases, corresponding to one, two and four trucks. Each load case had three levels of load corresponding to 0% (22.7 tons), 50% (43 tons), and 100% (63 tons) of the additional weight at which the truck can be loaded.

A comprehensive measurement plan was developed to assess the bridge's structural behavior within the available budget constraints. The primary variables monitored included strains, displacements, inclinations, temperature, and acceleration. Accordingly, the monitoring system comprised inclinometers, accelerometers, deflectometers, Fiber Optic Sensors (FOS), strain gauges, and thermocouples. The sensor layout is presented in Figure 22.

To evaluate the residual prestress force, both DT and NDT methods were used and compared. In this study it was used the data from the tests using the strain-cut and saw-cut methods, which are explained and discussed by Agredo Chávez et al. (2024).

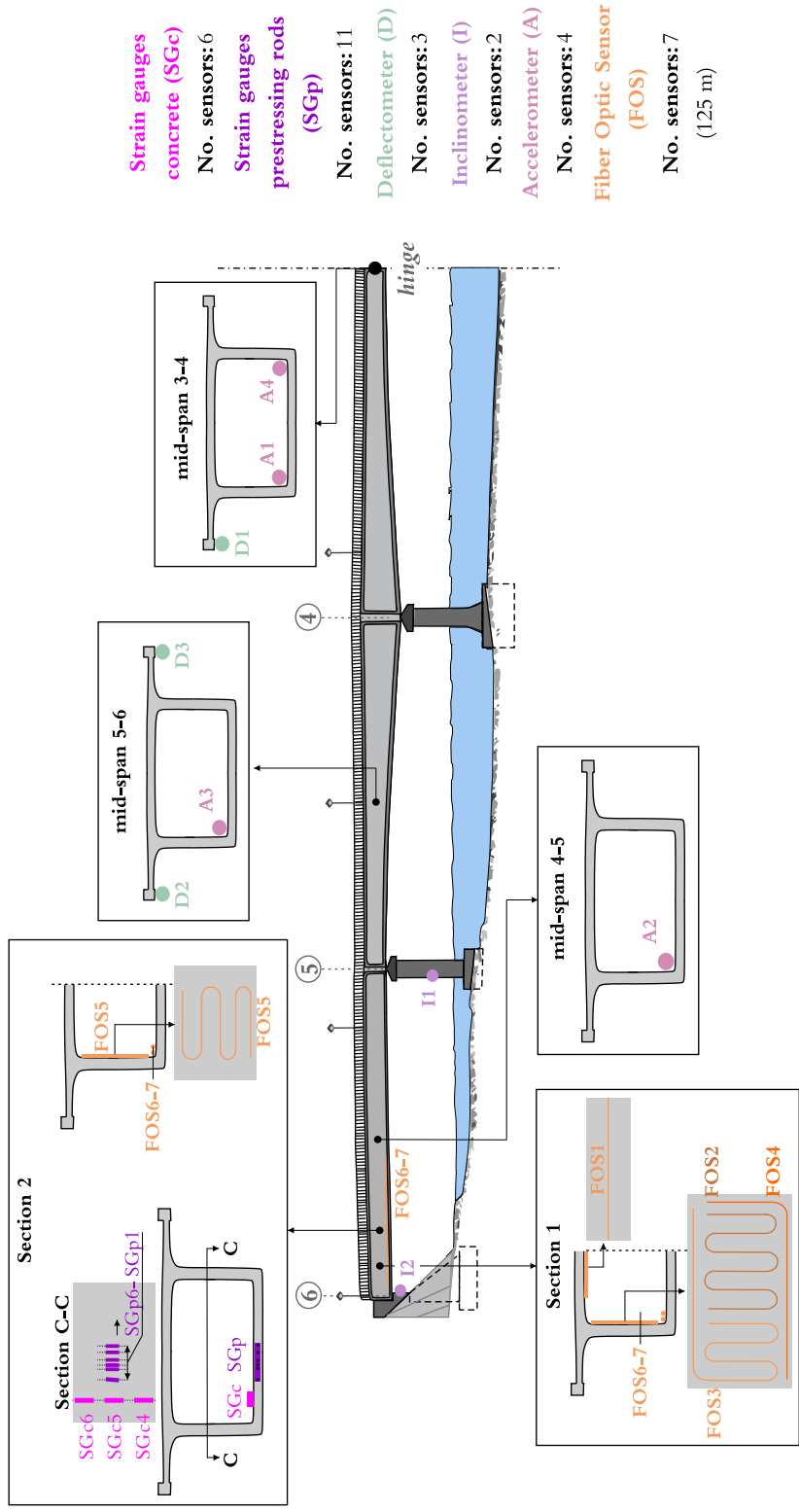


Figure 22. Kalix bridge instrumentation.

In addition to these tests and the proof loading, material testing was conducted. A total of 108 concrete cores were extracted from various sections of the bridge and from different elements of the box girder. Representative pictures of the concrete sampling, residual prestress tests, and FOS installation are presented in Figure 26 to Figure 28, respectively. The complete set of experimental results from all tests is compiled in a series of related publications (Agredo et al., 2023; Agredo-Chávez et al., 2023; Agredo Chávez et al., 2024; Sas et al., 2024).



**Figure 23.** Instrumentation for a. strain cut and b. saw cut methods.



**Figure 24.** Instrumentation with FOS.



**Figure 25.** a. Drilling of concrete cores and b. concrete strength test with Schmit hammer.

### *Step 3 – Structural FE modeling*

A linear elastic model was developed using Robot structural Analysis (Autodesk, 2022) by Agredo et al. (2023), and it was calibrated using experimental data from proof loading,

residual prestress, and material tests. The model consisted of continuous frame elements joined by a hinge which allows for independent longitudinal displacement and bending rotations of the two connected cantilever ends. The sectional and material properties were initially assigned based on the original design parameters. Prestressing was modeled using the load balancing method, in which the tendon effects are represented through an equivalent system consisting of nodal forces and a distributed load. The distributed component varies along the frame element in accordance with the local curvature of the tendon profile, ensuring that the equivalent balancing load reproduces the effects associated with the tendon's curvature.

A progressive calibration approach was employed to iteratively update material properties and boundary conditions, which gradually improved model alignment with the observed data. The calibration process indicated a stiffer structural response than initially predicted from the technical drawing. After the calibration, discrepancies of less than 8% between the numerical model and monitoring data were reached across the tested load cases (Agredo et al., 2023).

