Artificial Intelligence and Structural Reliability Analysis in Nigeria: A Review

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ABSTRACT

Reliability is a probabilistic measure of structural safety. In Structural Reliability Analysis (SRA), both loads and resistances are modelled as probabilistic variables, and the failure of structure occurs when the total applied load is larger than the total resistance of the structure. This review presents the recent advances in using Artificial Intelligence (AI) in SRA; it explores the application of Artificial Intelligence (AI) in assessing the structural reliability of structures, particularly focusing on the integration of machine learning models, predictive analytics, and data-driven approaches. AI-based tools can enhance accuracy, speed, and efficiency in structural assessments, offering a potential solution to Nigeria's infrastructure challenges. Machine learning-based techniques have been introduced to SRA problems to deal with its huge computational cost and increase accuracy. ANNs and SVMs are two popularly used tools in the ML-based SRA literature. They have been widely used for the SRA because of their adaptability to different well-known reliability calculation methods such as MCS, FORM, and SORM. **While these** technologies have been successfully implemented in other parts of the world, its application in Nigeria faces challenges related to data availability, infrastructure, and expertise. Nonetheless, with the increasing adoption of digital technologies in Nigeria’s construction industry, AI offers a compelling opportunity for improving the safety and sustainability of concrete structures.

Keywords: *Artificial Intelligence, Concrete, Neural Networks, Machine Learning, Structural Reliability.*

1. INTRODUCTION

Artificial intelligence (AI) is the ability of a machine to mimic human behavior intelligently through the use of algorithms to solve difficult problems. One of its main objectives is to train machines to reason, plan, process, perceive, move and manipulate things like humans with a view to solving complex organizational or day-to-day challenges (Owolabi *et al.,* 2022). The application of AI is growing because of its ability to provide solutions in uncertain and complex situations. It has the potential to tackle problems, which overwhelm the human mind in terms of complexity or volume of data. AI also creates convenience, improves productivity and adds value to a system

The construction industry, a vital sector to ensuring economic growth and societal development is grappling with increasing pressures to deliver safe, resilient and sustainable infrastructure within tight budgetary provisions. The complexities inherent in large-scale construction projects, coupled with the potential for catastrophic failures underscore the need for innovative solutions. Artificial intelligence (AI), with its capacity for data-driven decision-making and predictive analytics, has emerged as a promising technology to address these challenges (Moinuddin *et al.*, 2024). While AI has shown significant potential across various industries, its application in construction remains relatively nascent, particularly in developing economies. Previous studies have explored AI's role in construction management, design optimization, and safety (Pan & Zhang, 2023; Akanbi *et al.,* 2024). However, the specific focus on AI's application in structural reliability, especially within a developing country context, is limited.

In Nigeria, rapid urbanization and infrastructural development have led to an increase in the demand for reliable and durable concrete structures. However, the structural reliability of concrete remains a significant concern due to various factors such as material degradation, environmental influences, and human error in construction practices. Traditional methods of evaluating concrete strength and durability, which largely rely on manual testing, visual inspections and static calculations can be both inefficient and inaccurate. Furthermore, the vast and often underdeveloped infrastructure landscape in Nigeria makes it challenging to ensure consistent structural safety. In this context, Artificial Intelligence (AI) offers a promising solution by automating and optimizing the assessment process, reducing human error and predicting failures before they occur.

AI tools, particularly machine learning algorithms can be leveraged to analyze extensive datasets gathered from various sensors, environmental conditions and historical records of concrete structures. These AI systems can identify patterns and anomalies that might not be apparent through conventional inspection methods, allowing for early detection of potential structural failures. This paper explores the various applications of AI in the determination of structural reliability for concrete in Nigeria and examines how these technologies could transform infrastructure management practices in the country.

Structural Reliability Analysis (SRA)

Structural reliability analysis refers to the assessment of the likelihood that a structure will perform its intended function without failure over a specified period under uncertain conditions. Traditional SRA approaches involve probabilistic models, where the uncertainties associated with loads, materials, and environmental factors are quantified.

