# Reliability Analysis of Reinforced Concrete Jetty Structure

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***Abstract*—Reinforced Cement Concrete (RCC) structures are widely used in civil engineering because of their strength, durability, and cost-effectiveness. However, ensuring their reliability for long-term performance and safety is important. This research investigates the reliability of RCC structures using probabilistic approaches to determine their performance under different loads, material uncertainties, and environmental factors. The analysis is conducted using limit state design principles and considers uncertainties in material properties, loads, and degradation of things over time. Reliability indices are calculated using techniques like the First Order Reliability Method, Monte Carlo Simulation, and sensitivity analysis to evaluate failure risks. Different failure modes, including flexural failure, shear failure, and durability, are analysed to provide a comprehensive reliability analysis. The research also considers the impact of corrosion, fatigue, and seismic loads on RCC structures, including maintenance and risk reduction strategies. The results provide useful information on the safety margins of RCC structures and help engineers make better decisions on design optimization and life-cycle management. This research improves the strength and sustainability of RCC structures to perform optimally in the long term and minimizes the chances of catastrophic failures.**

***Index Terms*—Reliability Analysis, RCC Structures, Probabilistic Methods, Structural Safety, Failure Assessment**

## I. INTRODUCTION

Reinforced Cement Concrete structures are critical in contemporary buildings, such as bridges, sea structures, and industrial plants. They are used extensively because of their strength, durability, and ability to withstand various loads. RCC structures, however, are prone to uncertainties in material quality, construction standards, environmental factors, and changing conditions of loads. These uncertainties may lead to damage in the long term, hence the need to study reliability to ensure their safety and overall performance. Reliability analysis of RCC structures employs probability to determine the likelihood of their failure under various conditions. Conventional design procedures emphasize safety but do not consider the randomness of loads, material strengths, and environmental conditions. Probabilistic procedures such as the First-Order Reliability Method offer improved estimates by determining failure risks and reliability measures. These procedures enable engineers to determine the risks of various failures, such as bending, shear failure s, corrosion, and susceptibility to earthquakes. With the growing demand for resilient and strong infrastructure, reliability analysis is critical in strengthening RCC structure designs, and maintenance schedules, and saving money in the long term.

Factors such as chloride penetration, carbonation, fatigue, and extreme weather conditions can significantly impact RCC structures. This indicates the need for a structured approach to reliability in addressing risks. Incorporating structural reliability analysis in the design and maintenance process enables engineers to design RCC structures that are safer and more environmentally friendly.

This study takes into consideration various approaches to validate the reliability of RCC structures. It demonstrates the usefulness, limitations, and applicability of these techniques in actual applications.

With knowledge of how RCC structures behave under uncertainty, stakeholders can better decide to improve safety, usability, and long-term performance.

## II. REVIEW OF LITERATURE

Manolis Papadrakakis and Nikos D. Lagaros (2002) explored the use of neural networks (NN) in reliability-based structural optimization for large-scale systems facing uncertainties and potential plastic collapse. Two methods were studied: one where NNs handle both deterministic and probabilistic constraints, and another where NNs replace elasto-plastic analysis in Monte Carlo Simulation (MCS), significantly reducing computational effort. The study emphasizes that traditional deterministic optimization lacks realism due to uncertainties in design and manufacturing. By integrating NNs with MCS and importance sampling, the approach enhances efficiency and accuracy, offering a practical and computationally effective alternative for complex structural reliability assessments.