#### *Step 4 and 5 – Reliability analysis and Bayesian updating*

Two reliability analyses were conducted in this project, referred to as the prior and posterior reliability analyses, presented in [Paper III](#). The prior analysis was performed without incorporating information obtained from the residual prestress tests and material property measurements. Subsequently, a posterior reliability analysis was carried out using Bayesian updating of these parameters. This approach enabled quantification of the impact of the newly acquired information on the reliability estimates.

The procedure of the performed reliability analysis is displayed in Figure 26. The obtained results are presented in Figure 27a for when only concrete properties were updated and Figure 27b when both concrete and residual prestress were updated.

The results showed a significant increase in reliability levels after incorporating new test data. The measured concrete strength ( $f_c$ ) was higher than the one specified in the as-built drawings, leading to an increase in  $\beta$  from 0.78 to 1.75 in the year 66. When the results from the saw-cut and strand-cut tests were included,  $\beta$  further increased to 2.35 and 2.84, respectively. These findings emphasize the importance of obtaining accurate estimates of residual prestressing in existing prestressed concrete bridges, particularly those susceptible to crack development.

#### *Step 6 – Remaining Service life (RSL)*

After completing the reliability analysis, the results were compared with the target reliability indices specified in the Model Code 2010 (CEB-FIP M, 2012) and the JCSS Probabilistic Model Code (JCSS, 2001), which are 1.5 and 1.3, respectively, for the

Serviceability Limit State (SLS). It is worth noting that SLS target levels are difficult to define, as they are case-dependent and not well established for existing structures.

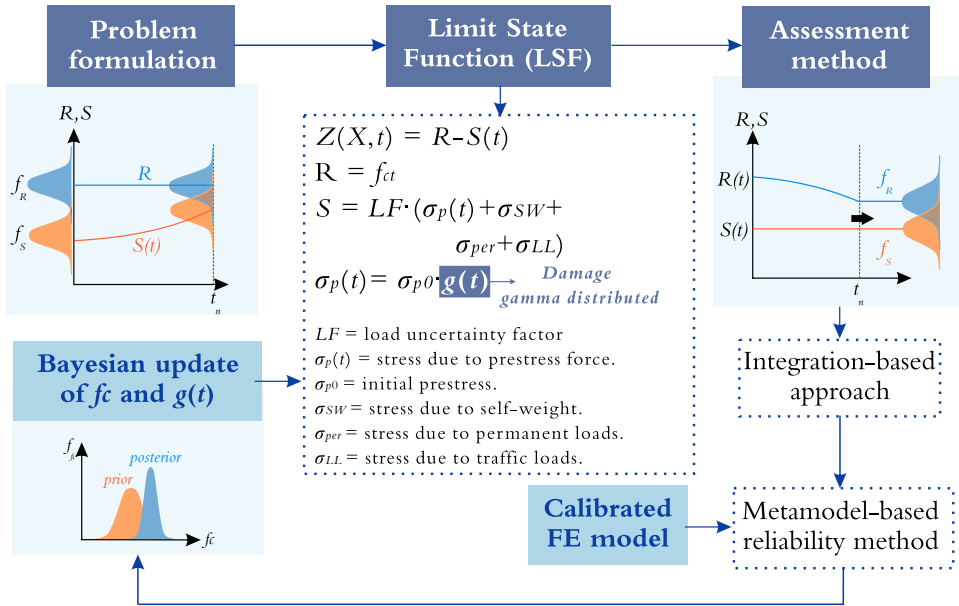


Figure 26. Reliability analysis procedure for the Kalix bridge case.

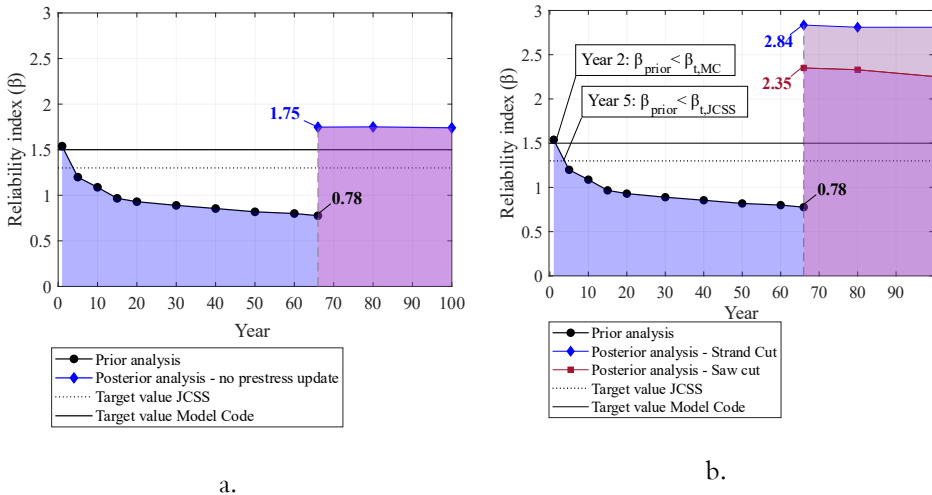


Figure 27. a. Reliability results for a. prior and b. posterior analyses.

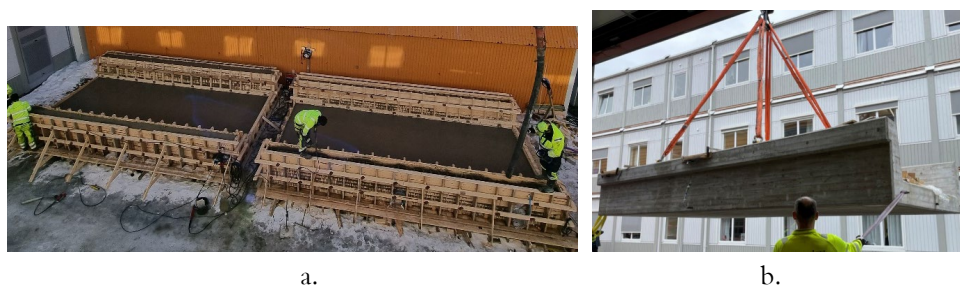
When compared to these reference values, the structure without updated information reached the target reliability levels within the first and fifth years of service according to

the Model Code and JCSS, respectively. In contrast, after updating the material properties, the reliability levels increased substantially, demonstrating a remaining service life exceeding 36 years and  $\beta$  values consistently above the required thresholds.