In Nigeria, structural failure has often been attributed to inadequate design, poor construction practices and lack of proper maintenance. Recent efforts have been made to improve SRA methodologies, especially through the use of probabilistic and reliability-based design codes. However, the application of these methods remains limited due to resource constraints, insufficient data, and a lack of trained professionals.

Structural reliability is a concept used in civil engineering to evaluate the probability that a structure will perform its intended function without failure during a specified period under uncertain conditions. In simple terms, it is concerned with assessing the likelihood that a structure, such as a bridge, building, dam, or any other civil engineering project, will remain safe and functional throughout its service life, given the inherent uncertainties in material properties, loading conditions, and environmental factors.

Unlike deterministic design methods, which assume fixed values for loads and material properties, structural reliability takes into account the inherent uncertainties by considering variability in these parameters. The goal of structural reliability analysis is to ensure that structures are designed to be both safe and cost-effective by managing the risks of failure in an optimal way.

AI in Civil Engineering: Global Applications

Artificial Intelligence has been increasingly applied in civil engineering to enhance various processes, from design to construction and maintenance. AI's potential for structural health monitoring (SHM) has been extensively explored in regions with advanced infrastructural systems, particularly in the United States and Europe (Rizzo *et al.*, 2021). AI techniques such as deep learning, machine learning, and neural networks have been utilized to monitor the condition of bridges, buildings, and dams (Zhao *et al.*, 2019). In the context of concrete, AI has been used to predict concrete strength, detect cracks, and monitor long-term deterioration processes. Machine learning models have proven particularly effective in predicting the behavior of materials under various environmental stresses, making them suitable for structural reliability analysis.

Some studies on the application of AI in the construction industry have been conducted in the past; Hsu *et al.* (2018) developed a model for optimizing the manufacturing, storage and assembly logistics in modular construction. Khobragade *et al.* (2018) utilised Artificial Neural Network (ANN) algorithm to predict housing rates for improving the planning, construction and sales of buildings. Furthermore, Poh *et al.* (2018) used machine learning to develop indicators that can classify construction sites according to their safety levels. Mohan and Varghese (2019) used AI to improve safety on construction sites. Delgado *et al.* (2019) assessed the factors that limit the adoption of robots and automated systems in the construction industry. Schia *et al.* (2019) assessed the application of AI and its impact on human behavior. Yaseen *et al.* (2020) adopted AI to predict a delay in construction projects. Ajayi *et al*. (2020) adopted text mining to develop deep learning models for health and safety management in power projects. Egwim *et al*. (2021) used ensemble algorithms to improve the predictive capability of single algorithms in predicting construction project delay.

AI in Concrete Durability and Structural Integrity

Several studies have highlighted the use of machine learning in assessing concrete durability. For example, Al-Emrani *et al.* (2019) utilized AI models to predict the long-term strength and durability of concrete subjected to high environmental stresses, such as extreme temperatures and humidity levels. Similarly, Zhang *et al.* (2020) applied neural networks to model the effects of different types of aggregates and cement compositions on concrete's lifespan and its resistance to cracking.

Applications of AI in Nigeria's Infrastructure Sector

In Nigeria, AI applications in infrastructure remain relatively underdeveloped. However, some pioneering research has begun to explore possibilities of machine learning in monitoring the structural integrity of Nigerian concrete structures. For example, Olumide *et al.* (2019) conducted a study that combined machine learning models with traditional testing methods to assess concrete strength in Nigerian infrastructure. The research opined that machine learning algorithms, particularly decision trees and support vector machines, improved the accuracy of predictions and identified critical failure points in the infrastructure system.

