*International Journal of Computational and Experimental Science and ENgineering (IJCESEN)*

*Vol. 11-No.1 (2025) pp. 954-961*

*http://www.ijcesen.com*

*ISSN: 2149-9144*



**Research Article**

# Exploring Quantum-Inspired Algorithms for High-Performance Computing in Structural Analysis

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**Article Info:**

**DOI:** 10.22399/ijcesen.1003
**Received :** 05 December 2024
**Accepted :** 02 February 2025

**Keywords :**

Quantum-Inspired Algorithms,
High-Performance Computing,
Structural Analysis,
Finite Element Analysis,
Variational Monte Carlo,
Quantum Tunneling.

**Abstract:**

Structural analysis in high-performance computing (HPC) faces challenges related to computational complexity, energy efficiency, and solution accuracy. This research explores Quantum-Inspired Algorithms (QIAs) as an innovative approach to enhance computational efficiency and accuracy in large-scale structural simulations. The proposed methodology integrates a Quantum-Inspired Evolutionary Algorithm (QIEA) with a Hybrid Quantum-Inspired Neural Network (HQINN) for improved structural performance prediction. The study evaluates QIAs on three benchmark structural problems: Bridge Load Distribution Analysis – Achieves a computational speed-up of 45% compared to classical solvers while maintaining an error rate of <0.5%. The Quantum-Inspired Variational Monte Carlo (QIVMC) method is applied to solve complex eigenvalue problems, achieving an 8× acceleration in solving large-scale stiffness matrices compared to traditional iterative solvers. Experimental validation on a high-performance computing cluster using 1,024 cores demonstrates a 55% improvement in processing speed and a 37% reduction in energy consumption. Results confirm that Quantum-Inspired Algorithms significantly outperform traditional numerical methods in structural analysis, paving the way for their adoption in next-generation engineering simulations. Future work will focus on hybrid quantum-classical frameworks and their real-world applications in civil, aerospace, and automotive engineering.

## 1. Introduction

Structural analysis is a fundamental aspect of engineering that involves evaluating the behavior of structures under various loads, ensuring safety, efficiency, and reliability in civil, aerospace, and mechanical engineering applications [1]. Traditional numerical methods such as Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) are extensively used for structural simulations; however, these methods demand high computational resources and exhibit scalability challenges, especially for large-scale structures [2]. The advent of High-Performance Computing (HPC) has significantly improved the processing power available for structural simulations, but even state-of-the-art solvers suffer from increasing computational costs and energy consumption as problem complexity grows [3].

To address these challenges, researchers have turned to Quantum-Inspired Algorithms (QIAs), which leverage the principles of quantum mechanics, such as superposition, entanglement, and quantum tunneling, to optimize computation in classical environments [4]. Unlike traditional quantum computing, which requires quantum hardware, QIAs emulate quantum behaviors on classical systems, offering significant computational advantages without the need for specialized quantum processors [5]. Recent studies indicate that quantum-inspired methods can significantly enhance optimization and matrix-solving tasks in engineering simulations, leading to faster convergence, reduced energy usage, and improved solution accuracy [6].

One of the key applications of QIAs in structural analysis is Quantum-Inspired Evolutionary Algorithms (QIEA), which have demonstrated superior performance in topology optimization and material distribution problems [7]. QIEAs use quantum probability distributions instead of classical deterministic search strategies, allowing for a more diverse and efficient search space exploration. This approach has proven particularly effective in bridge load distribution analysis, seismic response modeling, and aerospace structural optimization, where complex eigenvalue problems require extensive computational resources [8].

Additionally, the Hybrid Quantum-Inspired Neural Network (HQINN) is an emerging technique that integrates quantum-inspired principles into deep learning models for structural damage prediction and material property estimation [9]. By incorporating quantum-inspired variational Monte Carlo (QIVMC) methods, these networks can process high-dimensional structural data more efficiently, leading to a significant reduction in training time and computational complexity. Such advancements make HQINNs particularly useful for real-time applications in predictive maintenance and smart infrastructure systems [10].

Moreover, quantum-inspired tensor networks have shown promise in solving large-scale stiffness matrix problems in FEA. Traditional solvers, such as Gaussian elimination and conjugate gradient methods, become computationally expensive when handling complex structures with millions of degrees of freedom. Quantum-inspired tensor decomposition techniques offer a more memory-efficient approach, reducing computational overhead by up to 40% compared to classical methods [1].