### 4.3 Trough bridge

The second real case, presented in [Paper IV](#) and [Paper V](#), was selected due to the high representativeness of trough bridges within the Swedish railway bridge population, which comprises approximately 4400 bridges in total. Moreover, along one of the most important railway lines in northern Sweden, the *Malmbanan* (translated as the *Ore Line*, often referred to as the *Iron Ore Line*), trough bridges account for approximately 40% of its total bridge population. The Iron Ore Line is Sweden's most loaded railway, serving as a critical link for both passenger transport and freight operations. It extends approximately 500 km from Boden to Riksgränsen and continues to Narvik in Norway. The section between Boden and Luleå is officially part of the Main Line through Upper Norrland (Trafikverket, 2025).

Given the significance of the Iron Ore Line and the large proportion of trough bridges along this route, a representative RC trough bridge was selected as the case study. To this end, two RC trough bridges were cast at Luleå University of Technology (LTU) in 2022 (see [Figure 28](#)). The geometry and design of these structures were based on a previously tested and decommissioned trough bridge (Paulsson et al., 1996).



**Figure 28.** a. trough bridges cast at LTU and b. transportation of one of the bridges to the laboratory.

The application of the framework presented in [Chapter 3](#) to this case study is illustrated in [Figure 29](#), which outlines the main steps and highlights the key aspects of each. A brief description of each step, along with the main results and findings from the case study, is provided below.

#### *Step 1 – Hazard and condition assessment*

Since the primary action on the structure is cyclic loading representative of heavy railway traffic, fatigue is the main concern in this case. Replicating the environmental conditions

of full-scale bridges in a laboratory setting is challenging; therefore, only the loading effects were considered, with the focus placed on fatigue-induced damage. The available information for the design of the experimental test was:

- Geometrical properties
- Reinforcement layout
- Design material properties
- Traffic load (freight and passengers) from years 2009–2022, provided by Trafikverket.

Iron ore production estimates reported by LKAB for years before 2009.

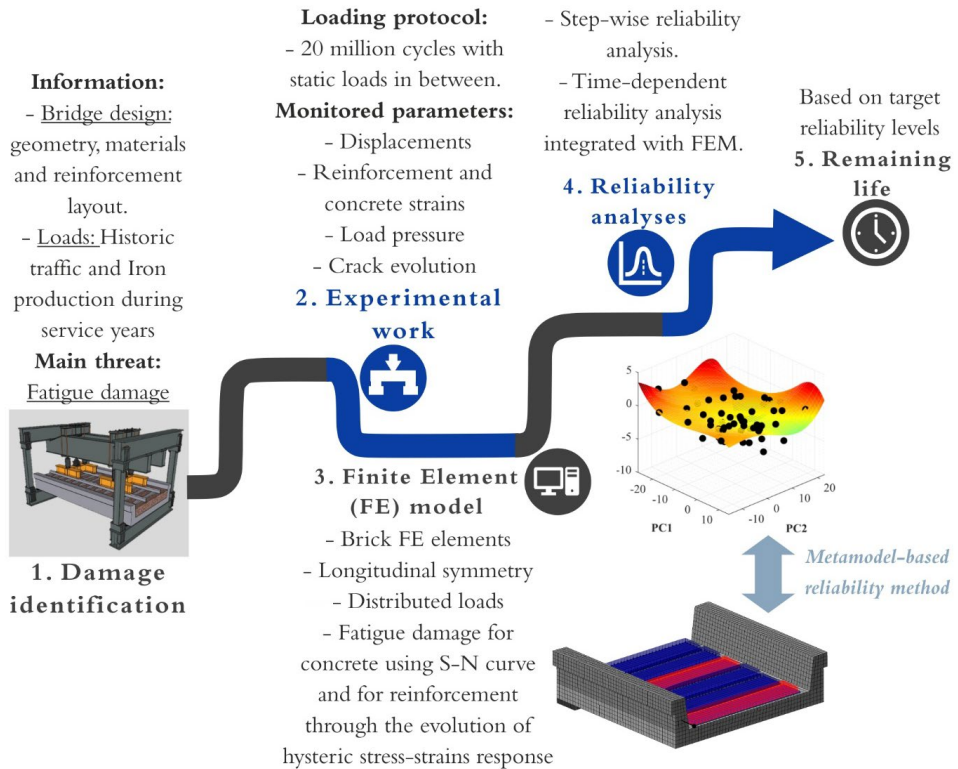


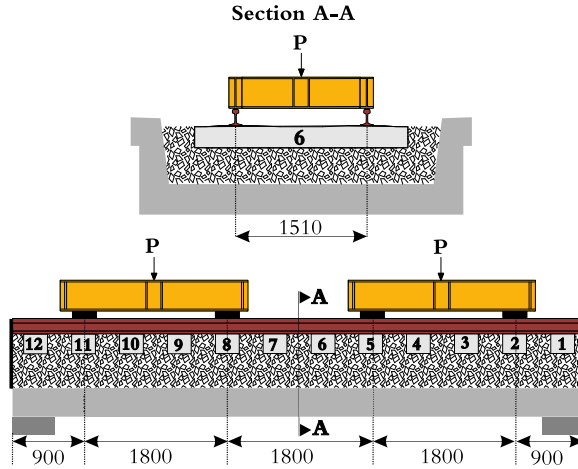
Figure 29. Framework applied to the case of an RC trough bridge.

### Step 2 – Monitoring and testing strategy

Based on the collected information, a load protocol was developed for the experimental test. The objective was to replicate the historical railway traffic loading from 1968 to the present and to project future traffic considering potential increases in axle loads. Historically, the allowable axle load has varied over time due to the growing demand for iron transport; these variations were therefore incorporated into the design of the load protocol. A total of 14 million cycles were estimated to represent the traffic from 1968

to 2025, with an additional 6 million cycles projected to simulate future traffic up to 2035, resulting in a total of 20 million cycles. The loading cycles were divided into stages, described in Paper IV, to allow for periodic inspections of the bridge, test setup and data acquisition systems.

The load configuration on the bridge was defined to represent the worst-case scenario of a fully loaded condition. Accordingly, four axle loads corresponding to two bogies positioned as depicted in Figure 30.



**Figure 30.** Test set-up.

The objectives of the test were to evaluate the evolution of fatigue degradation in the structure and to examine how traffic loads are distributed on the concrete slab, comparing the results with current design standards. Once the loading protocol and testing objectives were established, the monitoring system for the experiment was designed.

