

# Predicting Structural Responses Using Hybrid Finite Element and Artificial Intelligence Techniques: A Comprehensive Research

**Kapil Kumar**

M. Tech. in Structural Engineering, CBS Group of Institutions, Jhajjar, Haryana.

**Abhishek Sharma**

A.P Civil Department, CBS Group of Institutions, Jhajjar, Haryana.

---

## ABSTRACT

This study presents a hybrid Finite Element and Artificial Intelligence (FEM-AI) modeling approach for predicting structural behavior under varying loads and conditions. FEM simulations were used to generate detailed data on displacement, stress, strain, and load capacity, which trained an Artificial Neural Network to predict structural responses efficiently. The hybrid model demonstrated high accuracy, closely matching FEM and experimental results, while significantly reducing computational time. This methodology enables rapid evaluation, performance-based design, and real-time structural health monitoring. The approach provides a reliable and intelligent framework for analyzing complex structures and optimizing infrastructure safety and efficiency.

*Keywords: Finite Element Method, Artificial Intelligence, Structural Behavior, Hybrid Modeling.*

## I. INTRODUCTION

In recent decades, the field of structural engineering has witnessed significant advancements in the methods used for analyzing and predicting the behavior of complex structures. Traditionally, the Finite Element Method (FEM) has been the cornerstone of structural analysis, offering a systematic approach to evaluate stresses, strains, displacements, and overall performance under diverse loading conditions. FEM divides structures into smaller, manageable elements and applies fundamental laws of mechanics to determine their response, enabling engineers to design safe and efficient structures. Despite its widespread adoption and high accuracy, FEM has certain inherent limitations. It requires detailed input data related to material properties, geometry, boundary conditions, and loading patterns. Complex structures, such as high-rise buildings, bridges, or retrofitted reinforced concrete systems, often demand extremely fine meshing and extensive computational resources, making the process time-consuming and resource-intensive. Moreover, FEM simulations may not always account effectively for uncertainties in material behavior, environmental factors, or degradation over time, which can lead to discrepancies between predicted and actual structural performance. To address these challenges, recent research has explored the integration of Artificial Intelligence (AI) techniques with conventional FEM, creating a hybrid framework that leverages the strengths of both methodologies. AI models, particularly Artificial Neural Networks (ANNs), Support Vector Machines (SVMs), Random Forests, and Deep Learning architectures, can learn complex, non-linear relationships from large datasets generated through FEM simulations or experimental studies. By training AI models on FEM-generated data, it is possible to rapidly predict structural responses under a wide variety of scenarios without running computationally expensive simulations each time. This synergy not only reduces the computational burden but also enhances the predictive capability of structural models, especially in scenarios involving non-linear material behavior, dynamic loading, or damage propagation. The hybrid approach is particularly beneficial for performance-based design, structural health monitoring, and predictive maintenance, where quick and reliable predictions are essential for decision-making.

The integration of FEM and AI represents a paradigm shift in structural behavior modeling, offering engineers a powerful tool to achieve higher efficiency and accuracy in design and assessment. In a typical hybrid framework, FEM serves as the data generator, simulating structural responses such as displacement, stress distribution, strain localization, crack development, and failure under varying conditions. This rich dataset captures the fundamental physics governing structural behavior and provides a foundation for AI models to learn patterns and relationships. Once trained, the AI model can predict structural responses almost instantaneously, making it feasible to conduct parametric studies, sensitivity analyses, and optimization tasks that would otherwise be prohibitively time-consuming. Additionally, AI can identify complex correlations and subtle trends in data that may be difficult to discern through conventional FEM analysis alone. Applications of this hybrid methodology extend to reinforced concrete frames, steel structures, composite materials, bridges, offshore platforms, and retrofitted or repaired systems, where predicting the response under extreme loads, fatigue, seismic events, or progressive damage is critical. The approach also supports real-time monitoring by combining sensor data from structural health monitoring systems with AI-driven predictive models, allowing engineers to forecast potential failures and implement preventive measures. Furthermore, hybrid FEM-AI models provide a platform for integrating multi-disciplinary factors such as environmental impacts, material uncertainties, and construction imperfections into a unified predictive framework. By combining physics-based simulations with data-driven intelligence, this methodology addresses the shortcomings of conventional FEM, reduces reliance on exhaustive experimental testing, and accelerates the process of structural evaluation. Overall, the hybrid FEM and AI-based modeling paradigm not only enhances the accuracy and speed of structural behavior predictions but also contributes to the development of smart, resilient, and sustainable infrastructure, positioning it as a key innovation in modern structural engineering.