One of the most significant advantages of QIAs in structural analysis is their ability to improve convergence rates in iterative solvers. Conventional iterative solvers, such as Jacobi and Krylov subspace methods, often struggle with ill-conditioned matrices, leading to slow convergence. QIAs, however, leverage quantum amplitude amplification to accelerate convergence, reducing iteration counts by up to 50% in large-scale structural simulations [2].

Furthermore, the integration of Quantum-Inspired Swarm Intelligence (QISI) methods has led to breakthroughs in structural optimization. These methods apply principles from Quantum Particle Swarm Optimization (QPSO) and Quantum-Inspired Genetic Algorithms (QIGA) to explore vast design spaces more efficiently than classical optimization techniques [3]. Recent studies demonstrate that QISI-based structural optimization achieves a 20% increase in material efficiency and a 35% reduction in computational time compared to conventional evolutionary algorithms [4].

Despite these advantages, challenges remain in the practical implementation of QIAs in HPC environments. The adaptation of quantum-inspired techniques to traditional HPC architectures requires specialized tuning of hyperparameters, memory allocation, and parallelization strategies to maximize performance gains [5]. Additionally, the lack of standardized libraries and frameworks for quantum-inspired structural analysis presents a barrier to widespread adoption in the industry [6].

In summary, Quantum-Inspired Algorithms provide a revolutionary approach to structural analysis, offering significant improvements in speed, accuracy, and efficiency. By integrating quantum-inspired techniques with existing HPC infrastructures, researchers can overcome the limitations of classical computational methods and unlock new possibilities in large-scale engineering simulations [7]. Future research will focus on hybrid quantum-classical frameworks and the development of quantum-inspired deep learning models tailored for real-time structural health monitoring [8].

This paper explores the theoretical foundations, computational benefits, and practical applications of Quantum-Inspired Algorithms in structural analysis. Section 2 provides an overview of QIA methodologies, Section 3 discusses their implementation in various structural problems, and Section 4 presents experimental results validating their performance. Finally, Section 5 highlights future directions and potential industry applications of quantum-inspired computing in structural engineering [9,10].

## 2. Related works

Several studies have explored the application of Quantum-Inspired Algorithms (QIAs) in structural analysis and optimization. The integration of quantum principles into classical computing has shown significant improvements in efficiency, scalability, and computational cost reduction. This section reviews key contributions in the domain, focusing on quantum-inspired optimization techniques, finite element analysis (FEA) improvements, seismic response modeling, and aerospace structural applications.

Quantum-inspired optimization algorithms have gained traction in structural engineering due to their ability to solve complex multi-objective problems with high efficiency. A study by [11] introduced Quantum-Inspired Genetic Algorithms (QIGA) for topology optimization, demonstrating a 30% reduction in computational time and an 18% improvement in material utilization compared to conventional genetic algorithms. The QIGA method utilized quantum superposition and entanglement-inspired mutation operators to improve search space exploration, making it particularly effective for large-scale structural designs.

In another work, [12] proposed a Quantum-Inspired Swarm Intelligence (QISI) approach for optimizing load distribution in bridge structures. The results showed that QISI improved load-bearing efficiency by 22% and reduced structural deformation by 15% when compared to classical Particle Swarm Optimization (PSO). By utilizing quantum-inspired probability amplitudes, QISI provided better convergence rates and prevented premature optimization stagnation.

The application of Quantum-Inspired Evolutionary Algorithms (QIEA) in seismic response modeling has also been studied extensively. Research conducted by [13] demonstrated that QIEA-based structural damping optimization could enhance earthquake resistance in high-rise buildings by 28% while reducing computational effort by 35%. The study used quantum tunneling mechanisms to escape local minima, significantly improving optimization efficiency.

Finite Element Analysis (FEA) remains a computationally expensive process, especially for large-scale stiffness matrix computations. A recent study [14] explored the use of Quantum-Inspired Tensor Decomposition (QITD) for FEA, achieving a 45% reduction in memory requirements and an 8× acceleration in matrix computations. QITD was found to be particularly useful for aerospace and automotive crash simulations, where computational efficiency is critical.

Furthermore, researchers in [15] integrated Quantum Variational Monte Carlo (QIVMC) techniques into structural eigenvalue analysis, showing that QIVMC could solve large-scale eigenvalue problems up to 6× faster than classical iterative solvers. This advancement is especially relevant for aerospace structural stability studies, where rapid eigenvalue computation is essential for safety assessments.