The key structural responses relevant for fatigue assessment and stiffness degradation control included strains in concrete and reinforcement, displacements at locations of maximum bending moments, and crack propagation. These measurements correspond to the superstructure behavior; however, since the railway track system (ballast, sleepers, and rails) also significantly influences the structural response. Thus, additional measurements were taken, namely displacements and strains in the sleepers, strains in the rails, loads transmitted through the ballast, and strains in the load frame.

Considering the parameters to be monitored, the available budget, and the data acquisition capacity, the types and layout of sensors were defined accordingly, as illustrated in Figure 31. The placement of the sensors was determined based on preliminary calculations, which identified the mid-span and other sections of interest with

elevated stress levels, consistent with the single-span configuration and applied load pattern.

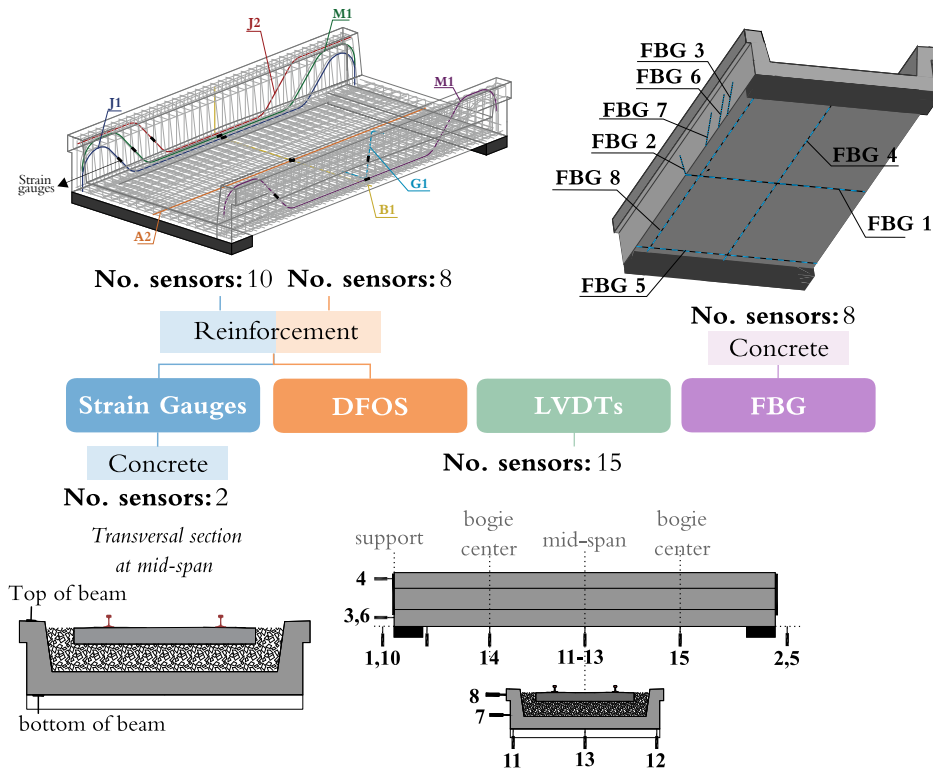
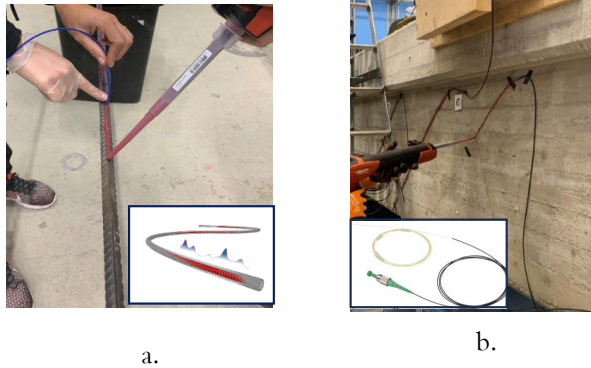


Figure 31. Sensors installed for monitoring of trough bridge.

Three types of sensors were used to measure strain: Distributed Fiber Optic Sensors (DFOS), Fiber Bragg Grating (FBG) sensors, and conventional strain gauges. DFOS enables continuous strain measurement along the entire fiber, while FBG sensors provide measurements at discrete points. Strain gauges were used to introduce redundancy and to validate the FOS measurements. Displacements were measured using Linear Variable Differential Transformers (LVDTs), while crack propagation was monitored through photogrammetry and visual inspections. Figure 32a shows the installation of the DFOS on a reinforcement bar, while Figure 32b illustrates the installation of the FBG sensors on the concrete surface of the beams.

The experimental results up to Stage 14 (10 million cycles) were presented and discussed in Paper IV. In addition to the loading tests, complementary material testing was carried out to determine key mechanical properties of the concrete, including compressive strength, tensile strength, fracture energy, and modulus of elasticity.

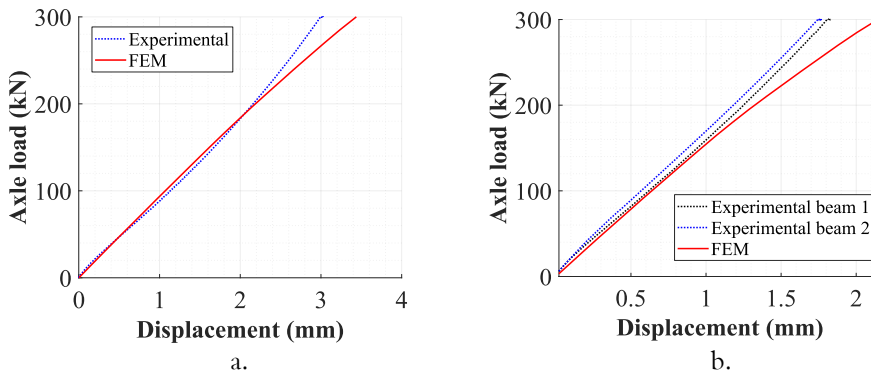


**Figure 32.** Instrumentation with a. DFOS and b. FBG.

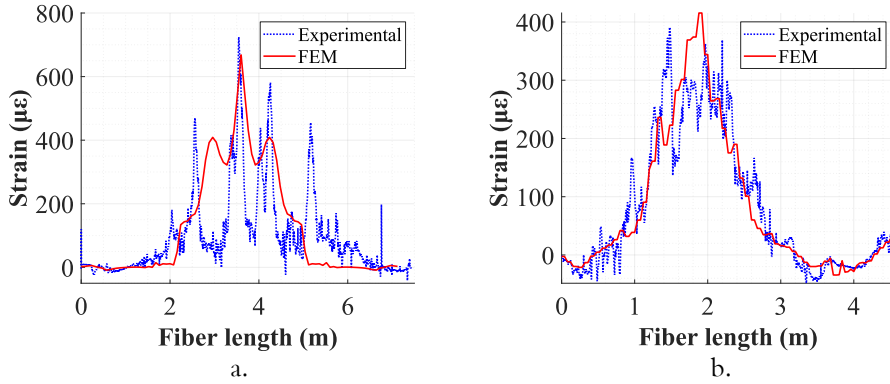
### Step 3 – Structural FE modeling

The FE model was developed using the ATENA Science software, and it is described in Paper V. The model incorporated the measured material properties, the actual geometrical characteristics of the tested bridge, and the damage due to cyclic loading. Calibration of the model involved adjusting the boundary conditions, material parameters, and load distribution to achieve the best possible agreement between the simulated and experimentally observed displacements and strains.