Deng, Gu, Li, and Yue (2004) proposed artificial neural network (ANN)-based methods to enhance structural reliability analysis, especially for complex systems with implicit performance functions. Traditional methods like Monte Carlo Simulation (MCS), FORM, and SORM are computationally intensive. To address this, the authors introduced ANN-based MCS, FORM, and SORM approaches using multi-layer feedforward networks to approximate performance functions, reducing computational demands while maintaining accuracy. The study showed that ANN-based methods achieve results comparable to conventional techniques but with greater efficiency. This highlights ANNs as a powerful tool for handling nonlinear behavior and improving structural safety evaluations in engineering applications

Gavin and Yau (2006) advanced the stochastic response surface method (SRSM) for structural reliability analysis by addressing the limitations of traditional Monte Carlo Simulation (MCS) and quadratic SRSM in handling highly nonlinear limit state functions. They proposed using higher-order polynomials and introduced an algorithm based on orthogonal polynomials to improve accuracy and reduce computational issues. This approach determines optimal polynomial orders through statistical analysis of coefficients, enhancing the precision of failure probability estimates. Numerical examples showed that the higher-order SRSM is more accurate and reliable than conventional methods, making it a robust and efficient alternative for complex structural reliability problems.

Cardoso, Almeida, Dias, and Coelho (2007) propose a methodology combining neural networks (NN) and Monte Carlo simulation (MCS) to improve structural reliability analysis. While MCS is a robust tool for evaluating failure probabilities, its application to very low probabilities demand extensive structural analyses, making it computationally expensive. To address this, the authors use neural networks to approximate structural behaviour, reducing computational effort while maintaining accuracy. However, accurately capturing complex structural responses remains a key challenge. The study evaluates the methodology through a test function and two structural examples, with one demonstrating its application in reliability-based structural optimization. The results indicate that when random variables influencing structural behaviour are well-defined, level 3 reliability methods like MCS provide a more rigorous design approach than level 1 Eurocode methods. The paper concludes that neural networks effectively approximate structural responses, significantly reducing computational costs and enhancing the practicality of reliability analysis.

Hao Zhang, Robert L. Mullen, and Rafi L. Muhanna (2010) address structural reliability assessment when statistical parameters are uncertain due to epistemic uncertainty. Instead of fixed values, these uncertainties are model using interval bounds derived from confidence intervals, leading to varying probabilities of failure within these intervals. To estimate failure probability under such conditions, the authors propose an Interval Monte Carlo method that integrates simulation with interval analysis. This approach separately propagates epistemic and aleatory uncertainties through finite element-based reliability analysis. The interval finite element method (FEM) ensures accurate modeling of structural response ranges. The study compares interval-based failure probability estimates with Bayesian methods, demonstrating the effectiveness of the proposed approach. The paper concludes that the Interval Monte Carlo method provides a reliable and efficient framework for structural reliability assessment under uncertain conditions. By incorporating interval FEM, it

enhances confidence in failure probability estimates, making it a valuable tool for engineering applications.
Hao Zhang, Hongzhe Dai, Michael Beer, and Wei Wang (2012) address the challenge of performing structural reliability analysis with limited data. In many real-world applications, defining precise probability distributions for input parameters is difficult due to insufficient data, making probabilistic analysis uncertain. To overcome this, the authors propose using a set of plausible distributions instead of a single one, capturing uncertainty more realistically. The paper introduces a probability box (p-box) approach, which defines bounds on the cumulative distribution function of a random variable. While existing sampling-based methods for reliability analysis with p-boxes are effective, they often require a large number of simulations, making them computationally expensive. To improve efficiency, the authors propose an interval quasi-Monte Carlo (QMC) simulation methodology, which leverages deterministic low-discrepancy sequences. These sequences are more evenly distributed than traditional pseudo-random numbers, allowing for a more efficient computation of structural failure probability bounds. The study demonstrates the effectiveness of the proposed method through two examples and explores the reliability implications of different p-box construction approaches. The findings show that interval QMC achieves comparable accuracy to direct interval Monte Carlo methods with significantly fewer simulations. This innovative approach enhances computational efficiency and adaptability in structural reliability analysis under uncertain conditions.