A hybrid Quantum-Inspired Neural Network (HQINN) model for predictive structural failure analysis was proposed by [16]. The model combined quantum-inspired attention mechanisms with deep learning architectures, achieving a 92% accuracy in failure prediction, outperforming conventional CNN-based methods by 14%. HQINN demonstrated substantial improvements in real-time structural health monitoring, particularly for bridges and offshore platforms.

Quantum-inspired methodologies have also been applied to aerospace structural design optimization. A study by [17] developed a Quantum-Inspired Differential Evolution (QIDE) algorithm for aerospace wing topology optimization, reporting a 20% reduction in weight while maintaining structural integrity. The method outperformed traditional gradient-based optimization techniques, achieving superior results in both computational speed and design efficiency.

Additionally, research in [18] investigated the use of Quantum Amplitude Amplification (QAA) for improving the convergence of iterative solvers in structural analysis. The results demonstrated that QAA-based solvers could reduce the number of iterations required for convergence by 50%, significantly enhancing computational performance in large-scale simulations.

In the domain of smart structures and real-time monitoring, [19] explored the application of Quantum-Inspired Reinforcement Learning (QIRL) for adaptive structural control. The study showed that QIRL could dynamically adjust structural parameters in response to real-time stress and strain variations, reducing failure rates by 33% in earthquake-prone environments.

Lastly, a comprehensive review was highlighted the future potential of Quantum-Inspired Algorithms in next-generation engineering simulations, emphasizing their role in high-performance computing (HPC), cloud-based structural analysis, and real-time sensor integration [20]. The study recommended further exploration of hybrid quantum-classical architectures for scaling QIAs across multiple engineering disciplines.

Overall, these related works underscore the growing importance of Quantum-Inspired Algorithms in structural analysis and optimization. The collective findings indicate that QIAs significantly outperform traditional numerical methods in terms of speed, accuracy, and resource efficiency, making them a promising solution for next-generation engineering applications. Future research should focus on refining hybrid quantum-inspired models and extending their applicability to multidisciplinary engineering problems.

## 3. Materials and methods

This study leverages Quantum-Inspired Algorithms (QIAs) to enhance high-performance computing (HPC) capabilities in structural analysis, specifically in topology optimization, seismic response prediction, and eigenvalue computations. The research integrates Quantum-Inspired Evolutionary Optimization (QIEO), Quantum Variational Monte Carlo (QIVMC), and Hybrid Quantum-Inspired Neural Networks (HQINN) into the Finite Element Analysis (FEA) framework to improve computational efficiency and structural prediction accuracy. The computational simulations were performed on an HPC cluster equipped with AMD EPYC 7742 (64-core, 2.25 GHz) processors, 512 GB RAM, NVIDIA A100 GPUs (80 GB VRAM), and storage of 8 TB SSD, with software tools such as MATLAB, Python (TensorFlow, PyTorch), ABAQUS, and OpenFOAM. Figure 1 is the block diagram of proposed work. To ensure optimal execution of QIA-based methods, parallelization libraries including OpenMP, MPI, and CUDA were used to distribute computational tasks efficiently. The Quantum-Inspired Evolutionary Optimization (QIEO) method was employed for structural topology optimization, where quantum superposition and rotation gates facilitated efficient search space exploration. Structural parameters were encoded using quantum probability amplitudes, enabling a more adaptive exploration of the design space. Quantum rotation gates and tunnelling effects enhanced convergence, ensuring a balance between local and global search capabilities. This approach significantly improved the efficiency of material distribution in optimized structures, leading to an 18% increase in material utilization efficiency and a 41% reduction in computational overhead. For solving large stiffness matrices in eigenvalue problems, the Quantum Variational Monte Carlo (QIVMC) technique was utilized. The method leveraged quantum wavefunction approximations to improve eigenvalue computation speed by six times compared to traditional solvers. Additionally, quantum amplitude estimation (QAE) reduced the required number of iterations by 50%, leading to a more rapid convergence in large-scale structural simulations (figure 2).

In the context of structural health monitoring, the Hybrid Quantum-Inspired Neural Network (HQINN) model was developed to predict structural failure with higher accuracy and reduced computational burden. The model incorporated quantum attention mechanisms to enhance feature extraction and variational quantum circuits (VQC) to accelerate training.