For the model calibration, the key parameters considered were the maximum displacements of the beams and slab, as well as the strain distribution in the reinforcement. Figure 33 and Figure 34 present a comparison between the FE model predictions and the experimental results after 10 million cycles. The calibration yielded a realistic representation of the structure's maximum responses, which are directly related to potential failure modes and reliability assessment. The FE model successfully reproduced the strain peaks and maximum slab displacements observed experimentally.



**Figure 33.** Comparison of experimental and FEM displacements at mid-span for a). the slab and b). the beams.

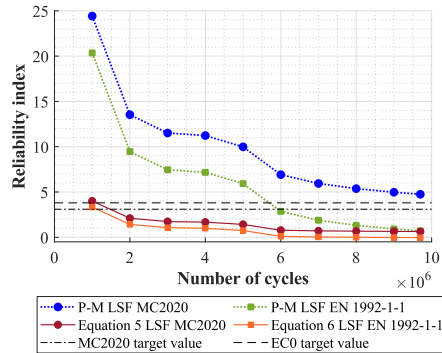


**Figure 34.** Comparison of experimental and FEM strains in the a). longitudinal reinforcement bar in the slab (A2) and b). transversal reinforcement bar in the slab (B1).

*Step 4 – Reliability analyses*

The reliability analysis was conducted by accounting for the degradation of resistance caused by fatigue accumulation in the reinforcement. Monitoring data indicated that the slab was the most heavily loaded component, with the highest strain levels observed in the longitudinal rebars within the slab. For this case study, a multi-level or stepwise reliability analysis was performed to evaluate how the incorporation of additional information and progressive refinement of the analysis influenced the accuracy of the safety assessment. A preliminary analysis was presented in Paper IV, where a slightly different set of random variables was adopted compared to Paper V, in which the factors were defined with greater precision and refinement.

The preliminary reliability results are shown in Figure 35, which compares the reliability obtained using the P-M LSF approach based on both MC2020 and EN 1992-1-1 codes, as well as the simplified code-based approach presented in Equations 23-24.

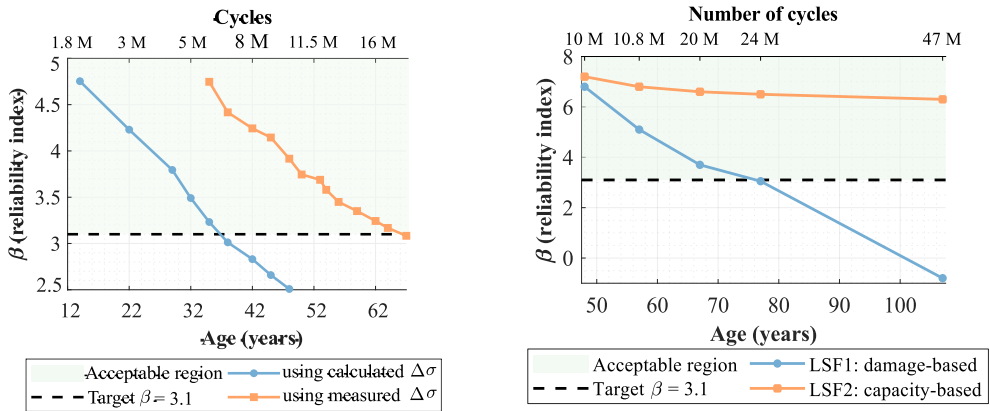


**Figure 35.** Preliminary reliability analysis.

$$\gamma_{Sd} \cdot \max \Delta \sigma_S \leq \Delta \sigma_{Rsk} / \gamma_{S, fat} \quad 23$$

$$\gamma_{F, fat} \cdot \Delta \sigma_{S, equ}(N^*) \leq \Delta \sigma_{Rsk}(N^*) / \gamma_{S, fat} \quad 24$$

In the final step of the reliability analysis, the calibrated FE model was integrated with the proposed metamodel-based reliability approach presented in Paper II. Two LSFs were considered: LSF1, based on the S–N curve and the Palmgren–Miner (P–M) rule for cumulative damage, where failure is defined by reaching a specified damage threshold; and LSF2, a capacity-based formulation comparing the static load resistance after 10 million cycles with the allowable axle load. The results of the simplified reliability analyses are presented in Figure 36a, while the outcomes of the final, more refined reliability analysis are shown in Figure 36b.



**Figure 36.** Comparison of reliability analyses for a. first and second level reliability analyses and b. third-level reliability analysis for LSF1 and LSF2.

The reliability analyses highlighted the significance of incorporating monitoring data to achieve accurate assessments of structural performance. When monitoring data was not considered, the reliability index remained below the target level before reaching 10 million cycles. In contrast, when the monitoring data were integrated, the reliability index reached the target at approximately 18 million cycles. Moreover, incorporating the calibrated FE model to represent the structural system and predict future responses led to an increase in the reliability index at 10 million cycles from 3.97 to 6.8 for LSF1. LSF2 exhibited higher reliability levels, indicating that the reserve capacity after cyclic loading was not the governing limit state; instead, LSF1 proved to be the more critical condition.

Step 4 – Failure probability updating

For this case, the reliability was updating using the survival information. This study has included experimental data until Stage 14 which corresponds to 10 million cycles and 48 years of service. The value of  $\beta$  was updated first considering that the structure has survived the 10 million cycles and then that the test continued and the structure was able to survive 18 million cycles. Figure 37 shows the comparison between the initial reliability values and the updated ones for both LSFs.

