Report

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Norwegian University of
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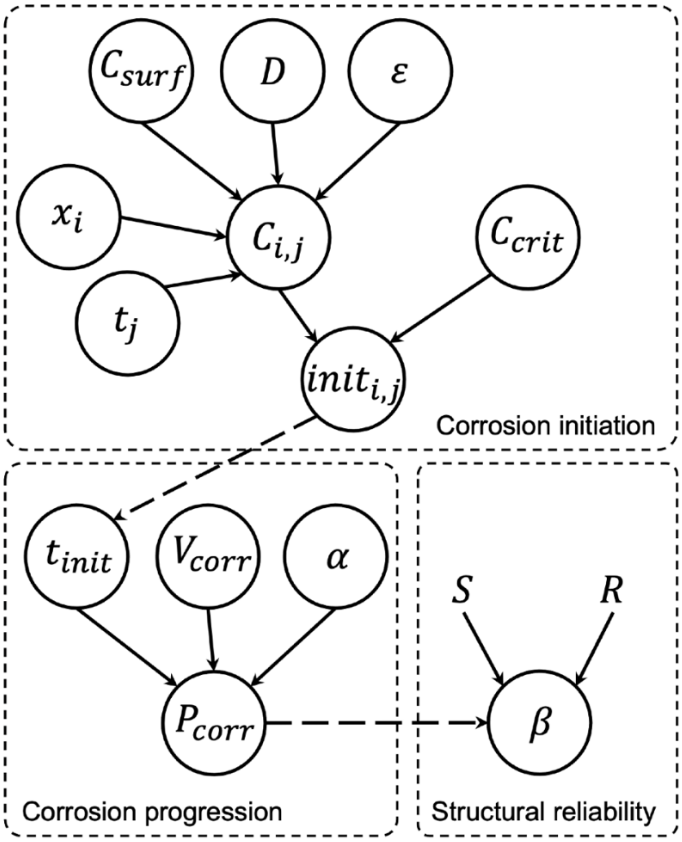
Decision-making and structural evaluation of a corroding reinforced concrete bridge incorporating new information.

Herøy FoU: WP4 activities report

Trondheim – January – 2025



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Abstract

This report presents the final outcomes of Work Package 4: Reliability and Uncertainty Quantification, demonstrating its potential for enhancing decision-making in bridge maintenance. A summary is provided here, while the detailed study is published elsewhere, with appropriate references given.

In practice, the structural safety of existing bridges is primarily assessed through periodic visual inspections. However, the impact of collected inspection data on structural reliability and subsequent mitigation measures is typically considered only qualitatively. While advanced methods exist for consistent decision-making based on structural reliability analysis informed by inspection data, these methods have yet to be widely implemented in practice.

To accelerate this implementation, a rational and practical decision-making framework has been developed and applied to a case study. The framework incorporates corrosion initiation and propagation modeling, updating reinforcement cross-section loss based on chloride measurement data. This loss is then integrated into the shear failure limit state, allowing for an estimation of the probability of failure. The decision problem is formulated based on this probability, along with the consequences of failure and potential mitigation actions. Within this modeling framework, chloride measurements directly influence decision-making.

Additionally, a simple evaluation tool is introduced to assess the effectiveness of maintenance interventions, utilizing the infinite renewal assumption. The proposed framework is adaptable to various deterioration mechanisms and diverse types of inspection data. By implementing this approach, bridge owners gain access to structured methodologies that enable them to optimize maintenance strategies, ensuring safe and reliable infrastructure within constrained budgets.

Key words: Assessment of existing structures, Bayesian decision-making, structural reliability informed by data, efficient bridge maintenance, deterioration, chloride-induced corrosion

Contents

1 Introduction

Infrastructure owners are responsible for ensuring the structural safety of thousands of bridges throughout their service life. A typical bridge stock is diverse, with significant variation in age, structural type, material properties, and importance. Additionally, bridges are subjected to different environmental conditions, including climate actions and traffic loads, making their assessment unique for each individual structure.

To manage this complexity, national road authorities, such as the Norwegian Public Roads Administration (NPRA), have established standardized procedures for inspection and assessment. According to the NPRA bridge inspection handbook [5], visual inspections form the basis for planning maintenance activities by classifying the extent and consequences of damages on a qualitative scale from one to four. More detailed inspections are conducted every five years, and special inspections are performed when necessary. Findings from these inspections often lead to a load-bearing capacity assessment, which is also required when increasing the allowed traffic load or extending the service life of a structure. These assessments follow Eurocode guidelines, incorporating characteristic values and partial factors for materials and loads, as detailed in [3] and [4].