M. Jirgl, Z. Bradac, K. Stibor, and M. Havlikova (2013) The paper examines the reliability analysis of complex systems, highlighting the importance of early reliability prediction during the design phase to prevent failures and extend system lifespan. It compares the Monte Carlo simulation method with traditional approaches like Reliability Block Diagram (RBD) analysis, noting that RBD can be cumbersome for intricate systems. Monte Carlo simulation offers advantages such as flexibility, simplicity, and accuracy for systems with arbitrary structures and component reliability distributions. By using random sampling and statistical analysis, it effectively estimates overall system reliability. Unlike expensive commercial software, Monte Carlo methods can be implemented in various programming languages with efficient random number generation, making them a cost-effective alternative. The study concludes that Monte Carlo simulation is a powerful tool for reliability analysis, supporting economic decision-making by enabling cost-effective reliability improvements. Its versatility and ease of implementation make it a practical choice for assessing and optimizing complex system reliability.
Bruno Gaspar, Arvid Naess, Bernt J. Leira, and C. Guedes Soares (2014) The paper explores system reliability analysis using Monte Carlo simulation (MCS) and finite element structural models. While MCS is a powerful tool for predicting the reliability of complex structural systems, its primary drawback is the high computational cost, particularly for highly reliable systems requiring numerous simulations to achieve accurate failure probability estimates. To address this challenge, the authors propose a new Monte Carlo-based method that reduces computational costs while maintaining accuracy. The method is demonstrated through a numerical example involving a nonlinear finite element structural model. To further enhance efficiency, the approach integrates a response surface model, which approximates nonlinear finite element analysis, thereby reducing the computational burden. The results confirm that the proposed method accurately estimates system failure probabilities while significantly cutting computational costs compared to traditional MCS approaches. By leveraging response surface models, the method enables efficient reliability analysis of complex structural systems, making it particularly valuable for real-world engineering applications with limited computational resources. In conclusion, the paper presents an effective Monte Carlo-based method that improves the efficiency of reliability analysis without compromising accuracy. By combining MCS with a response surface model, this approach offers a practical and computationally efficient solution for reliability estimation in nonlinear structural systems.

Mahdi Shadab Far and Yuan Wang (2016) addressed the high computational cost of Monte Carlo (MC) simulation in estimating low failure probabilities for structural reliability analysis. They proposed a simplified algorithm that significantly reduces sample size while maintaining accuracy comparable to traditional MC methods. Presented through a step-by-step flowchart, the method is easy to implement and was validated through case studies and geotechnical applications. Key strategies include curve fitting, multiple analyses to reduce variation, and use of importance sampling. The study concludes that this simplified approach is a practical, cost-effective alternative for accurate reliability analysis in resource-limited scenarios

Behrooz Keshtegar and Ozgur Kisi (2017) The paper introduces an efficient structural reliability analysis method by integrating the M5 model tree (M5Tree) with Monte Carlo simulation (MCS). Traditional MCS can be computationally intensive for complex, implicit performance functions, making failure probability estimation challenging. The M5Tree model addresses this by breaking down complex problems into smaller sub-problems, improving both efficiency and accuracy. Two key methods are explored: the first-order reliability method enhanced by conjugate search direction (CFORM) and the M5Tree+MC approach. While CFORM improves traditional FORM-based searches, M5Tree+MC enhances MCS by approximating the performance function with the M5Tree meta-model, significantly reducing computational costs while maintaining accuracy. The method is tested on five nonlinear mathematical and structural reliability problems, demonstrating superior efficiency and accuracy over CFORM and traditional MCS, particularly for highly nonlinear performance functions. The study concludes that M5Tree+MC is a powerful tool for structural reliability analysis, offering an efficient and accurate solution for complex engineering problems.

Seghier et al. (2018) conduct a structural reliability analysis of corroded X60 steel pipelines using a hybrid method that combines the M5 model tree algorithm with Monte Carlo simulation. This approach enhances computational efficiency in estimating failure probabilities. A burst-corroded performance function is developed to assess the effects of operating pressure and corrosion defect geometry. Results show that defect depth significantly impacts reliability, while corrosion length has minimal effect. The study recommends a maximum operating pressure of 8 MPa for safety. The proposed method offers practical, accurate reliability assessments and underscores the importance of precise defect characterization in pipeline integrity