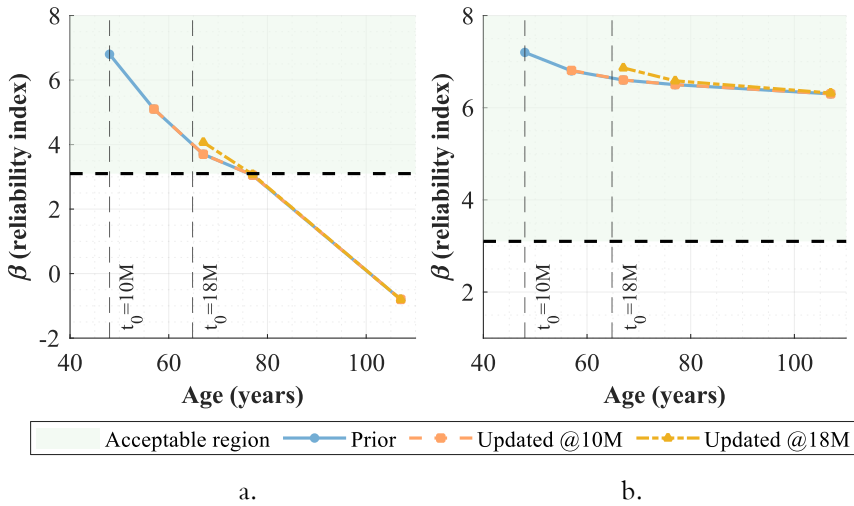


Figure 37. Updating of reliability index with survival information for a. LSF1 and b. LSF2.

Updating the survival information led to only minor changes in the reliability index, indicating that when the prior reliability is already high, survival data contribute limited additional information. When using the survival information at 18 million cycles, a more pronounced effect was obtained, attributed to the fact that the structure had exceeded its original design life by a significant margin, and the prior failure probabilities were closer to the target threshold, thereby making the survival evidence more informative.

Step 5 – Remaining Service Life (RSL)

After completing the design loading of 10 million cycles, the tested trough bridge demonstrated an RSL of approximately 27 years (see Figure 38). This finding indicates that the bridge has sufficient fatigue resistance to endure loading beyond 10 million cycles without compromising the prescribed reliability criteria.

Step 6 – Allowable axle load

After performing the reliability analysis and confirming that the reliability levels exceeded the required thresholds, an additional analysis was carried out in which the mean axle load was incrementally increased until the target reliability level was reached. This

procedure was repeated at different points in time. Figure 39a illustrates the extent to which the mean of the axle load distribution can be increased to achieve the target reliability index ( $\beta_t$ ), while Figure 39b presents the corresponding load increase factors.

The results demonstrate how reliability analysis can be effectively employed to estimate potential increases in allowable axle loads for existing bridges in service, while explicitly accounting for real monitoring data and inherent uncertainties.

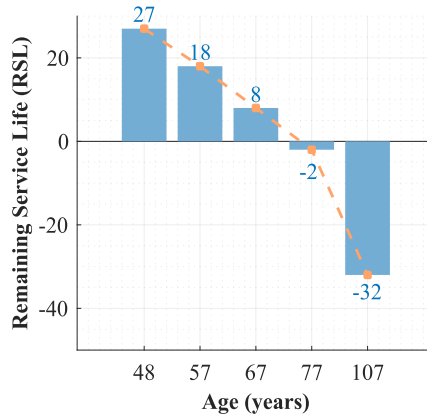


Figure 38. Remaining useful life using LSF1.

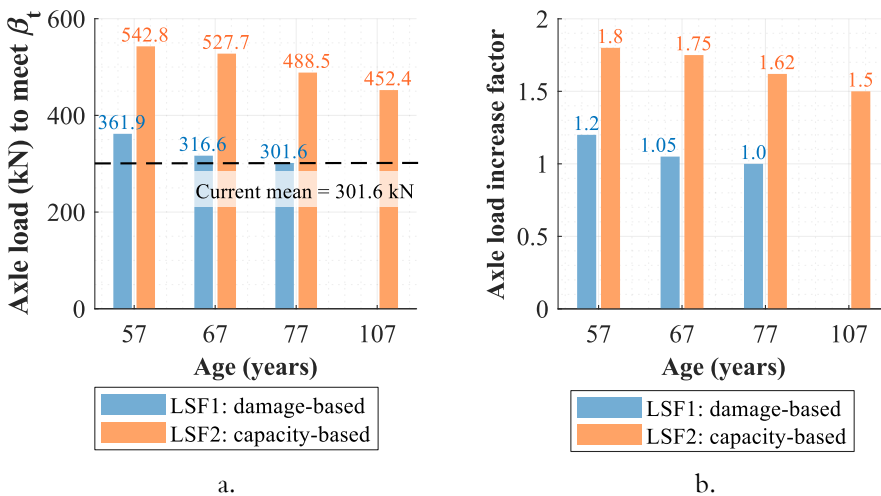


Figure 39. a). Maximum load for the different points in time for LSF1 and LSF2 and b). Load factors increase for LSF1 and LSF2.

Overall, the fatigue reliability results reveal significant differences between code-based verification methods and the proposed framework. The preliminary analyses performed using the simplified fatigue verification formulations yielded very low reliability indices,

after 10 million cycles it was obtained a  $\beta = -0.04$  according to Eurocode EN 1992-1-1 and  $\beta = 0.63$  using the fib Model Code 2020 (MC2020). When the P–M-based reliability analysis was implemented, the value improved to  $\beta = 0.7$  for Eurocode and  $\beta = 3.97$  for MC2020, indicating that the latter provides a less conservative fatigue model. However, when the P–M rule was combined with a calibrated FE model, allowing the inclusion of additional random variables such as the concrete mechanical properties, the reliability index increased markedly to  $\beta = 6.8$  (70% more).

This demonstrates that code-based formulations, which rely on simplified fatigue models and include the use of partial safety factors, substantially underestimate the actual fatigue performance of existing structures. These methods are primarily intended for new designs and are therefore less suited to in-service bridges, as they adopt stress-based simplifications and neglect the variability and interaction of material properties. In contrast, the combined P–M and FE-based probabilistic framework provide a more realistic representation of fatigue behavior by explicitly considering uncertainties in parameters governing structural degradation, thereby enabling more accurate service-life predictions.



## 5. Conclusions

### 5.1 Methodological contributions and findings

This thesis developed and applied a comprehensive methodology for evaluating the RSL of existing bridges by integrating TdR analysis, FE modelling, and full-scale experimental data. This methodology demonstrates that combining probabilistic modelling, numerical simulation, and experimental evidence provides a robust and realistic assessment of structural performance and degradation over time.