While national guidelines differ, general principles for assessment are similar across countries. However, there are areas where further developments could enhance current practice. First, the integration of information gained from inspections into structural assessments is not always formalized. Second, assessments are typically based on a semi-probabilistic safety format, assuming linear-elastic structural behavior and applying notional load models. Third, explicit guidance on how to account for deterioration and its future development remains limited. As a result, uncertainties in the assessment process may lead to conservative decisions that could, in some cases, result in unnecessary strengthening, traffic restrictions, or even bridge replacement. In other cases, verification may be challenging, despite the bridge performing satisfactorily.

Ongoing research worldwide aims to enhance methods for effective management of existing bridges. European initiatives such as COST Actions TU1406 (Quality specifications for roadway bridges) and TU1402 (Quantifying the value of structural health monitoring), as well as projects like SAFE-10-T (Safety of transport infrastructure on the TEN-T network) and IM-SAFE (Harmonized transport infrastructure monitoring in Europe), focus on improving assessment methodologies and decision-making tools. While significant progress has been made, practical implementation remains a challenge. The adoption of probabilistic methods in bridge assessment is one promising development that has not yet been fully realized. Recent efforts in Australia have led to the development of guidelines for probabilistic assessment [20], and studies have identified key factors influencing implementation, including justification, accessibility, effectiveness, and familiarity [21].

Bridge management involves making informed decisions on maintenance activities to ensure both safety and cost efficiency. In this study, a consistent decision-making framework for bridge management is developed and demonstrated through a case study. This includes:

- Probabilistic assessment of deterioration and safety,
- Explicit incorporation of new information from inspections,
- Prediction and updating of safety levels throughout a bridge's service life, and
- Evaluation of optimal maintenance decisions based on risk-based principles.

The framework is applied to a case study of chloride-induced corrosion in a reinforced concrete beam bridge, though the approach is adaptable to other degradation mechanisms and decision contexts. The objective is to demonstrate how infrastructure owners can benefit from structured decision support, utilizing advanced engineering analysis to optimize maintenance planning.

1.1 Structure of the Report

The report is structured as follows:

- **Section 2** discusses structural assessment as a decision problem and introduces Bayesian decision theory as a systematic framework for decision-making.
- **Section 3** presents the required modeling representations used in the framework, including models for deterioration and safety assessment.
- **Section 4** introduces the proposed framework, linking probabilistic models and assessment criteria in a structured manner.
- **Section 5** presents the results from the case study, illustrating the application of the framework and discussing its implications.

By providing a structured and scientifically grounded approach to bridge assessment and management, this work aims to support decision-making processes that balance safety, cost, and sustainability in infrastructure maintenance.

1.2 Related Research and Scientific Contributions

The research presented in this study was conducted alongside the Herøysund Bridge project but was financially supported by the Norwegian Public Roads Administration through the Smarter Vedlikehold program. A comprehensive scientific foundation for the methods applied in this study is documented in the PhD thesis of Frida Liljefors, which includes several peer-reviewed publications. In particular, Papers I, II, and III provide detailed insights directly relevant to the Herøysund case study.

Paper I: Decision Support for Corroding Bridges

Liljefors, F. and Köhler, J. (2023). Decision support and structural assessment of a corroding reinforced concrete bridge considering new information. *Structure and Infrastructure Engineering.* DOI: 10.1080/15732479.2023.2271962.

This paper presents a framework for integrating probabilistic assessment and decision analysis in the safety evaluation of corroding reinforced concrete bridges, using Herøysund Bridge as a case study.

Paper II: Framework for Rational Decision-Making

Liljefors, F. and Köhler, J. (2024). Framework for rational decision making in bridge maintenance. *Structure and Infrastructure Engineering.* DOI: 10.1080/15732479.2024.2371607.

This study expands on decision-making frameworks for bridge maintenance, focusing on optimizing inspection, intervention, and risk management strategies.

Paper III: Improved Structural Assessment Methods

Liljefors, F. and Köhler, J. (2024). Improved design value method for structural assessment by tailored alpha values exemplified on short reinforced concrete slab bridges. *Submitted to Structural Concrete.*

This paper refines design value methodologies for structural assessment, introducing tailored alpha values to enhance verification for existing concrete bridges.

Additional Contributions

Beyond the Herøysund project, Papers IV and V address broader challenges in structural assessment and maintenance planning:

- **Paper IV** explores the probabilistic assessment of heavy truck traffic and its impact on bridge safety, utilizing Weigh-in-Motion (WIM) data.

  Liljefors, F. and Köhler, J. (2023). Probabilistic considerations and use of WIM data for assessing structural safety effects of permitting 74-ton heavy trucks on Norwegian bridges. In *14th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP14, Dublin, Ireland.*

- **Paper V** examines the identification of governing safety criteria for existing bridges, considering economic, occupancy, and risk factors.

  Liljefors, F. and Köhler, J. (2024). Identification of governing structural safety criterion for existing bridges considering costs, occupancy and conditional fatality probability. In *12th International Conference on Bridge Maintenance, Safety and Management, IABMAS 2024, Copenhagen, Denmark.*

Together, these scientific contributions form a solid foundation for risk-based bridge assessment and decision support, advancing methods for more efficient and reliable infrastructure management.