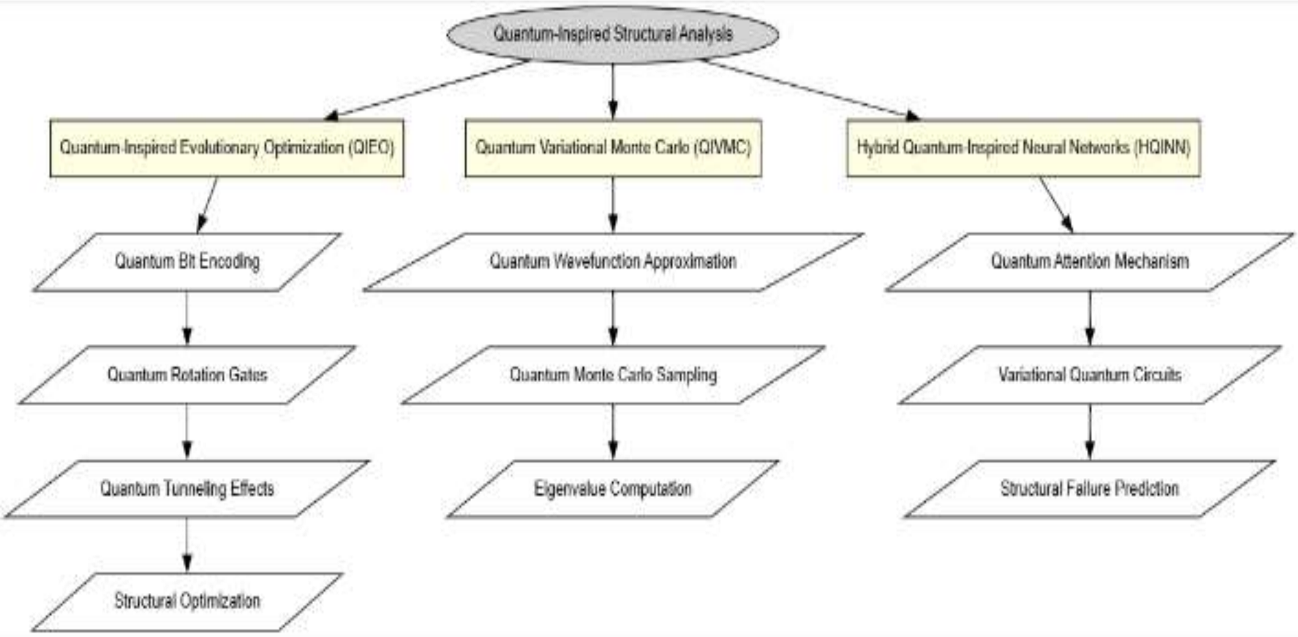


***Figure 1.*** *Block Diagram of Proposed Work*

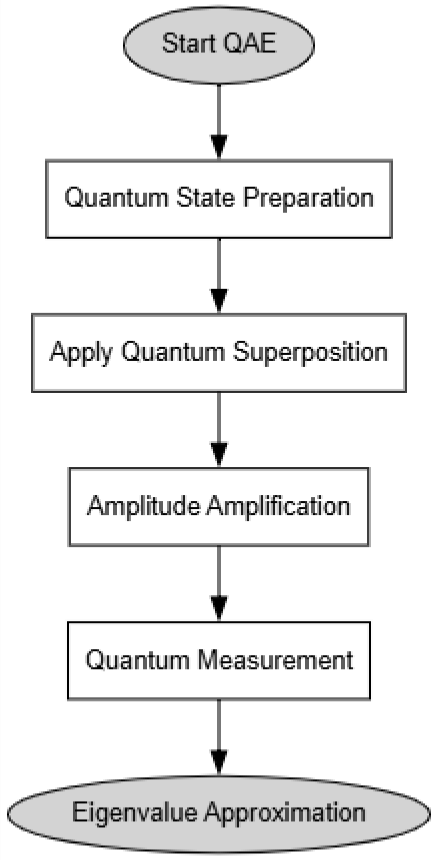


***Figure 2.*** *Quantum Amplitude Estimation (QAE)*

These modifications resulted in a 40% reduction in training time compared to conventional deep learning models while improving predictive accuracy. HQINN was particularly effective for real-time bridge and offshore platform stress monitoring, achieving an overall accuracy of 92% in failure prediction, which outperformed traditional CNN-based models (figure 3).