M. Gordini et al. (2018) examine how initial curvature imperfections affect the reliability of double-layer space structures. Recognizing that real structures often have imperfections, the study models these as gamma-distributed random variables and applies nonlinear analysis to assess collapse behavior and load capacity. Using Monte Carlo simulation, the researchers evaluate performance variability under different support conditions. Results show that structural strength and collapse behavior are highly sensitive to these imperfections. The study highlights the need to consider imperfections in reliability assessments and demonstrates that Monte Carlo simulation is effective for analysing their impact in complex structural systems. Changqi Luo et al. (2021) propose a Hybrid Enhanced Monte Carlo Simulation (HEMCS) method that integrates Monte Carlo simulation with artificial neural networks (ANNs) to improve failure probability estimation in structural reliability analysis. Traditional methods are accurate but computationally expensive; HEMCS enhances efficiency by using a probabilistic model with a scalar factor derived from the coefficient of variation. The ANN, trained via back-propagation, focuses on active regions, optimizing hidden nodes and training strategies. This hybrid approach significantly boosts both accuracy and efficiency, making it effective for analysing complex, nonlinear structural systems with reduced computational demands.

Chenxiao Song and Reiichiro Kawai (2023) present a comprehensive review of Monte Carlo methods for structural reliability analysis, with a strong focus on variance reduction techniques. The paper serves as a detailed methodological guide, reviewing 444 references and covering a wide range of Monte Carlo formulations, sub-categories, and their integration with surrogate models and other simulation techniques. It highlights the flexibility, broad applicability, and ongoing importance of Monte Carlo methods in structural analysis. The authors emphasize that advancements in variance reduction and hybrid approaches have significantly improved the efficiency and accuracy of these methods, making this review a valuable resource for researchers and engineers.

## III. OBJECTIVES OF THE STUDY

1. To identify the design parameters, including material properties (such as concrete strength, reinforcement steel properties), loadings, and

environmental factors (corrosion) that affect the reliability of RCC structures**.**

2. To integrate the Monte-carlo simulation method and finding reliability index of structure
3. To find out probability of behavior of the structure and failure.

## IV. METHOD OF ANALYSIS

Reliability Analysis of member

Structural reliability is the study of how safe and functional a structure remains over time, considering the many uncertainties in its design, material, and real-world conditions. Unlike traditional methods that assume fixed values for loads and material strengths, reliability analysis acknowledges that these factors are unpredictable due to physical variations, limited data, imperfect models, and human error. Because of these uncertainties, absolute safety is impossible. Structures can never be guaranteed against failure. Hence engineers calculate the probability that a structure will perform as intended throughout its lifespan under expected conditions, such as loads, weather, and wear. Nevertheless, their structural reliability is important for long term performance and safety. The present research work is concerned with the reliability analysis of RCC structure based on probabilistic approaches to evaluating their performance under different loading conditions, material uncertainty, and environmental conditions. The analysis applies Monte carlo simulation concept with allowance for uncertainties in material properties, loading.

## V. STRUCTURAL DETAILS

Jetty structure consists of deck slab, grid of beams, supported with piles.

Dimensions:

Jetty size: 685 m × 40.5 m

Slab Thickness: 400 mm

Main Cross Beams: 1600 mm × 1925 mm

Crane Beams: 1000 mm × 1725 mm

Secondary Beams : 750 mm × 1000 mm

Deck Slab Top: (+) 7.10 m RL

Sea bed level: (General – 13.0 m)

Founding Level of Piles: (-) 24 m

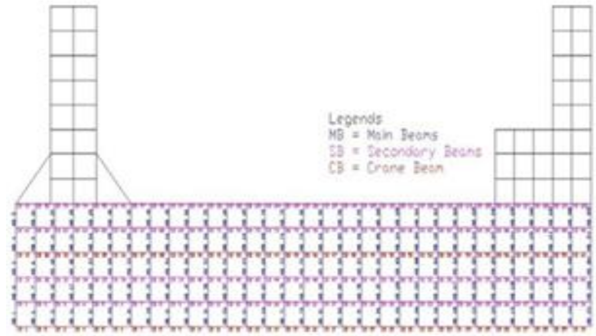


Fig 1: Layout of beams

Fig 2: Container Jetty JNPT Navi Mumbai

## VI. RESULTS AND DISCUSSION

Non-Destructive Testing

Rebound Hammer test: This test is use to estimate compressive strength of hardened concrete without damaging the structure. And to assess the uniformity of concrete.