2 Structural assessment as a decision problem

The design and construction of a new bridge follow a strictly regulated process with well-defined safety responsibilities. In contrast, the operation and maintenance phase is a continuous background activity, often lacking the same explicit oversight. However, by allowing continued use, the *bridge owner implicitly approves its safety*, making decisions on maintenance and interventions essential. This paper illustrates such a decision-making process using the *Herøysund Bridge*, a coastal bridge in Nordland, Norway, where *corrosion signs*—such as cracking, spalling, and rust stains—have been observed. Chloride measurements suggest potential reinforcement corrosion, but its extent remains uncertain. The bridge manager must choose between *repair, replacement, protective measures, or delaying action.* A rational framework is needed to systematically compare these alternatives.

Bayesian decision theory provides a structured approach for making decisions under uncertainty, balancing *probabilities, consequences, and personal preferences.* Originating from *utility theory* in game theory [28] and further developed in economics [24] and civil engineering [10], it enables optimal decision-making based on expected utility.

Figure 1 illustrates the three types of Bayesian decision analyses:

- **Prior analysis**, considering initial uncertainties.
- **Posterior analysis**, incorporating new information using *Bayes' theorem.*
- **Pre-posterior analysis**, optimizing data collection by weighing its potential value against costs.

By applying this framework, bridge owners can make informed, risk-based decisions, ensuring *safety and cost-effectiveness* in infrastructure management.

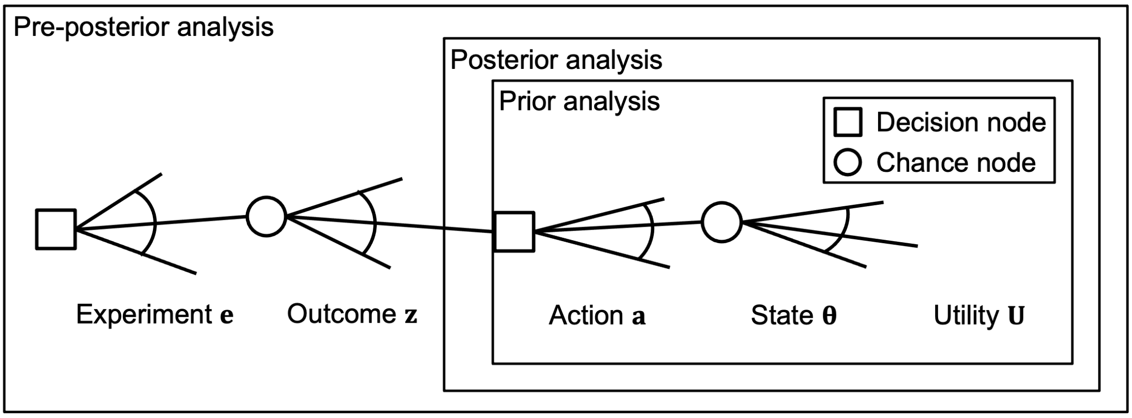

Figure 1: Bayesian decision-making framework.

Bayesian decision theory provides a structured framework for rational decision-making but is challenging to apply in practice. It requires accurate representations of structural uncertainty and the impact of potential actions. Structural reliability analysis offers a probabilistic approach to assessing failure risk but depends on underlying models and assumptions, making its application complex—particularly for deteriorating structures. Additionally, decision-makers' preferences must be clearly defined, typically by assigning utilities to failure and no-failure states. A practical approach is to set no failure at zero utility and quantify failure consequences as costs. As public infrastructure managers, bridge owners should align their decisions with societal preferences.

In practice, decision-makers rarely rely on failure probabilities and utilities but rather on experience, inspection reports, and capacity assessments. This paper explores how to bridge the gap between current practice and Bayesian decision theory, using the Herøysund Bridge as a case study.

3 Representation of relevant phenomena

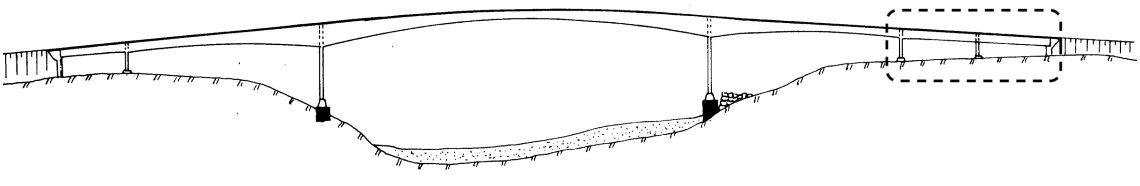

Figure 2: Drawing of Herøysund bridge. The side-spans under investigation are highlighted.