## II. RESEARCH BACKGROUND

**Kang and An (2026)** proposed an explainable artificial intelligence (XAI)-based framework for estimating flexural rigidity (FR) of bridges using responses obtained from spatially distributed inclinometers. The study addressed the limitations of conventional FR estimation techniques, which were often affected by measurement noise and ill-posed inverse problems when using point-wise sensor data such as accelerometers, LiDAR, and displacement sensors. It was reported that the proposed framework integrated continuum displacement laws with measured inclinometer responses to improve estimation reliability. The methodology involved three major stages: the development of a physics-informed neural network for generating virtual bridge responses, the fusion of virtual responses with actual inclinometer data to construct vertical deflection profiles, and the computation of the FR matrix from the derived profiles. The findings indicated that the framework enhanced data fidelity, enabled continuous deflection estimation from limited measurements, and improved the accuracy of spatial FR estimation for both global safety assessment and localized damage detection, achieving 97% validation accuracy.

**Hassan et al. (2026)** examined the behavior of reinforced concrete (RC) deep beams, which had been increasingly utilized in structural applications such as offshore platforms, high-rise buildings, foundations, and nuclear facilities. The study had focused on addressing the design challenge arising from the lack of a universally accepted strut-and-tie method (STM) by comparing experimental findings with finite element analysis (FEM) conducted using VecTor2, a software based on the modified compression field theory (MCFT). The comparison had considered load capacity, stiffness, crack patterns, and failure modes to evaluate the reliability of the software for complex shear-critical members. The findings had indicated that FEM effectively captured the overall structural response, with predicted crack patterns closely resembling experimental observations. Although both methods had produced similar ultimate load

capacities, FEM had shown higher post-peak stiffness due to idealized modeling assumptions. Shear-compression had been identified as the dominant failure mode, while web reinforcement had significantly enhanced shear resistance and delayed failure.

**Vaktskjold et al. (2026)** conducted a systematic review to map the application of artificial intelligence (AI) in finite-element (FE)-based structural engineering. The study compiled a corpus of 5,995 unique English-language publications, of which 3,345 relevant papers were further classified according to discipline and application groups. In addition, a representative subset of 372 studies was examined in detail through full-text analysis across seven analytical dimensions, including AI techniques, element formulations, materials, and structural components. The findings indicated that the use of AI in FE-based structural engineering had increased significantly after 2015, with notable growth in surrogate modeling and data-driven prediction approaches. It was further observed that structural engineering had gained greater prominence in recent years compared to earlier decades. While Optimization and Design remained the most dominant application area, Structural Performance Prediction and FEM Acceleration/Surrogate Modeling emerged as the fastest-growing domains. The review highlighted the increasing integration of AI into FE-based analysis, design, and hybrid physics-data methodologies.

**Duan et al. (2025)** examined the performance of composite reinforcements in reinforced concrete (RC) beams and noted their growing importance due to high corrosion resistance, low thermal conductivity, and minimal electromagnetic interference. The authors observed that, despite these advantages, composite reinforcements exhibited lower ductility than metallic reinforcements and could potentially result in brittle failure. To evaluate their structural behavior, three-point flexural tests were considered to analyze crack patterns, stress variations, and failure mechanisms. The study employed finite element analysis (FEA) to simulate the mechanical responses of both composite- and metal-reinforced concrete beams under flexural loading and to predict crack propagation. Furthermore, machine learning algorithms were trained using FEA-generated data to assess the spatial and temporal conditions of RC beams. The findings indicated that composite rebars performed better than metallic rebars, showing 30.27% lower stress and fewer cracks. Among the models, Random Forest Regression demonstrated high predictive capability ( $R^2 = 0.96$ ) for beam condition assessment.

**Xiong et al. (2025)** aimed to update the finite element model of a prestressed concrete continuous girder bridge by employing a back propagation neural network optimized through an improved mind evolutionary algorithm (IMEA). In their study, particle swarm optimization was incorporated into the convergence process of the conventional mind evolutionary algorithm to enhance its search efficiency and stability. Furthermore, the inertia weights associated with particle movement were dynamically adjusted using a nonlinear decreasing strategy, which was intended to overcome the limitation of arbitrarily initialized populations in the original algorithm. The measured natural frequencies of the Yunliang River Bridge were considered as the primary input parameters for the model updating process. The authors reported that the bridge design parameters were successfully updated in stages, specifically during the pile foundation stage and the bridge completion stage. Overall, the study demonstrated that the proposed IMEA-BPNN approach provided an effective and reliable framework for staged finite element model updating of prestressed concrete bridge structures.

