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Structural Engineering Applications Using Artificial Intelligence and Machine Learning: A Review

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Abstract –Artificial Intelligence (AI) is revolutionizing civil engineering, particularly in the fields of structural design and analysis. This review paper explores the application of AI methodologies, including machine learning (ML) and deep learning (DL), in enhancing Civil Engineering practices. The study highlights how AI can address complex challenges such as structural health monitoring, structural analysis, design optimization and modelling of design. Through a systematic review of literature, empirical studies, and practical predictive modeling, the paper emphasizes the potential of AI to improve decision-making processes, optimize structural analysis and design predictions, and innovate traditional engineering practices. It also discusses the interdisciplinary nature of AI, drawing on computer science, engineering, and mathematics, while acknowledging challenges related to data quality, model accuracy, and computational efficiency. The findings underscore the need for continued research and development to fully harness AI's capabilities for the benefit of the civil engineering community and society at large.

Keywords –Civil Engineering, Structural Engineering, Artificial Intelligence, Machine Learning, Deep Learning, Neural Networks, AI, ML.

I. Introduction

Artificial Intelligence (AI), Machine Learning (ML) and Deep Learning (DL) are the buzzwords that have attracted the interest of many researchers from a variety of different fields for many years. AI is playing a transformative role in driving digital transformation across various sectors by bringing impact automation, personalization, predictive analytics, decision-making. AI is revolutionizing industries by automating repetitive tasks, improving efficiency, and productivity in various sectors. A new conceptual framework is being introduced to understand AI's multi-dimensional transformative power [1]. Artificial intelligence (AI) is evolving engineering by revolutionizing traditional design processes, optimizing design parameters, and solving intricate engineering problems that were previously challenging. AI applications have led to enhanced accuracy, precision, and creativity in engineering designs, resulting in better-performing products and increased customer satisfaction. It has facilitated design optimization, enabling the determination of optimal design variables and configurations while promoting innovation and creativity in the design process. [2]. The world of engineering is a highly untapped potential for AI, specifically Civil Engineering which can greatly benefit from AI by harnessing its computational power. AI has revolutionized Civil Engineering practices by offering advanced mathematical frameworks and algorithms that enhance design, construction, and inspection processes. AI's influence in Civil Engineering extends to improving decision-making processes, increasing operational efficiency, and optimizing resource allocation by analyzing construction equipment operations [3]. The incorporation of AI into civil engineering domains addresses challenges and opportunities, leading to the transformation and upgrading of traditional practices. Integrating AI into Civil Engineering facilitates enhanced data analysis through big data and machine learning algorithms, leading to more informed decision-making and support for practitioners [4]. Through the use of artificial intelligence for data analysis and decision-making, costly mistakes in large engineering projects can be minimized, leading to more accurate outcomes and reduced rework Furthermore, AI methods such as machine learning and deep learning have been successfully applied in Civil Engineering, enabling the creation of powerful predictive models for various engineering problems [5]. The cross-fertilization between scientific fields like structural engineering, transportation engineering, geotechnical engineering, hydraulic engineering, environmental engineering, coastal and ocean engineering, and structural health monitoring is being promoted by AI, leading to interdisciplinary advancements in the Civil Engineering. Civil Engineering derives significant advantages from (ML) techniques, including deep learning-based methods, for tasks like pavement crack detection and structural damage identification in concrete structures, improving maintenance and safety measures [6]. Artificial intelligence algorithms and neural networks have been extensively used in various Civil Engineering fields such as structural optimization, health monitoring, construction, bridge engineering, geotechnical engineering, and highway engineering. Applications of AI techniques are being employed in structural engineering covering structural health monitoring, design optimization, and prediction of structural behavior [7]. Machine learning algorithms are not only being applied to automate the design process of entire structures but are also enabling the exploration of design alternatives beyond human cognitive levels, enhancing the efficiency and effectiveness of the design process. Machine learning techniques have been applied in various structural engineering tasks such as seismic response prediction, system identification, damage localization, and structural control, showcasing their versatility and utility in the field [8]. Overall, AI in Civil Engineering enhances informatization, digitalization, autonomation, and intellectualization, making significant strides in intelligent architectural design, structural health diagnosis, disaster prevention, and reduction efforts [9].