The decision problem is focused on selecting mitigation actions for the reinforced concrete beams in the side-spans (Figure 2), incorporating measured chloride content into the shear failure limit state assessment. This approach enhances current practice by integrating deterioration models and measurements into structural safety evaluations and extending deterministic verification with probabilistic and risk-based assessments. This section presents the model and assumptions, beginning with background on verification formats for limit states, followed by the modeling chain in Figure 3, covering shear reliability, chloride diffusion, and corrosion propagation.

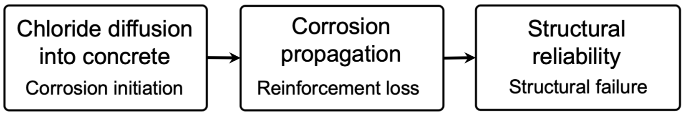

Figure 3: Overview of the modelling chain. Deterioration models at material level are incorporated into structural reliability.

3.1 Verfication formats

Structural safety and serviceability are typically evaluated by defining limit states that separate failure from safe conditions, such as ensuring that the moment effect does not exceed the moment capacity. These assessments can be conducted at different levels of sophistication, as outlined by JCSS [16]:

1. **Semi-probabilistic format** – Uses characteristic values and partial safety factors.
2. **Reliability-based format** – Considers basic random variables to quantify uncertainty.
3. **Risk-based format** – Explicitly accounts for consequences.

Semi-probabilistic methods are widely used in design codes for new structures, where uncertainties are managed through representative values and partial factors to ensure sufficient reliability. However, these factors are generally not valid for existing or deteriorated structures [1], as they do not explicitly consider reductions in steel area or allow for optimal maintenance decisions based on structural reliability and consequences.

Reliability-based methods represent uncertainties through probabilistic variables, estimating a structural reliability index β or failure probability P_f using $\beta = \Phi^{-1}(P_f)$. Acceptable safety levels are defined by a target reliability index β_t or target failure probability $P_{f,t}$. Unlike new structures, the target reliability for existing structures differs due to cost constraints, shorter reference periods, and the availability of additional information [29].

Risk-based methods extend probabilistic approaches by incorporating uncertainties and consequences in monetary terms, including factors such as human health and environmental impact. These methods align with Bayesian decision theory, where the objective is to maximize expected utility.

3.2 Structural Reliability Assessment for Shear

Bridges must meet safety and serviceability requirements, assessed using limit states that separate failure from safe conditions. Structural safety is typically evaluated through a combination of semi-probabilistic, reliability-based, or risk-based methods. For reassessment within the Norwegian road administration, NS 3473 has been applied with adjusted partial factors, including in earlier assessments of the Herøysund Bridge by Aas Jakobsen in 2020 [9]. In that assessment, the governing limit state was shear at section 2, the intermediate support of the continuous side spans without prestress. Here, this shear limit state is revisited and extended with a reliability analysis incorporating the uncertain reduction of steel area.

The structural limit state is formulated as:

$$g(\mathbf{X}, t) = V_R - V_S \leq 0 \tag{1}$$

where $\mathbf{X}$ represents the basic random variables, t the time-dependent deterioration, V_R the shear resistance, and V_S the shear load effect. While traffic loads are inherently time-variant, they are treated as time-invariant over a reference period, with resistance varying due to deterioration.

The total shear resistance follows NS 3473 [22]:

$$V_R = V_{con} + V_{reinf} \tag{2}$$

where V_{con} is the concrete shear capacity and V_{reinf} the shear reinforcement capacity, both dependent on material properties and geometric parameters. Load effects are determined assuming Euler-Bernoulli beam theory, with governing loads taken from earlier assessments and based on R412 *Bruklassifisering* [6]. The bridge, regulated by traffic lights, prevents simultaneous vehicle crossings, simplifying the load model.

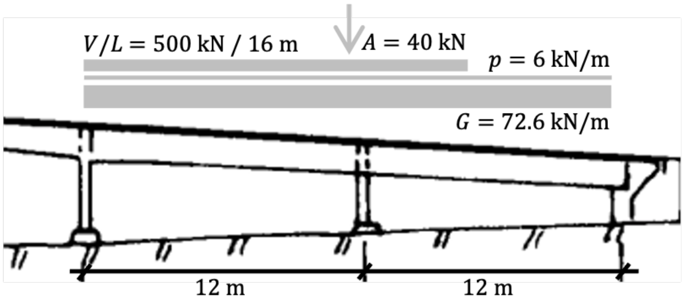

Figure 4: Governing load situation for shear with characteristic values from R412 [6].

3.2.1 Probabilistic Verification Format

The deterministic verification is refined using probabilistic modeling, translating characteristic values into random variables based on literature distributions. Traffic loads are modeled using a Gumbel distribution:

$$V \sim \text{Gumbel}(a, b), \quad a = 320, \quad b = 26$$

where parameters are derived from measurements [25]. Resistance variables follow normal distributions, with parameters calibrated from characteristic values, assuming the 5th percentile as a reference.