To improve the applicability of TdR, a time-integration approach is suggested, allowing the evaluation of reliability at discrete time intervals using time-invariant reliability methods. This makes TdR analyses more practical while preserving accuracy in capturing degradation effects. In addition, an enhanced metamodel-based reliability algorithm integrating Kriging, learning functions, and Copula theory was proposed to accelerate convergence and maintain high precision in the estimation of failure probability, particularly for nonlinear FE models and dependent random variables.

The resulting workflow effectively links experimental measurements, FE model calibration, and probabilistic updating, enabling reliability assessments that reflect the actual structural condition rather than relying on assumed parameters. This integration advances existing frameworks by providing a clear and efficient procedure for coupling TdR with FE modelling and monitoring data to achieve more realistic RSL estimations.

### 5.2 Application and case study insights

The proposed framework was applied and validated through two representative bridge case studies: a PC roadway bridge and a RC railway trough bridge. These applications demonstrated the practical feasibility and benefits of integrating monitoring data, FE modelling, and reliability-based evaluation.

Both case studies confirmed that incorporating measured structural data, such as residual prestress, strains, and displacements, significantly reduces epistemic uncertainty and

improves the accuracy of RSL predictions. They also showed that combining FE model calibration with TdR analysis provides a consistent means to capture degradation mechanisms and evaluate performance evolution under realistic conditions. Both cases have shown that they could remain safely in service well beyond their nominal design life when evaluated using the proposed methodology.

Overall, the case studies validated the framework's practical applicability to different structural typologies and degradation processes, illustrating its versatility as a tool for assessing existing concrete bridges based on available experimental or monitoring data.

### **5.3 Practical and research implications**

The methodology proposed supports more realistic, data-informed evaluations of structural safety and serviceability, enabling more confident decisions regarding maintenance, load capacity, and remaining service life. For practice, it offers engineers a pathway to move beyond simplified code-based assessments by incorporating monitoring information and model updating, while maintaining a level of simplicity that facilitates its practical implementation. By structuring the reliability evaluation within a clear and computationally efficient framework, the proposed approach reduces the complexity often associated with probabilistic methods, making it more suitable for real-world engineering applications. This, in turn, enables better resource allocation and contributes to extending the service life of ageing infrastructure.

For research, the methodology provides a foundation for further developments toward network-level reliability assessments, risk-based maintenance planning, and decision-support systems that combine probabilistic performance evaluation with broader bridge management strategies.

### **5.4 Hypothesis and research questions**

This section addresses the central hypothesis and the research questions formulated in [Chapter 1](#) of the thesis. The answers are supported by the results obtained through the development and application of the proposed framework across the different case studies.

#### **Hypothesis:**

The remaining life of existing bridges can be more accurately assessed by integrating full-scale experimental data, calibrated FE models, and time-dependent reliability analysis.

The findings across the conducted studies confirm this hypothesis. The integration of experimental data, numerical modelling, and probabilistic analysis proved essential for accurately capturing the structural condition and predicting the RSL of existing bridges.

Experimental measurements, such as strains, displacements, and residual prestress, reduced epistemic uncertainty in key parameters governing degradation, while the calibrated FE models replicated actual structural behavior under realistic loading conditions. The combination with TdR enabled quantification of reliability degradation over time, linking observed deterioration with probabilistic failure estimates.

Specifically, the application to both Kalix and trough bridges demonstrated that this integration yields into reliability indices that are significantly more consistent with observed performance than code-based or purely analytical assessments. Thus, the framework not only supports the hypothesis but also demonstrates that each component plays a complementary role: experimental data constrain uncertainty, FE modelling translates physical behavior into quantifiable response, and TdR generalizes these insights over time to provide a probabilistic measure of remaining life.

**Research questions:**

- (i) How can existing reliability methods be enhanced to improve the efficiency of failure probability ( $P_f$ ) estimation when integrated with FE modeling, while avoiding added analytical complexity?

Among the various metamodel strategies, the integration of Kriging models and learning functions has proven to be one of the most cost-effective approaches for reliability analysis. However, most existing strategies rely on achieving global accuracy across the entire response surface, which introduces unnecessary computational cost since reliability problems are inherently local, with accuracy required primarily near the failure domain, close to the most probable point (MPP). Current learning functions typically do not incorporate the MPP location into the adaptive sampling process when selecting the next optimal point.

To address these limitations, this study proposed a new Kriging-based metamodel algorithm that integrates learning functions with Copula theory. The algorithm, presented in [Paper II](#), utilizes information from the joint probability density function (PDF) to guide the adaptive search toward the most relevant region of the input space, thereby improving efficiency and convergence speed. Implemented using a Gaussian Copula, the method remains straightforward to apply and employs a convergence criterion based on the stabilization of the estimated failure probability, rather than solely on the learning function value.

This methodology demonstrated through several numerical examples significant advantages for problems involving FE modelling and dependent random variables, reducing the computational burden while maintaining high accuracy in failure probability estimation. The results from the FE example in [Paper II](#) demonstrated that, compared with a reference algorithm such as LHD-K-U, the proposed method reduced the number of FE simulations by 67% while maintaining a difference in failure probability of only 16%, representing a substantial gain in computational efficiency.

- (ii) To what extent can an integrated framework enhance the reliability and practical applicability of RSL assessments for existing bridges?

The integrated framework improves both the reliability and practical applicability of RSL assessments by unifying three essential components, TdR analysis, FE modelling, and experimental data, into a coherent methodology. TdR provides a means of quantifying resistance degradation and reliability evolution over time, while experimental data reduce epistemic uncertainties and enable calibration of FE models, which in turn improve the accuracy of structural response predictions. Ensuring that each component is implemented using practical and engineering-feasible tools enhances the framework's applicability in real-world settings.

The extent of improvement was assessed through validation using multiple real bridge case studies featuring different damage mechanisms. These applications demonstrated both methodological robustness and practical value. In [Paper I](#), TdR was used to assess corrosion-induced degradation and the resulting changes in reliability, redundancy and robustness. Two additional case studies, one involving a PC bridge and another a RC bridge, presented in [Papers III–V](#), further illustrated the benefits of integrating measured data and FE modelling within the framework. These studies confirmed that incorporating monitoring and testing data substantially enhances RSL predictions by reducing uncertainty in key parameters governing the failure modes.