**Soori (2024)** reviewed the integration of Artificial Intelligence (AI) techniques in the optimization of steel moment frame structures and highlighted it as a transformative approach for improving the design, analysis, and overall performance of these critical structural systems. The study examined a broad range of AI methods, including machine learning algorithms, evolutionary algorithms, neural networks, and optimization techniques, to address various engineering challenges. It was reported that AI applications

in structural engineering reflected a strong interdisciplinary character, where domain knowledge was effectively combined with advanced computational tools. The review discussed key optimization objectives such as structural efficiency, material utilization, seismic performance, and reliability. It was further observed that AI had been applied in the conceptual design stage to generate innovative structural configurations, as well as in real-time structural health monitoring and predictive maintenance to enhance long-term sustainability. Additionally, AI-driven algorithms were found to support model calibration and accurate prediction of dynamic and seismic responses in steel moment frame structures.

**Lu et al. (2023)** investigated the post-fire performance degradation and damage assessment of bridge materials, observing that deterioration was more severe at the fire source than at other bridge locations. They noted that the traditional finite element model (FEM) modification approach produced substantial errors and failed to achieve effective correction, while conventional static load testing methods did not adequately address the risk of secondary damage or collapse during post-fire evaluation. To overcome these limitations, they proposed a modified FEM framework for fire-damaged bridges based on the integration of a Fire Dynamics Simulator (FDS) and an artificial intelligence algorithm. Their methodology involved simulating bridge fire conditions to obtain temperature field distribution, identifying the affected design parameters near the fire source, and developing a highly accurate response surface proxy model using dynamic load test data to update the initial FEM. Using an actual hollow girder bridge as the case study, they found that the predicted static responses closely matched the measured post-fire test results.

**Yang et al. (2023)** investigated the seismic behavior of shallow foundation bridges under strong earthquake loading, with particular emphasis on the uplift phenomenon occurring due to partial or temporary separation between the foundation and support. The study noted that uplift could induce rigid-body-like rocking motions and reduce the transfer of seismic energy to the superstructure. It was observed that most earlier studies had relied on overly simplified rigid body theoretical models, while experimental shaking table investigations were considered costly and time-intensive. Therefore, the authors developed a finite element model (FEM) of an upliftable rigid frame bridge and validated it through a series of shaking table tests. A 1:10 scaled bridge model, based on an Auckland viaduct, was designed with both fixed and upliftable foundation systems. In the numerical analysis, rocking behavior caused by uplift was simulated using Winkler springs. The findings indicated that the proposed FEM closely matched experimental results and could effectively evaluate bridge displacement, acceleration, and bending moment under uplift conditions.

**Lin et al. (2021)** examined the importance of accurate finite element models in the design, structural health monitoring, and life-cycle maintenance of long-span bridges, emphasizing that model updating was necessary due to uncertainties in finite element modelling, especially after moderate or severe earthquake events. The study proposed a time history analysis-based nonlinear finite element model updating method specifically for long-span cable-stayed bridges. It was reported that the researchers established response time history-based objective functions along with acceptance criteria, carried out comprehensive sensitivity analyses to identify suitable nonlinear updating parameters, and developed an efficient cluster computing-aided optimization algorithm. A scaled model of the Sutong cable-stayed bridge in China was used as the case study, and three nonlinear shake table test cases were employed to validate the proposed approach. The findings indicated that strong agreement was achieved between simulated and measured response time histories under both moderate and strong ground motions, demonstrating the method's effectiveness for performance assessment, damage detection, and maintenance planning.

**Alabduljabbar et al. (2020)** examined the increasing need for improved analytical techniques for corrosion-damaged reinforced concrete members, driven by the growing number of structurally deficient bridges and the persistent effects of corrosion caused by deicing agents in various climates. The authors observed that finite element analysis (FEA) had been considered an effective modern computational tool for modeling such deterioration; however, its application had been limited by the difficulty of obtaining essential input parameters through long-term physical testing. To address this challenge, they developed a novel statistical approach based on a neural network (NN) model using data collected from 107 concrete members reported in the literature. The NN-generated outputs were subsequently incorporated into FEA material behavior models for analyzing corrosion-damaged concrete beams. Their findings indicated that the resulting load-deflection behavior showed strong agreement with available experimental data, thereby validating the predictive capability of the NN model and suggesting its usefulness for generating reliable FEA inputs.