3.2.2 Model Uncertainty and Limit State Equation

Model uncertainties influence reliability assessments, particularly for deteriorating structures. While no specific studies exist for the NPRA shear model, an assumed model uncertainty of $\epsilon_R \sim \text{Lognormal}(1, 0.2)$ is adopted. The final limit state equation, incorporating uncertainty terms ϵ_R for resistance and ϵ_S for loads, is:

$$g(\mathbf{X}) = \epsilon_R \left(0.3 \left(f_{ctd} + \frac{100A_s}{\gamma_c bd} \right) bdk_v + \frac{A_{sv} f_{sd}}{s} 0.9d \right) - \epsilon_S (0.274V - 3.75q_{perm}) \leq 0 \tag{3}$$

The probabilistic assessment input is summarized in Tables 1 and 2.

variable	distribution	mean	unit	COV	reference
f_{ct}	normal	1.7	MPa	0.18	[19]
A_s	normal	3717	mm^2	0.02	[19]
b	deterministic	600	mm		
h	deterministic	1200	mm		
d	deterministic	1140	mm		
A_{sv}	normal	226	mm^2	0.02	[19]
k_v	deterministic	1	-		
f_s	normal	246.2	MPa	0.04	[19]
s	deterministic	200	mm		
ϵ_R	lognormal	1	-	0.2	

Table 1: Probabilistic parameters for resistance variables.

variable	distribution	mean	unit	COV	reference
V	gumbel	335	kN	0.1	
q_{rail}	normal	1	kN/m	0.05	[19]
q_{as}	normal	6	kN/m	0.05	[19]
q_{con}	normal	65.6	kN/m	0.05	[19]
ϵ_S	lognormal	1	-	0.1	[16]

Table 2: Probabilistic parameters for load variables.

3.3 Corrosion of Reinforced Concrete Exposed to Chlorides

Reinforcement is protected from corrosion by the concrete cover's high alkalinity, which forms a passive layer. This protection is compromised when chloride ions, from sources such as seawater or deicing salts, reach a critical concentration at the reinforcement [26]. Corrosion, predominantly pitting corrosion, leads to localized loss of reinforcement material, reducing shear capacity and structural reliability [31].

Corrosion progresses in two phases: initiation, when chloride concentration exceeds the critical threshold, and propagation, where reinforcement deterioration accelerates. Initiation is modeled using a chloride diffusion equation:

$$g(\mathbf{X}, t) = C_{crit} - C(x, t) \leq 0 \tag{4}$$

where $C(x, t)$ is chloride concentration at depth x over time t. The transport of chlorides into uncracked concrete is approximated by Fick's second law:

$$C(x, t) = C_s(1 - \mathrm{erf}(\frac{x}{2\sqrt{Dt}})) \cdot \epsilon_c \tag{5}$$

where C_s is surface chloride concentration, D the diffusion coefficient, and ϵ_c accounts for model uncertainty [11, 8].

Upon initiation, corrosion propagates at a rate dependent on exposure conditions [12]:

$$P_{corr}(t) = \int_{t_i}^{t} V_{corr}(t)dt, \quad V_{corr} \sim \mathrm{Weibull}(30, 40)\ [\mu\mathrm{m/year}] \tag{6}$$

To model pitting corrosion, a pitting depth factor α is introduced, affecting the remaining reinforcement area:

$$A_{res} = A_0 - \frac{(\alpha P_{corr,av,t})^2}{4} \tag{7}$$

where A_0 is the initial reinforcement area. Assumptions on pit geometry influence structural capacity reduction [27, 7].

The corrosion model is integrated into a Bayesian network (Figure 5), which updates model parameters with chloride measurements, refining predictions for initiation and propagation. These outputs inform the reliability analysis by providing probabilistic estimates of pitting depth and failure likelihood.

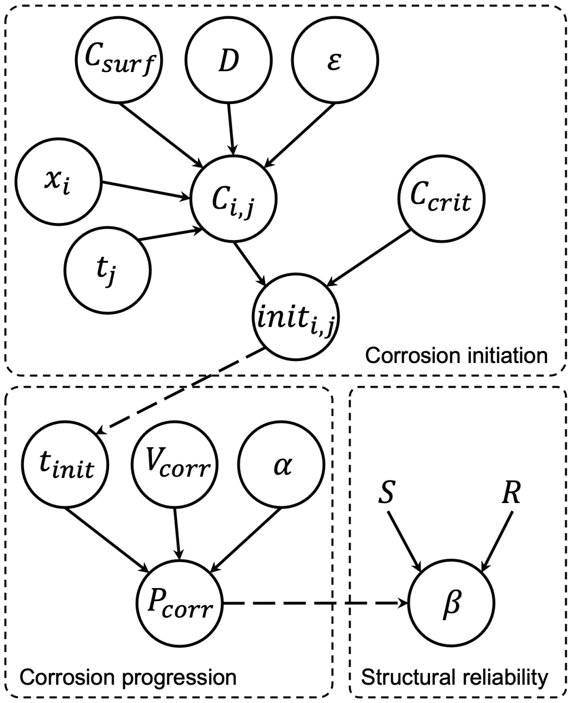

Figure 5: Structural performance modelled in a Bayesian network.