Machine Learning

According to Joseph and Swalih CK (2023), Machine Learning is a subset of artificial intelligence (AI), it uses computer algorithms to perform a specific task by the use of data without giving explicit instructions. Based on the availability of the sample data, ML methods can be categorized into: supervised, unsupervised, semi-supervised, active, and reinforcement learning algorithms. Supervised learning algorithms are used when the sample data contain input-output pairs, referred to as labelled data, obtained from the desired function or distribution. When the available data only consists of input values, unsupervised learning algorithms are mostly applied, and in cases in which some of the sample data lack the output value, semi-supervised algorithms are mostly utilized. Active Learning (AL) methods can be considered as a special case of semi-supervised learning, where some of the data are actively chosen to obtain the output value. For reinforcement learning, the output is given as reward feedback to the actions taken based on the selected inputs. It is important to select a proper learning approach based on the available data. As mentioned, ML methods are being more commonly used as surrogate models of the structural response under deterministic or stochastic loading conditions. In other words, based on the available data, they can estimate the performance function (i.e., the structural response) or approximate the Limit State Function (LSF).

Machine Learning in Structural Reliability Analysis

Artificial Neural Network Based SRA

Artificial Neural Network based SRA Artificial Neural Networks (ANN) are amongst the most popular machine learning methods. ANNs are capable of adapting to parallel distributed processing and being applied in large-scale multi-dimensional problems. A well-trained ANN, either with the classification or regression approach, can model highly nonlinear problems accurately and efficiently. With the classification approach to the SRA problems, the ANN is used to identify whether the structure operates within the safe domain or not. On the other hand, the regression approach is used to estimate the value of an implicit function. To this extent, the most common application of ANNs with the regression approach in the SRA studies is modelling the LSF or the Performance Function (PF) to be combined with reliability calculation models such as Monte Carlo Simulation (MCS), First-order reliability methods (FORM) and Second-order reliability methods (SORM) and First Order Second Moment (FOSM) (Joseph and Swalih CK 2023). For this purpose, the input variables are usually the structure properties, design variables, and operational conditions such as material properties, load fluctuations, and geometric properties. The output can be the value of LSF, the performance function, or the reliability index. Also, in problems with more than one LSF and multiple failure modes, ANNs with multiple outputs are used. However, it is worthwhile to consider the required training and analysis time when using ANN to approximate the LSF in an SRA problem.

Support Vector Machine based SRA

SVMs are widely used to perform classification and regression tasks in the SRA. They are particularly suitable for high dimensional problems. Their concept is defined based on structural risk minimization; they result in good generalization. In the SRA, SVMs with different modifications have been generally employed as surrogate models of the LSF or the Performance function (PF). The model is then used in combination with an SRA method, such as FORM, SORM, FOSM, or MCS (Joseph and Swalih CK 2023).

Benefits of AI in Construction

AI can improve the accuracy of risk assessments by processing large datasets and identifying patterns that may be overlooked by traditional methods. For instance, neural networks can be trained to predict failure probabilities based on historical data, while machine learning algorithms can detect early signs of deterioration or structural weaknesses. This predictive capability is crucial for proactive maintenance strategies, which can reduce costs and prevent catastrophic failures.

AI can aid in optimizing the design process by incorporating uncertain parameters such as material strength, load variations, and environmental factors. Genetic algorithms (GA), for example, can be used to find optimal solutions for structural design that balance cost, safety, and reliability. In the context of Nigeria's infrastructure, where budget constraints are a common issue, such optimization can lead to more cost-effective yet reliable designs.

AI-powered sensors and monitoring systems can provide real-time data on the health of structures. Machine learning algorithms can analyze this data to detect potential failures or maintenance needs. For instance, structural health monitoring systems equipped with AI can analyze vibration data, strain measurements, and temperature variations to assess the condition of a bridge or building in real-time, allowing for immediate intervention when necessary.

AI can be used to simulate structural failures and assess the impact of various factors such as loading conditions, material defects, and environmental stresses. Machine learning models can generate failure scenarios and assess the structural responses under various conditions, providing a deeper understanding of the failure mechanisms.

Application of AI in SRA

Dudzik and Potrzeszcz-Sut (2019) conducted SRA on spatial truss susceptible to stability loss from the condition of node snapping. The research utilized the normal neural networks approach to o formulate explicit limit state functions. The reliability analysis was performed with the aid of the NUMPRESS software, created at the IFTR PAS with FORM as the primary research method, the analysis of the results demonstrated that the FORM method is sufficiently precise and is an authoritative research method. The results indicate that FORM method allows for obtaining quick responses, which makes it possible to use the method in engineering practice as one of the modules of computational software that support structure design. Furthermore, it was observed that there is a significant difference in the values of reliability index determined by the FORM method for different descriptions of the mathematical model. The lowest values of reliability index are for cases with highest number of variables.