Table No 1: Rebound Hammer test results

| Beam Type | Nos. | Mean | Std. Deviation |
|---|---|---|---|
| Main Beam | 45 | 31.2546 | 3.154562 |
| Secondary Beam | 30 | 31.43004 | 1.971776 |
| Crane Beam | 15 | 24.95840 | 2.159745 |

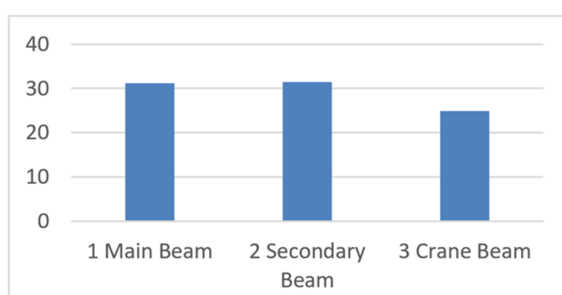


Fig 3: Comparison of Rebound Hammer test results

Table 2: Ultra sonic Pulse velocity test results

| Beam Type | Nos. | Mean | Std. Deviation |
|---|---|---|---|
| Main Beam | 45 | 108.35 | 8.9405 |
| Secondary Beam | 30 | 113.56 | 9.5688 |
| Crane Beam | 15 | 124.680 | 9.8410 |

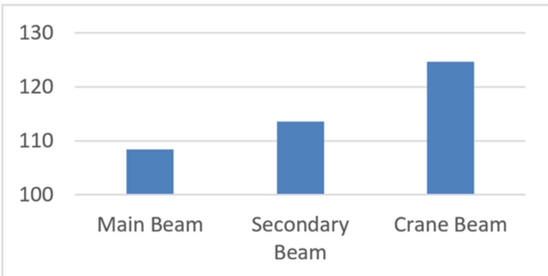


Fig 4: Comparison of UPV test results

Ultrasonic pulse velocity test: The Ultrasonic Pulse Velocity Test is a non-destructive test used to evaluate the quality, uniformity, and integrity of concrete by measuring the velocity of ultrasonic pulses passing through it

Finding probability of failure of RCC jetty structure and calculating reliability index of main beams, secondary beams and Crane beams and showing comparisons of the beams.

*1. Data*

Beam span = l= 40.5 m

Concrete grade = M25

Steel grade = Fe

Area of steel

$Ast = 2060\ mm^2$

Self-weight $w = 43 \frac{kN}{m}$

Live load (L) normally distributed

$\mu L = 7.5 \frac{kN}{m}$ $\sigma L = 1.1 \frac{kN}{m}$

Random Variables:

fcu (concrete cube strength): normally distributed

fy (steel yield strength): normally distributed

Dimensions: b = 1600 mm d= 1925 mm

Mean values: $\mu fcu = 124.68\ Mpa$

$\mu fy = 550\ Mpa$

Standard deviation: $\sigma fcu = 9.8410\ Mpa$ $\sigma fy = 25\ Mpa$

*2. Calculate load effects:*

$$MD = \frac{w.l^2}{8} = (8.816 \times 10^3)\ kN.m$$

Live load moment parameters $\mu L = 6\ kN/m$

$\sigma L = 3kN/m$

Total Moment parameters

$$\mu S = MD + \left(\frac{\mu L \times l^2}{8}\right) = (1.035 \times 10^4)\ kN.m$$

$$\sigma S = \sigma L \times \left(\frac{l^2}{8}\right) = 225.534\ kN.m$$

*3. Define the resistance functions:*

Resistance function parameters:

Ast = 2060 $mm^2$

b = 1000mm

d = 1725mm

Resistance function

*4. Calculate Mean Resistance* $(\mu R)$

$$\mu R = \mu fy \times Ast \times d \times \left(1 - \frac{0.77 \times Ast \times \mu fy}{b \times d \times \mu fcu}\right) =$$

$(2.176 \times 10^3) kN.m.$

*5.Calculate partial derivatives of variance*

Partial derivative w.r.t. fy

$$dRdfy = Ast \times d \times \left(1 - \frac{1.54 \times Ast \times \mu fy}{b \times d \times \mu fcu}\right)$$

$$= 3.947\ L$$

$$dRdfcu = \left(\frac{0.77 \times Ast^2 \times \mu fy^2}{b \times \mu fcu^2}\right) = 0.04L$$

*6. Calculate standard deviation*

$$\sigma R = (dRdfy)^2 \times (\sigma fy)^2 + (dRdfcu)^2 \times (\sigma fcu)^2$$

$$\sqrt{\sigma R} = 98.688\ kN.m$$

*7. Calculate failure probability*

$$pf = cnorm\left(\frac{\mu S - \mu R}{(\sigma S^2 + (\sqrt{\sigma R})^2)^{0.5}}\right)$$

Pf = 1.78

Table 3: Reliability Index

| Beam Type | Reliability index | Probability failure |
|---|---|---|
| Main beam | 2.57 | 0.0228 |
| Crane beam | 1.00 | 0.1587 |
| Secondary beam | 2.89 | 0.00135 |

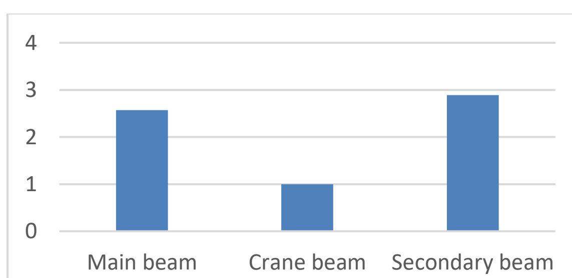


Fig 5: Comparison of Rebiliability Index

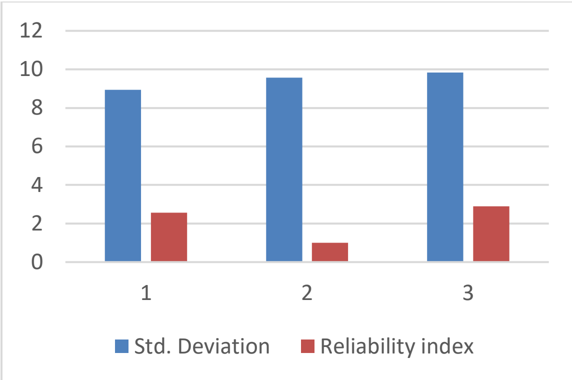


Fig 6: Comparison of Rebiliability Index and Std deviation

The reliability index represents the safety margin of beam by relating the mean strength and variability of resistance against the applied load. A higher mean strength or lower standard deviation improves the reliability index the higher reliability index shows safety of the beam.

## VII. CONCLUSION

The present Study shows that, the reliability of Reinforced Cement Concrete jetty structure is assessed using probabilistic methods, combined with non-destructive testing techniques.

- The structural components analysed included main beams, crane beams, and secondary beams of a jetty structure. Results from the Rebound Hammer Test and Ultrasonic Pulse Velocity test indicated that the main and secondary beams possess good material strength.
- However, the crane beams showed lower compressive strength and pulse velocity values, indicating potential internal flaws or material degradation. The calculated reliability indices support these findings, with the main beam scoring 2.57 and the secondary beam 2.89 both within safe and acceptable limits.
- In contrast, the crane beam recorded a reliability index of 1.0, highlighting a significant risk of failure under current conditions. This suggests an urgent need for further inspection, strengthening, of crane beams to ensure structural safety. It emphasizes the importance of reliability-based design and maintenance in enhancing the long-term safety, durability, and cost-effectiveness of RCC structures exposed to variable loads and environmental factors.

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