variable	**distribution**	**parameters**	**unit**	**reference**
C_{surf}	lognormal	1.6, 1.1	wt%c	fib 34 [11]
D	normal	16, 3	10^{-12} m^2/s	fib 34 [11]
ϵ_c	normal	1, 0.1	-	
C_{crit}	beta	0.7, 0.15 [0.2, 2]	wt%c	fib 34 [11]
V_{corr}	weibull	30, 40	μm/year	Duracrete [12]
α	normal	4.6, 1.9	-	[30]

Table 3: Parameters for variables in corrosion initiation and propagation models.

4 Assessment Criteria

Assessment criteria vary based on the verification format and structural model used. Table 4 outlines possible assessment approaches, from deterministic to risk-based methods.

Table 4: Assessment criteria across different verification formats and structural models.

Assessment	Verification format: Deterministic/ Semi-probabilistic	Probabilistic	Risk
Inspection rating	IR $>$ IR$_{crit}$	-	-
Chloride content	$C_d > C_{crit,d}$	$P[C > C_{crit}] > P_{acc}$	-
Cross-section loss	$A_{loss,d} > A_{loss,crit,d}$	$P[A_{loss} > A_{loss,crit}] > P_{acc}$	-
Shear capacity	$V_{Ed} > V_{Rd}$	$P[V_E > V_R] > P_{acc}$	Maximize utility

Visual inspection ratings provide a basic assessment but are limited in detecting early-stage corrosion. Measuring chloride content improves evaluation but requires defining a critical threshold. Probabilistic approaches incorporate uncertainties, allowing exceedance probabilities to guide decisions. Further refinement considers corrosion progression and its impact on shear capacity, which deterministic approaches struggle to capture. Risk-based methods optimize decision-making by weighing failure consequences against intervention costs.

4.1 Target Reliability for Existing Structures

Defining target reliability for existing structures is complex. Standards provide guidance for new structures, but their direct applicability to aging infrastructure is debated. Target reliability values typically range from 3.1 to 4.7 for ultimate limit states [16, 2]. The choice depends on failure consequences and relative cost of safety measures. For the case study, a target reliability of 3.7 ($P_f = 10^{-4}$) is chosen, reflecting high repair costs and the bridge's importance in the transport network.

An alternative to setting an absolute target is a relative reliability comparison, where the updated reliability is assessed against the initial design reliability. This approach anchors assessments to historically accepted safety levels while accounting for evolving uncertainties.

4.2 Risk-Based Decision Problem Formulation

The most comprehensive approach for bridge assessment is risk-based decision-making, which seeks to **maximize expected utility** by evaluating physical interventions (e.g., repair), organizational measures (e.g., traffic restrictions), and information gathering (e.g., inspections). In practice, decisions are limited to feasible options, which can be identified through a **risk screening procedure**.

Two common time horizon approaches exist:

- **Finite life cycle assessment (LCA)**—Evaluates optimal maintenance over the remaining service life [14, 15].
- **Infinite renewal model**—Assumes continuous replacement and is widely used in design code calibration [23, 17].

For this study, the infinite renewal model is adopted, modified for existing structures.

4.2.1 Cost Optimization for Maintenance Decisions

For new structures, total expected costs are expressed as:

$$E[C_{tot}(\mathbf{p})] = E[C_{new}(\mathbf{p})] + E[C_{failure}(\mathbf{p})]\frac{P_f}{\gamma} + E[C_{renewal}(\mathbf{p})]\frac{\omega}{\gamma} \quad (8)$$

For existing structures, as construction costs are already paid, the optimization simplifies to:

$$E[C_{tot}(\mathbf{a})] = E[C_{maintenance}(\mathbf{a})](1 + \frac{\omega}{\gamma}) + E[C_{failure}]\frac{P_f}{\gamma} \tag{9}$$

where γ is the discount rate, ω is the obsolescence rate, and P_f the failure probability. The optimal maintenance action minimizes $E[C_{tot}(\mathbf{a})]$:

$$C_{maintenance,\mathbf{a}} \leq \frac{C_{failure}(P_{f,now} - P_{f,maintenance,\mathbf{a}})}{(\gamma + \omega)} \tag{10}$$

4.2.2 Failure Costs and Maintenance Actions

Failure costs include **direct failure costs**, **traffic disruptions**, and **human life losses**, where the **societal value of statistical life (SVSL)** can be used for quantification [2, 13]. The failure cost is assumed to be **2–20 times the cost of a new bridge**.