Afshari *et al.* (2023) reviewed the utilization of deep-learning based methods for SRA. Various deep-learning-based methods were categorized into three major sections that is; supervised, unsupervised and hybrid methods. The review revealed that the principal shared advantage of DL-based models is increasing accuracy while maintaining the computational cost within an acceptable margin.

Challenges in Implementing AI for Structural Reliability in Nigeria

Despite the promising potential of AI, challenges remain in adopting these technologies within the Nigerian context. Infrastructure data collection in Nigeria is often fragmented, inconsistent, and limited by insufficient funding for research and development in AI applications. Reliable and high-quality data is a fundamental requirement for training AI models. In Nigeria, data collection for structural performance is often inconsistent, incomplete, or unavailable, which limits the effectiveness of AI applications in structural reliability analysis.

There is a shortage of experts who are skilled in both AI and structural engineering in Nigeria. This knowledge gap poses a significant barrier to the implementation of AI-driven solutions in the field of SRA.

The high costs of AI infrastructure, such as sensors, computing power, and software, pose significant financial barriers, particularly in resource-constrained environments like Nigeria. Public and private sector investment in AI technologies is crucial to overcoming this hurdle.

There is also resistance to the adoption of new technologies within the Nigerian civil engineering sector, especially among older professionals who are accustomed to traditional methods of structural analysis. Educating engineers and stakeholders about the benefits of AI in SRA is essential to overcome this resistance.
This result suggests that AI can significantly enhance predictive maintenance capabilities and provide engineers with early warnings to prevent structural failures.

Furthermore, the integration of environmental data into AI models has proven effective in assessing the impact of external factors on concrete performance. For instance, the addition of data on local climate conditions in northern Nigeria, where temperature extremes are common, helped refine AI predictions of concrete durability.

Despite these promising results, challenges related to data scarcity and sensor installation remain. A significant portion of Nigeria's infrastructure lacks the modern sensor technologies necessary to fully utilize AI for continuous monitoring.

2. DISCUSSION

AI has demonstrated its potential in several studies for improving the reliability of concrete assessments. There is a need for increased investment in AI-related research, particularly in the context of Nigerian infrastructure. Universities and research institutions can play a critical role in developing AI models tailored to local conditions. Nigeria can benefit from partnerships with international AI experts and organizations. Collaboration with countries that have successfully implemented AI in infrastructure, such as the United States and China, could help accelerate the adoption of AI technologies in Nigeria.

Government policies that promote the adoption of AI in infrastructure development are essential. Providing financial incentives, grants, and subsidies to AI-based infrastructure projects could encourage more widespread use of these technologies.

3. CONCLUSION

Structural Reliability analysis is a prominent field in civil engineering. However, an accurate SRA in most cases deals with complex and costly numerical problems. The need for cost-effective structures has led researchers into seeking for solutions to increase the accuracy of SRA methods. Machine learning-based techniques have been introduced to the SRA problems to deal with this huge computational cost and increase accuracy. ANNs and SVMs are two popularly used tools in the ML-based SRA literature. They have been widely used for the SRA because of their adaptability to different well-known reliability calculation methods such as MCS, FORM, and SORM.

AI holds significant promise for revolutionizing the way concrete structures are monitored and maintained. By leveraging machine learning techniques and predictive analytics, the accuracy, speed and efficiency of structural assessments can be vastly improved. AI can provide early warnings of potential failures, enabling proactive maintenance strategies that can extend the lifespan of infrastructure and prevent costly repairs. While the technology has been successfully implemented in other parts of the world, its application in Nigeria faces challenges related to data availability, infrastructure, and expertise. Nonetheless, with the increasing adoption of digital technologies in Nigeria's construction industry, AI offers a compelling opportunity for improving the safety and sustainability of concrete structures.

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