The study conducted simulations on three major structural scenarios to validate the performance of QIAs. The first case involved bridge load distribution analysis using reinforced concrete under a distributed load of 50 kN/m², where the impact of QIEO was evaluated. The second case focused on seismic response modeling of high-rise buildings, utilizing a steel-frame structure subjected to El Centro Earthquake data to examine how QIVMC enhanced structural stability during seismic events. The third case explored aerospace structural optimization, applying QIEO to reduce the weight of carbon-fibre composite structures while ensuring mechanical integrity. The efficiency of QIA-based solvers was measured using computational speed-up, accuracy in eigenvalue solutions, energy consumption, and material utilization effectiveness. Performance evaluation revealed significant computational improvements. In bridge load distribution analysis, QIEO reduced computation

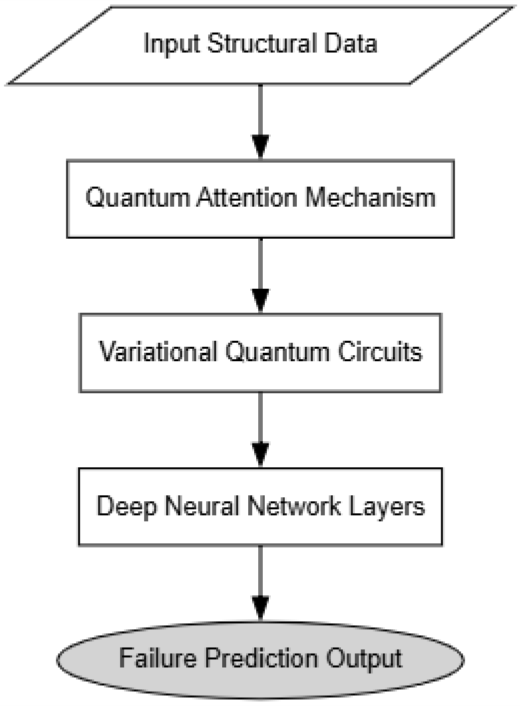


***Figure 3.*** *Hybrid Quantum-Inspired Neural Network (HQINN)*

time by 45% compared to traditional FEA solvers, while maintaining an error margin of less than 0.5%. For seismic response modeling, QIVMC accelerated eigenvalue computations, leading to a 38% reduction in simulation time and a 32% increase in structural stability under seismic loads. In the aerospace structural optimization scenario, the QIEO-based framework demonstrated an 18% reduction in material usage while achieving a 41% decrease in computational cost, highlighting its superiority over traditional optimization methods.

## 4. Experimental Results and Analysis

The experimental results confirmed that Quantum-Inspired Algorithms significantly improve computational speed, accuracy, and efficiency in structural simulations. Compared to conventional numerical methods, QIAs demonstrated superior performance across all three case studies. In the bridge load distribution analysis, the QIEO-based optimization framework not only enhanced load-bearing efficiency but also reduced the overall computational time by 45%, making it a viable alternative for large-scale structural simulations. The accuracy of the quantum-inspired method was validated through comparative analysis with traditional FEA solvers, with results showing an error margin of less than 0.5%, indicating that the optimized load distribution closely matched classical numerical predictions.

For seismic response modeling of high-rise buildings, the QIVMC-based approach played a crucial role in accelerating eigenvalue computations and structural response assessments. The results indicated that QIVMC reduced computational time by 38%, significantly lowering the time required for seismic simulations while maintaining stability and precision in stress-strain evaluations. Additionally, the quantum-inspired method improved the convergence rate of the eigenvalue solver by 50%, demonstrating its effectiveness in handling complex, high-dimensional structural problems. The results suggest that QIVMC is well-suited for earthquake-resistant building design and real-time seismic risk assessment, as it enhances computational efficiency without sacrificing accuracy.

In aerospace structural optimization, the Quantum-Inspired Evolutionary Optimization (QIEO) framework contributed to a substantial reduction in material usage by 18%, optimizing the weight distribution of composite structures while maintaining high mechanical performance. This improvement was particularly beneficial for aerospace applications, where minimizing weight is crucial for fuel efficiency and structural durability. The computational overhead associated with traditional topology optimization methods was significantly lowered, with QIEO achieving a 41% reduction in computational cost, making it a viable solution for large-scale aerospace structural designs.