Quantitatively, the improvements were significant. Compared with simplified analyses, integrating FE modelling and experimental data led to considerably higher reliability estimates. Increases of 201% and 264% for the PC bridge at 66 years of service in [Paper III](#) (using two different testing approaches), and an increase of 172% for the RC bridge at 48 years of service in [Paper V](#). These results demonstrate that the proposed integrated framework provides more reliable, data-informed, and practically applicable RSL assessments for existing bridge structures.

- (iii) What is the impact of destructive and non-destructive testing for residual prestress measurement on the evaluation of the RSL and reliability levels of prestressed concrete (PC) bridges?

Although long-term prestress losses have a limited effect on the ultimate load capacity of PC bridges, they have a significant influence on their long-term performance and serviceability. Therefore, accurately predicting these losses is essential to ensure the durability and serviceability of PC structures throughout their lifespan. Despite their importance, few studies have fully integrated uncertainties into predictive models for estimating a structure's RSL based on updated residual prestress data obtained from on-site testing.

[Paper III](#) addresses this gap by incorporating experimental data from both DT and NDT into TdR assessments. The probabilistic analysis conducted for the Kalix Bridge demonstrated that the inclusion of residual prestress measurements substantially improved the accuracy of RSL predictions. Updating the probabilistic distributions of prestress

losses and concrete compressive strength yielded notable improvements in reliability levels, with the calculated  $\beta$  increasing from 0.78 to 2.35 and 2.84 when using the saw-cut and strand-cut methods, respectively.

These findings underscore the importance of integrating experimental prestress data into reliability-based assessments to achieve more realistic and data-driven evaluations of structural performance. This approach enables more accurate condition assessments and supports informed decision-making for effective lifecycle management of existing PC bridges.

- (iv) What are the degradation and reliability levels of typical railway RC bridges after completion of their design fatigue cycles?

After experimentally applying a load history representative of a full design fatigue life, equivalent to 10 million cycles, the tested railway RC bridge exhibited a 29% reduction in global stiffness, yet all key response parameters remained within acceptable performance limits. The highest recorded strain occurred in the longitudinal reinforcement of the slab at mid-span, reaching 710  $\mu\epsilon$ , which remains well below the typical yield strain of reinforcement steel (2000–2500  $\mu\epsilon$ ). The observed cracks had a maximum width of 0.25 mm, and the maximum mid-span displacement in the slab was 3.0 mm, all indicating that the overall structural condition remained satisfactory after the applied loading.

Using the proposed framework, the reliability index for a representative railway RC bridge was  $\beta = 6.8$  for a fatigue damage-based LSF, a value substantially higher than the target fatigue reliability indices prescribed in design codes such as fib Model Code 2020 ( $\beta = 3.1$ ) and EN 1990 ( $\beta = 3.8$ ). This result indicates that typical railway RC trough bridges demonstrate safety margins well above those required by current design codes, suggesting that such structures may possess reserve capacity or RSL beyond their nominal design assumptions.

By projecting future traffic scenarios and estimating cumulative fatigue damage, it was determined that the bridge could safely sustain an additional 27 years of service before reaching the target reliability threshold. Alternatively, an increase in axle load of approximately 20% (factor = 1.2) would still satisfy the prescribed safety criteria. The analysis also revealed that fatigue reliability governed the structural performance over time: while the ultimate capacity reliability index decreased only slightly (from  $\beta = 7.2$  to  $\beta = 6.3$ ) over a projected 100-year service life, the fatigue-based reliability dropped more sharply (from  $\beta = 6.8$  to  $\beta = -0.8$ ).

These findings indicate that this type of bridge remains structurally safe under existing traffic loads but highlight the need for additional information on environmental influences, such as temperature variations and corrosion effects, to refine future reliability and RSL predictions. If traffic load effects alone are considered, the current structures can be regarded as structurally sound and performing well within safe limits.

Overall, this research contributes to the ongoing transition toward more data-driven and performance-oriented bridge management practices, strengthening the connection between reliability research and practical engineering applications. It aligns with international efforts to shift from prescriptive, design-based evaluations toward performance- and reliability-based assessment frameworks, complementing these developments by offering a practical and transparent approach that links structural monitoring and digital modelling with reliability-based evaluation.

## 6. Future work

Although the developed framework successfully integrates a group of strategies and analyses to evaluate the RSL of existing bridges, several aspects can be further explored to enhance its applicability and accuracy in future research.

From a methodological perspective, since the framework developed in this thesis was applied at the individual bridge level, future efforts could extend the framework to the network scale, enabling the assessment of entire bridge inventories. A network-level approach would facilitate prioritization of maintenance and rehabilitation actions, contributing to more efficient allocation of resources across infrastructure systems. Furthermore, future research can be addressed to incorporate combined effects of different degradation mechanisms, such as corrosion–fatigue interaction, alkali–silica reaction (ASR), frost damage, and chloride-induced cracking, particularly in bridges exposed to harsh climates. Integrating these mechanisms into the time-dependent reliability framework would provide a more comprehensive representation of structural degradation processes over service life.

Additionally, experimental extensions are essential to validate and strengthen the conclusions drawn from this work. The experimental program developed in this thesis can be further expanded to obtain more detailed insights into the condition and degradation of the structures studied. For example, a section of the Kalix Bridge has been transported to LTU facilities, providing an opportunity for in-depth inspections to identify signs of deterioration and to perform supplementary evaluations of residual prestress. In the case of the laboratory-tested trough bridge, additional fatigue cycles should be applied to track the continued progression of damage and its effects on stiffness, cracking, and residual capacity. Once significant damage has occurred, strengthening strategies could be implemented and experimentally assessed to evaluate their effectiveness in restoring structural performance, thereby generating valuable data for future model calibration and reliability-based assessment of rehabilitated bridges.

Alongside laboratory testing, to better capture the complex behavior of these structures under in-service conditions, on-site experimental campaigns are recommended. Field

testing would allow the inclusion of environmental factors such as temperature fluctuations, humidity, freeze–thaw cycles, and corrosion progression, which have significant effects on material properties and long-term resistance. This would enable the validation and calibration of the degradation models under more representative conditions and further improve the predictive accuracy of the proposed framework.

Finally, to strengthen the practical relevance of the proposed methodology, future work should aim to integrate reliability-based assessments with risk and decision analysis tools. Such integration would support maintenance planning, life-cycle cost optimization, and resilience-based decision-making, allowing engineers and asset managers to evaluate trade-offs between safety, cost, and service continuity.

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