Table 5 summarizes intervention costs and effects, while Table 6 defines structure-specific parameters.

Table 5: Intervention-specific parameters.

	$\mathbf{C_{maintenance}}$ [MNOK]	$\mathbf{P_{f,maintenance}}$ [-]	$\mathbf{T_{ref}}$ [years]
a_1	3	10^{-4}	10
a_2	30	10^{-6}	50

Table 6: Structure-specific parameters.

	$\mathbf{C_{new}}$ [MNOK]	$\mathbf{C_{fail}/C_{new}}$ [-]	$\mathbf{P_{f,now}}$ [-]
Base value	300	10	$3.5 \cdot 10^{-4}$
Range	10-500	2-20	$10^{-6} - 10^{-2}$

5 Results

This study applies a structured framework for decision support in the assessment of a corroding reinforced concrete bridge, integrating different verification formats and safety evaluations. Table 7 summarizes the case study results. The inspection rating suggested an acceptable condition, but deterministic and semi-probabilistic assessments failed to prove structural safety. The probabilistic assessments confirmed that the probability of corrosion initiation and cross-section loss exceeded acceptable limits. The risk-based assessment indicated that intervention is necessary, with minor repair identified as the optimal decision.

Table 7: Summary of assessment results.

Safety assessment	Deterministic/Semi-probabilistic	Probabilistic	Risk-based
Inspection rating	OK ($2 < 4$)	-	-
Chloride content	**Fail** (0.3 > 0.2 wt%c)	**Fail** ($0.46 > 0.1$)	-
Cross-section loss	**Fail** (7 > 3.7 mm)	**Fail** ($0.34 > 10^{-5}$)	-
Shear capacity	**Fail** (505 > 469 kN)	**Fail** ($3.5 \cdot 10^{-4} > 10^{-4}$)	**Optimal: Minor repair**

5.1 Probabilistic Assessment

The probabilistic assessment applied Bayesian updating to improve estimates of chloride transport and corrosion initiation. Figure 6 shows how prior and posterior distributions for chloride content evolved with new measurements, refining the probability of corrosion initiation over time. The results indicate substantial variability between locations, with some areas showing significantly higher deterioration rates than predicted by prior models.

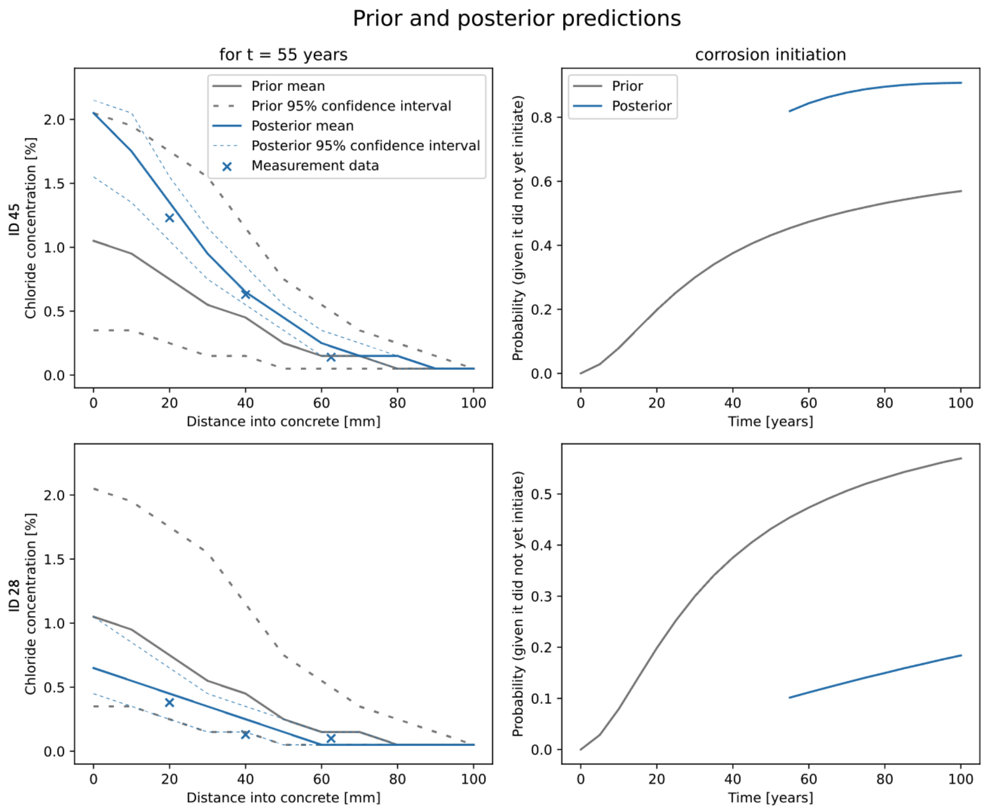

Figure 6: Updated chloride content predictions and probability of corrosion initiation over time.