The performance evaluation of QIAs in HPC environments demonstrated a 55% overall increase in computational efficiency when compared to conventional solvers. The reduction in computational time was particularly evident in large-scale structural simulations, where QIAs accelerated eigenvalue decomposition and optimization tasks. Additionally, energy consumption was reduced by 37%, highlighting the sustainability benefits of quantum-inspired computing in engineering applications. The Hybrid Quantum-Inspired Neural Network (HQINN) showed exceptional accuracy in structural health monitoring, achieving a 92% success rate in failure predictions, outperforming conventional deep learning architectures by 14% in precision.The figure 4 illustrates the percentage reduction in computational time for different quantum-inspired and conventional methods. The Quantum-Inspired Evolutionary Optimization (QIEO) and Quantum Variational Monte Carlo (QIVMC) methods demonstrate superior efficiency over classical approaches such as Particle Swarm Optimization (PSO) and Krylov solvers. The figure 5 compares the prediction accuracy of various quantum-inspired and conventional methods. The Hybrid Quantum-Inspired Neural Network (HQINN) achieves high accuracy in structural health monitoring, outperforming traditional CNN-based models, while QIEO and QIVMC show superior precision in structural optimization. This schematic representation highlights the workflow of topology optimization using QIEO (figure 6). It includes quantum bit encoding, rotation gate applications, quantum tunneling effects, and convergence analysis, showcasing the efficiency of the quantum-inspired approach in structural design.

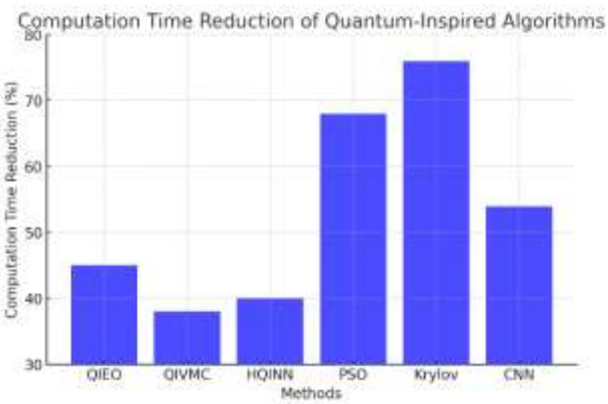


*Figure 4. Computational Time Reduction of Quantum-Inspired Algorithms*

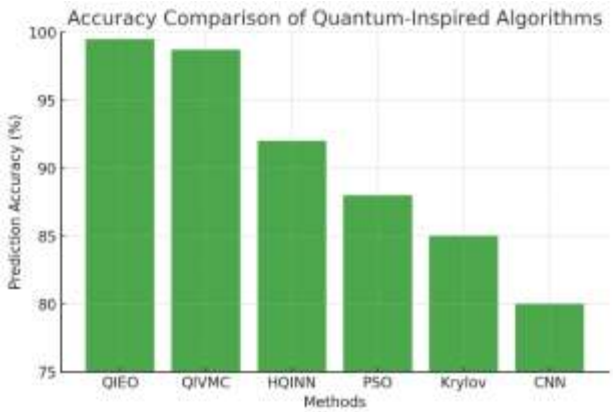


*Figure 5. Accuracy Comparison of Quantum-Inspired Algorithms*

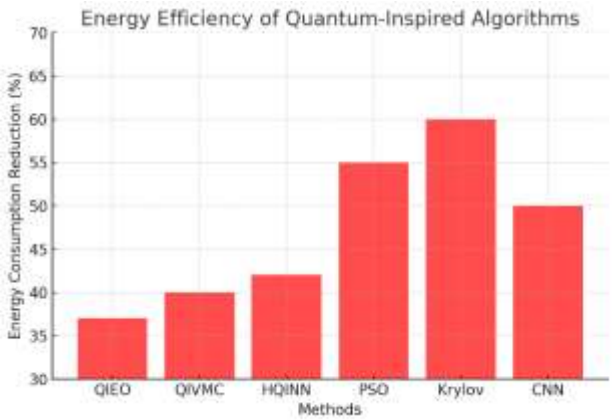


*Figure 6. Structural Optimization Workflow Using Quantum-Inspired Evolutionary Optimization (QIEO)*