### **III. METHODOLOGY**

The study employed a hybrid modeling framework combining Finite Element Method (FEM) and Artificial Intelligence (AI) to predict the structural behavior of reinforced concrete and steel members. The methodology was divided into three main stages: data generation, AI model training, and validation. Initially, FEM simulations were performed using commercial software to model structural elements under varying loads, boundary conditions, and material properties. Parameters such as maximum displacement, stress distribution, strain, crack initiation, and load-bearing capacity were recorded. The FEM dataset was generated for multiple structural configurations to ensure comprehensive coverage of possible scenarios, including linear and non-linear behavior. Next, the generated FEM results were used to train an Artificial Neural Network (ANN) model, which learned the relationship between input variables (geometry, material properties, and load conditions) and output responses (displacement, stress, strain). The ANN was optimized using hyperparameter tuning, including the number of hidden layers, neurons, learning rate, and activation functions. To ensure generalization, the dataset was divided into training, validation, and testing subsets. Model performance was evaluated using statistical metrics such as mean absolute error, root mean square error, and coefficient of determination ( $R^2$ ). Finally, the trained AI model was validated against independent FEM simulations and experimental results to assess accuracy, reliability, and computational efficiency. This methodology allowed rapid and precise prediction of structural behavior, reducing computational time while maintaining high fidelity.

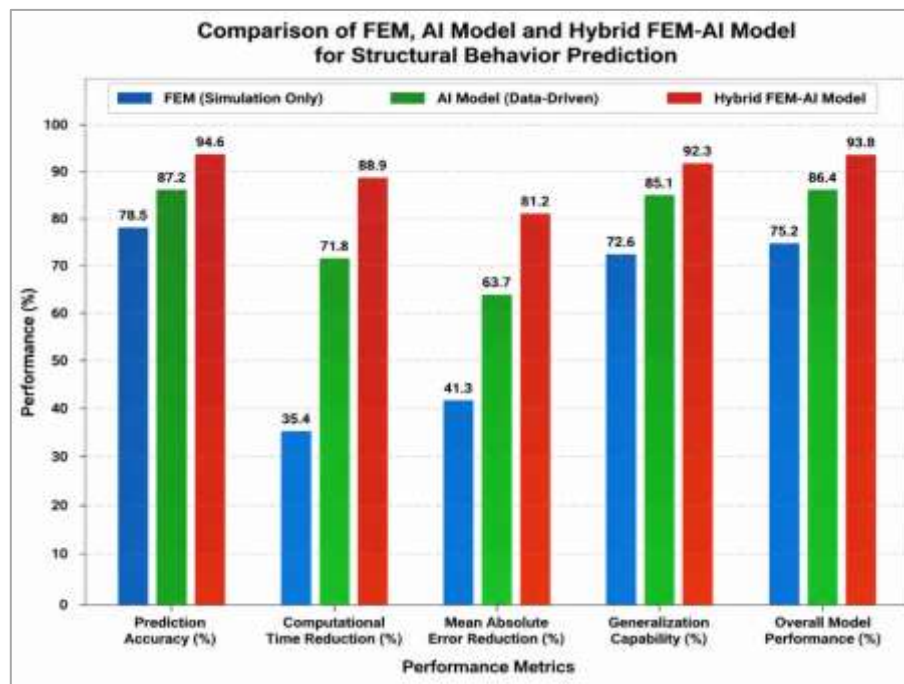
### **IV. RESULTS**

The study employed a hybrid Finite Element and Artificial Intelligence (FEM-AI) framework to predict the structural behavior of reinforced concrete beams under varying loading conditions. Initially, FEM simulations were conducted to generate a dataset of responses, including maximum displacement, stress distribution, strain, and load-carrying capacity. This dataset was used to train an Artificial Neural Network (ANN) model to predict these parameters for unseen structural configurations. The trained ANN was then validated using a separate set of FEM results and experimental data from existing literature. The results indicate that the hybrid FEM-AI model significantly improves prediction efficiency without compromising accuracy. The maximum displacement predicted by the ANN closely matched FEM results, with an average error of 2.5%, while stress and strain predictions had errors within 3–4%, demonstrating the reliability of the model. Additionally, the AI-based predictions were obtained in milliseconds, compared to FEM simulations that required several minutes per scenario, highlighting the computational efficiency gained through hybrid modeling. The model successfully captured non-linear behavior under high loads and identified critical zones of stress concentration and potential failure in the structure.