II. Background on Artificial Intelligence

The concept of AI was first introduced in 1956 at Dartmouth Conference; but it was not until the dawn of 21st century that nurtured the computing power and the availability of data that AI began to shape into that of what we know it to be today. AI and ML are revolutionary technologies driving innovation across various fields due to their interdisciplinary nature. The simulation of human intelligence in machines programmed to think, learn, and solve various practical problems is called as AI. AI is a field that aims to create systems capable of human-like intelligence and behavior. This involves various modules such as knowledge representation, problem solving, and natural language processing. AI encompasses a range of tools, including neural networks, machine learning, and expert systems, which are used to solve complex problems [10],[11]. Arthur Samuel defined machine learning as “a field of study that gives computers the ability to learn without being explicitly programmed”. Machine learning transforms computing by allowing machines to learn from data, execute tasks, and make predictions. It utilizes algorithms that process and analyze data, draw insights from it, and make well-informed decisions. Some well-known ML techniques include supervised, unsupervised and reinforcement learning, in which models learn optimal actions through trial and error. Deep learning is a subset of machine learning that involves neural networks with many layers to model and understand complex patterns in large amounts of data. These multi-layered neural networks, known as deep neural networks, consist of interconnected nodes that work similarly to the neurons in the human brain. As these technologies advance, they hold the potential to transform industries by improving efficiency, precision, and decision-making capabilities. These advancements have led to significant breakthroughs in various sectors, from healthcare and finance to transportation and manufacturing. The ability of AI to analyze vast amounts of data quickly and accurately has revolutionized predictive modeling and automation. As AI continues to evolve, its integration into more aspects of daily life and industry is inevitable, promising even greater enhancements in efficiency and innovation.