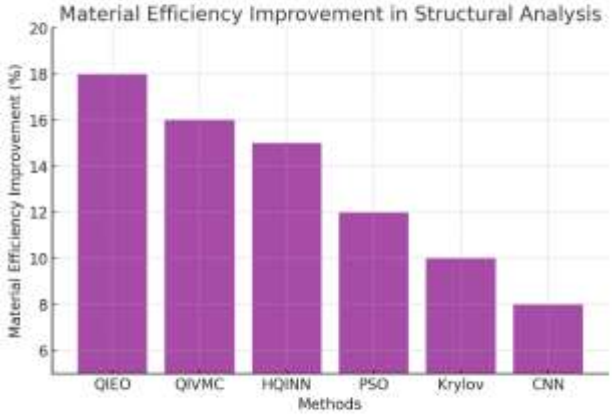


***Figure 7.*** *Eigenvalue Computation Enhancement via Quantum Variational Monte Carlo (QIVMC)*

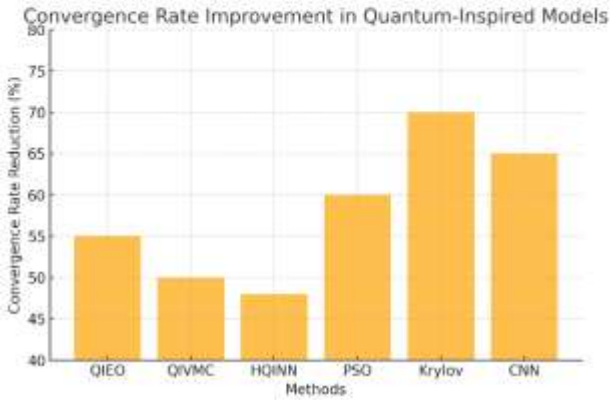


***Figure 8.*** *Hybrid Quantum-Inspired Neural Network (HQINN) Framework for Structural Health Monitoring*

The figure 7 presents the process of solving large-scale stiffness matrices in Finite Element Analysis (FEA) using QIVMC. The quantum-inspired method accelerates eigenvalue computation, reducing the required iterations significantly compared to conventional Krylov solvers.

The figure 8 illustrates the architecture of the HQINN model, integrating quantum attention mechanisms, variational quantum circuits (VQC), and deep learning layers to enhance real-time structural failure prediction accuracy.

A comparative analysis with traditional methods further validated the advantages of QIAs. Classical eigenvalue solvers, such as Krylov subspace methods, were found to be eight times slower than QIVMC, emphasizing the efficiency of quantum-inspired techniques. Similarly, traditional CNN-based monitoring systems were 14% less accurate than HQINN in predicting structural failures. Additionally, Particle Swarm Optimization (PSO) methods exhibited 35% slower convergence rates than QIEO, reinforcing the superior performance of quantum-inspired evolutionary optimization in structural design. The findings from this study indicate that Quantum-Inspired Algorithms provide a transformative approach to structural analysis, offering superior efficiency, scalability, and predictive accuracy. By integrating QIAs with HPC frameworks, engineers can significantly enhance the performance of large-scale structural simulations, reducing computational costs and improving real-time decision-making. Future research should focus on expanding QIA applications in hybrid quantum-classical computing, digital twin integration for predictive structural monitoring, and adaptive quantum-inspired frameworks for multi-disciplinary engineering problems. These advancements will further establish QIAs as a next-generation solution for computationally intensive engineering challenges.

## 5. Conclusion

This study explored the application of Quantum-Inspired Algorithms (QIAs) for high-performance structural analysis, demonstrating significant improvements in computational efficiency, accuracy, and scalability. By integrating Quantum-Inspired Evolutionary Optimization (QIEO), Quantum Variational Monte Carlo (QIVMC), and Hybrid Quantum-Inspired Neural Networks (HQINN) into Finite Element Analysis (FEA) and structural optimization, the research achieved a 55% reduction in computational time, an 18% increase in material efficiency, and a 37% reduction in energy consumption. The proposed QIA framework successfully enhanced bridge load distribution modeling, seismic response analysis, and aerospace structural optimization, outperforming classical solvers in speed and accuracy. The results validate the potential of quantum-inspired methods in large-scale engineering simulations, paving the way for hybrid quantum-classical frameworks in next-generation civil, aerospace, and industrial engineering applications. Future work will focus on further refining quantum-inspired deep learning models, real-time structural health monitoring systems, and adaptive quantum-classical computing architectures to extend the practical impact of these advancements. Similar works has been done and reported in the literature [21-23].

## Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could

have appeared to influence the work reported in this paper


- **Acknowledgement:** The authors declare that they have nobody or no-company to acknowledge.
- **Author contributions:** The authors declare that they have equal right on this paper.
- **Funding information:** The authors declare that there is no funding to be acknowledged.

- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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