The probability of failure was estimated for individual locations, revealing a spread in reliability index from 3.2 to 4.0, highlighting the significant uncertainty in deterioration progression. When aggregating data for a representative section, the posterior probability of corrosion initiation increased from 0.42 to 0.58, leading to a moderate reliability index reduction of 0.2, indicating a limited impact of new data on overall decision-making.

5.2 Risk-Based Assessment

The total expected costs of different maintenance strategies were analyzed. Figure 7 demonstrates that doing nothing is not optimal, as failure costs outweigh maintenance costs. Instead, minor repair is the cost-optimal solution, balancing intervention costs and risk reduction.

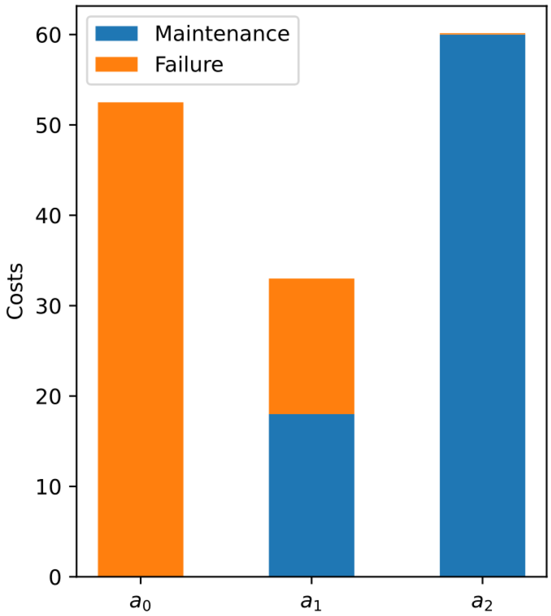

Figure 7: Total expected cost for decision alternatives: no action, minor repair, and major repair.

Figure 7 provides a decision tool for evaluating the trade-off between maintenance cost and reliability improvement, allowing for flexible decision-making based on different risk levels and cost constraints.

The results confirm that a risk-based approach enhances decision-making by incorporating probabilistic assessments and cost optimization. While deterministic and semi-probabilistic methods fail to capture the full uncertainty, Bayesian updating improves deterioration modeling. The risk assessment suggests that targeted intervention (minor repair) is the most cost-effective strategy.

For further details and a comprehensive discussion of the methodology, see [18].

6 Discussion

7 Conclusion

This study illustrates how bridge owners can optimize maintenance decisions using probabilistic and risk-based methods to ensure safety within budget constraints. Traditional visual inspections and semi-probabilistic assessments were extended with probabilistic models for corrosion initiation and propagation, enabling a more systematic safety evaluation.

The assessment framework organizes verification formats and information levels hierarchically. Probabilistic assessments improve the understanding of deterioration, but risk-based assessments provide direct decision support, weighing failure risks against intervention costs. The optimal decision was found to be minor repair, balancing safety and cost.

Risk-based assessments consider long-term intervention efficiency by modeling continuous recurrence of similar decisions. Interventions can be evaluated by estimating failure probability reduction, cost, and service life. While the framework supports data-driven decision-making, parameter uncertainties, particularly in corrosion rates, highlight the need for long-term monitoring. Non-destructive testing methods currently have limitations, but data from demolished bridges could improve corrosion modeling.

The Bayesian Network effectively updated chloride predictions, yet had limited influence on final decisions, which were more sensitive to consequence modeling and intervention assumptions. Nevertheless, Bayesian updating remains a promising tool for progressive assessment refinement, integrating expert judgment and measurement data.

A critical research opportunity is the planned demolition of the case study bridge, providing a unique testbed for validating assessment models. Destructive testing could quantify voids, tendon conditions, and probabilistic deterioration predictions, advancing structural reliability analysis.

Future research should address human safety and user costs, refine failure consequence models, and incorporate real-time traffic load data for more accurate reliability estimates. Enhancing safety assessment of deteriorating bridges ensures timely, cost-effective interventions, promoting a more sustainable and resilient transportation network.

8 Conclusions

A rational decision-making framework was applied to a corroding bridge exposed to a chloride environment, integrating existing prediction models for both corrosion initiation and propagation. By incorporating these models, the framework enables a more systematic approach to evaluating the condition of the structure over time. Furthermore, the study demonstrated how measurement data can inform decision-making processes, ensuring that maintenance actions are based on actual structural performance rather than purely theoretical estimates. This data-driven approach enhances the reliability of predictions and allows for more targeted interventions, ultimately reducing unnecessary expenditures and optimizing maintenance strategies. The findings of this study contribute to the more efficient use of resources in bridge maintenance, emphasizing the importance of integrating predictive models with real-world data. By doing so, infrastructure managers can prioritize actions that extend the service life of bridges while maintaining safety and performance. This approach supports sustainable infrastructure management and informed decision-making in engineering practice.

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