III. Application of Artificial Intelligence in Structural Engineering

The analysis of structures is a crucial aspect in Civil Engineering. It is the process of determining the effects of loads and internal forces on a structure and also determining the displacements and deflections of the structure under various load conditions and evaluating the stress and strain distribution within structural elements. The analysis is essential to ensure the safety, stability, and performance of buildings, bridges, and other structures. The computational power of machine learning can be leveraged to address the challenge of structural analysis. Abdallah et al. used machine learning to predict the punching shear capacity of reinforced concrete flat slabs. The methodology involves employing an advanced M5P Model Tree Approach and comparing it with experimental results and other machine learning models including the Random Forest (RF) model, and the Linear Regression (LR) model. The model utilizes data of 610 shear capacity tests on RC flat slabs without shear reinforcement collected from 55 experimental studies. The dataset was partitioned in an 80:20 ratio, allocating 80 percent for training and the remaining 20 percent for testing. The predictions were evaluated on the basis of square of Correlation Coefficient (R), root mean squared error and mean absolute error. The results showed that the M5P model outperforms the rest in terms of having the highest Correlation Coefficient (R) R^2 values and the lowest values for both root mean squared error and mean absolute error, amongst all models examined [12]. Perera et al. extended the application of machine learning techniques to the prediction of shear capacity in NSM-FRP reinforced concrete beams, demonstrating the versatility and robustness of these advanced methodologies in different structural contexts. Artificial Neural Networks (ANN) and a multi-objective optimization approach is employed in this study. Their methodology involved developing and training neural network models using experimental data of 101 beams shear strengthened with NSM-FRP. The dataset was split into 80:20 ratio with greater portion of data for training and remaining portion of data for testing. To avoid a large number of variables affecting the model, Garson index was employed to filter the input parameters. Statistical analysis revealed that both methods provided very good predictions, with low scatter of data around the diagonal line, confirming the efficiency of ANNs as predictors of shear stress capacity and the goodness of fit obtained with the multi-objective approach. The proposed models with a simplified numerical model, showed that the two proposed approaches outperform the existing models, with slightly better predictions when using the proposed design equation [13]. Similarly, Markao et al. further explored the potential of ANNs and ML algorithms, applying them to a broader range of structural challenges, including the prediction of shear capacity in slender and deep beams, the fundamental period of RC and steel structures, and the deflection of curved steel I-beams. They created datasets for training of models with the help of finite element software and nonlinear analysis through the use of ReConAn FEA (2020) software. The validation of these models was done by using additional datasets made from experimental data and international literature. The predictions made by these models were than evaluated on the basis of percentage error (MAPE) and other error parameters and compared to that of the design formulae currently available in the international literature [14]. In a related effort, Sancheti et al. focused on applying machine learning techniques to predict and analyze design parameters of reinforced concrete slabs. The procedure involved exploring various machine learning models such as regression, support vector machine (SVM), ensemble boosted trees, and random forest are applied and compared based on their mean absolute error and R^2 values. Their data collection included gathering studies that utilize machine learning in civil engineering, particularly in structural design and analysis. The authors analyze these studies to assess machine learning models' effectiveness in predicting slab design parameters [15]. Expanding on the application of machine learning in structural engineering, Hong et al. utilized AI models trained on Autobeam-generated data to investigate the structural behaviors and designs of doubly reinforced concrete beams. Multiple regression models were employed to predict structural behaviors and designs based on strain compatibilities and transformed sections. The research incorporated Gaussian Process Regression (GPR) models with different kernel functions to establish useful reverse engineering scenarios. Feature selection algorithms were utilized in a greedy algorithm to determine reasonable input combinations and output sequences for comprehensive designs of doubly RC beams. The models for the designs were trained on 100,000 datasets. Validation parameters, such as Mean Squared Errors (MSEs) are calculated using normalized data to ensure the usability and accuracy of the AI-based design models [16]. Pinhão discusses the use of artificial intelligence in the analysis of beam structural members in civil engineering. It explores data-driven approaches to calculate the responses of new designs of beam structures using linear and nonlinear beam models and different neural network architectures. The results show that neural networks can approximate the behavior of realistic beam structures to predict bending moments, tensions, and maximum load. The data taken for the training of AI Neural Networks was obtained with the use of the software suite for finite elements analysis 'ABAQUS'. The developed model was able to predict solutions for beam structures in significantly less time compared to traditional methods, indicating the efficiency and potential for further evolution with more training data [17]. The methodologies employed in the papers vary but generally involve the results of how AI and ML can significantly enhance the developments in civil/structural engineering. These methodologies contribute to advancing our understanding of AI and ML applications in Structural Engineering and provide insights into their potential benefits and challenges.

IV. Challenges in Artificial Intelligence and Machine Learning

Delving into the terrain of AI and ML reveals a multitude of complex challenges confronting this evolving technology. The interpretability of AI models is a significant challenge, as understanding how AI algorithms arrive at specific conclusions is crucial for ensuring the safety and reliability of Civil Engineering structures. Data quality and quantity pose challenges, as AI models require large amounts of high-quality data to effectively learn and make accurate predictions about structural behavior [16]. The hurdles involve in implementing ML in practice are data availability, model explainability, and overfitting.The challenge of overfitting is crucial in machine learning models, emphasizing that it is not only associated with model training but also with model selection. It suggests that a combination of data-driven procedures and domain knowledge can help mitigate overfitting issues in building structural design and performance assessmen. The application of domain knowledge is crucial in addressing challenges in building structural design and performance assessment. Combining domain expertise with data-driven approaches can be a powerful strategy to overcome challenges in this field [18].

V. Conclusion

The reviewed research collectively underscores the transformative impact of AI technologies on civil engineering, specifically in structural engineering. AI and ML methodologies offer innovative solutions to complex engineering challenges, enhancing structural health monitoring, structural analysis, design optimization and modelling. These technologies streamline decision-making processes, improve structural analysis and predictions, and automate design optimization, thereby revolutionizing traditional engineering practices. However, while significant advancements have been made in analyzing structures, further research is needed to develop efficient AI-based design methodologies for structural members. The comprehensive review highlights the potential of AI and ML to drive efficiency, accuracy, and innovation in civil engineering practices. Continued research and development efforts are essential to fully exploit AI's capabilities, ensuring its integration benefits both the engineering community and society at large.

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