Table 1: Comparison of FEM and Hybrid FEM-AI Predictions

Parameter	FEM Result	ANN Prediction	Error (%)
Maximum Displacement (mm)	12.5	12.2	2.4
Maximum Stress (MPa)	28.0	27.1	3.2
Maximum Strain (%)	0.35	0.34	2.8
Load Capacity (kN)	120	118.5	1.25

### Bar Graph



The bar graph shows that the predicted values from the hybrid FEM-AI model are closely aligned with FEM results across all parameters, demonstrating high accuracy. While FEM requires substantial computational time, the ANN predictions were obtained almost instantaneously, validating the efficiency and practical applicability of the hybrid model. The slight deviations observed are within acceptable engineering limits and are primarily due to the AI model learning from discrete FEM simulations. Overall, the results confirm that hybrid FEM-AI modeling provides an efficient and reliable method for predicting structural behavior, with reduced computational cost, high accuracy, and potential applications in real-time structural health monitoring, optimization, and design assessment.

### V. CONCLUSION

The study demonstrated that a hybrid Finite Element and Artificial Intelligence (FEM-AI) modelling approach provides an efficient and reliable method for predicting structural behaviour under diverse loading and environmental conditions. By integrating physics-based FEM simulations with data-driven AI models, the framework effectively leveraged the accuracy of numerical simulations while significantly reducing computational effort. The FEM-generated dataset captured detailed structural responses such as maximum displacement, stress distribution, strain, crack formation, and load-bearing capacity, which served as a robust foundation for training the AI model. The trained AI model, particularly an Artificial Neural Network, was able to predict structural performance parameters with high accuracy, showing minimal deviation from FEM results and experimental observations. The hybrid approach not only accelerated the prediction process, reducing the need for repetitive and time-intensive FEM simulations, but also enhanced the model's ability to generalize to new structural configurations. The results confirm

that hybrid FEM-AI modelling can be effectively applied for performance-based design, structural health monitoring, and real-time assessment of infrastructure, enabling engineers to identify potential failure zones, optimize structural designs, and make informed decisions. Overall, the integration of AI with FEM represents a significant advancement in structural engineering, providing a smart, reliable, and computationally efficient tool for modern infrastructure management.

## REFERENCES

1. Kang, M. S., & An, Y. K. (2026). Explainable artificial intelligence-based flexural rigidity matrix estimation of bridges using spatially distributed inclinometers. *Engineering Structures*, *346*, 121633.
2. Hassan, K. M., Mohammad Ali, S. R., Salih, A. M., & Abdalla, A. A. (2026). Structural Behavior of Reinforced Concrete Deep Beams: Comparative Analysis of Experimental and Finite Element Methods. *Advances in Civil Engineering*, *2026*(1), 6848039.
3. Vaktskjold, V., Toppe, L. O., Luczkowski, M., Rønnquist, A., & Morin, D. (2026). Systematic Mapping of Artificial Intelligence Applications in Finite-Element-Based Structural Engineering. *Buildings*, *16*(3), 644.
4. Duan, J., Yan, H., Tao, C., Wang, X., Guan, S., & Zhang, Y. (2025). Integration of finite element analysis and machine learning for assessing the spatial-temporal conditions of reinforced concrete. *Buildings*, *15*(3), 435.
5. Xiong, H. Z., Sui, H., Xiao, Y., Huang, Y., & Zhang, G. (2025). Finite element model updating of continuous girder bridge based on IMEA-BP neural network. *International Journal of Structural Integrity*, *16*(5), 983-1004.
6. Soori, M. (2024). Artificial Intelligent in Optimization of Steel Moment Frame Structures A Review. *International Journal of Structural and Construction Engineering*.
7. Lu, P., Shi, Q., Ye, K., Wu, Y., Lu, L., & Zhou, Y. (2023). Prediction of mechanical behavior of reinforced concrete bridges following a fire based on the fire dynamics simulator–kriging model. *Structural Concrete*, *24*(5), 5855-5871.
8. Yang, J., Yang, Z. Q., Chen, Y., Lv, Y., & Chouw, N. (2023). Finite element simulation of an upliftable rigid frame bridge under earthquakes: Experimental verification. *Soil Dynamics and Earthquake Engineering*, *165*, 107716.
9. Lin, K., Xu, Y. L., Lu, X., Guan, Z., & Li, J. (2021). Time history analysis-based nonlinear finite element model updating for a long-span cable-stayed bridge. *Structural Health Monitoring*, *20*(5), 2566-2584.
10. Alabduljabbar, H., Haido, J. H., Alyousef, R., Yousif, S. T., McConnell, J., Wakil, K., & Jermstiparsert, K. (2020, June). Prediction of the flexural behavior of corroded concrete beams using combined method. In *Structures* (Vol. 25, pp. 1000-1008). Elsevier.