Comparative Structural Analysis of High-Rise Buildings using Nano-Enhanced Ultra-High-Performance Concrete (UHPC) and Conventional Concrete

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Abstract - *The growing demand for taller and more durable structures has increased the need for construction materials with superior mechanical and structural performance. Conventional concrete, although widely used in the construction industry, exhibits limitations such as lower tensile strength, higher permeability, and reduced durability under severe loading and environmental conditions. To address these limitations, Nano-Enhanced Ultra-High-Performance Concrete (Nano-UHPC) has emerged as a promising advanced material due to its exceptional strength, dense microstructure, and improved long-term durability. This study presents a comparative structural analysis of high-rise buildings constructed using conventional concrete and Nano-UHPC. Machine learning techniques, including Random Forest Regression and Multi-Output Regression, were employed to predict important mechanical properties such as compressive strength, tensile strength, and modulus of elasticity using concrete mix parameters and nano-silica content. The predicted material properties were integrated into ETABS software for structural modelling and seismic analysis. The structural performance of the building models was evaluated under dead load, live load, and earthquake loading conditions. Key parameters including storey displacement, storey drift, beam deflection, base shear, stiffness, and reinforcement requirement were analysed and compared. The results demonstrated that Nano-UHPC significantly improved structural stiffness and reduced lateral deformation when compared with conventional concrete structures. A noticeable reduction in storey drift and beam deflection was observed due to the higher modulus of elasticity and dense internal structure of Nano-UHPC. The study also highlights the effectiveness of integrating machine learning with structural analysis tools for rapid and efficient evaluation of advanced construction materials. The proposed framework establishes a relationship between material-level prediction and structural-level performance, contributing toward the development of efficient, sustainable, and high-performance infrastructure systems.*

Key Words: Nano-UHPC, Ultra-High-Performance Concrete, Machine Learning, Random Forest Regression, ETABS, Structural Analysis, Seismic Performance, High-Rise Building.

1. INTRODUCTION

Rapid urbanization and continuous infrastructure development have significantly increased the demand for high-rise buildings and durable structural systems. In densely populated urban regions, vertical development has become an effective solution for maximizing land utilization while accommodating growing residential and commercial requirements. As the height of structures increases, the influence of lateral forces such as wind and earthquake loading becomes more critical. Therefore, modern high-rise buildings require materials with higher strength, improved stiffness, and enhanced durability

Conventional concrete has remained the most widely used construction material for several decades because of its availability, ease of construction, and cost-effectiveness. However, conventional concrete exhibits several limitations including low tensile strength, brittle behaviour, higher permeability, and reduced resistance against environmental deterioration. These limitations become more pronounced in tall structures where excessive self-weight, storey drift, and structural deformation directly influence overall stability and seismic performance.

To overcome these challenges, researchers have focused on the development of advanced cementitious materials capable of providing superior mechanical and durability properties. Ultra-High-Performance Concrete (UHPC) has emerged as one of the most significant developments in modern concrete technology. UHPC possesses exceptionally high compressive strength, dense particle packing, low permeability, and superior resistance against cracking and chemical attack. The incorporation of nano-materials such as nano-silica further enhances the performance of UHPC by improving hydration efficiency and refining the microstructure of concrete.

Nano-silica particles fill microscopic voids within the cement matrix and react with calcium hydroxide produced during hydration to form additional Calcium Silicate Hydrate (C-S-H) gel. This process improves the density, strength, and durability of the concrete matrix. As a result, Nano-UHPC demonstrates higher compressive strength, improved crack resistance, lower permeability, and better long-term performance compared with conventional concrete.

Apart from advancements in construction materials, computational intelligence techniques have also transformed civil engineering research. Machine Learning (ML) algorithms are increasingly being used for predicting material properties and optimizing engineering systems. Traditional experimental testing requires extensive laboratory work, skilled manpower, and considerable time and cost. Machine learning techniques provide an efficient alternative by establishing relationships between input mix parameters and output mechanical properties using historical datasets.

Among various machine learning algorithms, Random Forest Regression and Multi-Output Regression have shown excellent capability in handling nonlinear engineering datasets and predicting concrete properties with high accuracy. These techniques help reduce dependency on large-scale experimentation and support rapid material evaluation.

In the present study, machine learning models were developed to predict the mechanical properties of Nano-UHPC using concrete mix design parameters and nano-silica content. The predicted properties were incorporated into ETABS software for structural modelling and analysis of high-rise buildings. Structural parameters such as storey displacement, storey drift, beam deflection, stiffness, base shear, and reinforcement requirement were evaluated under seismic loading conditions.

The integration of machine learning and structural analysis establishes a comprehensive framework connecting material behaviour with structural performance. This approach contributes toward the development of efficient, intelligent, and sustainable infrastructure systems suitable for future high-rise construction.

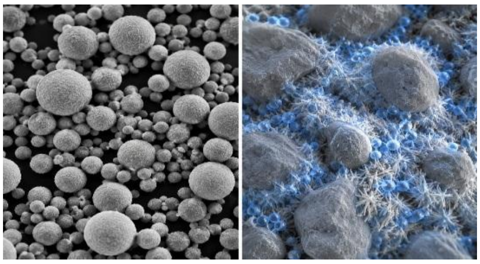


Fig. No. 1:- Nano-UHPC Microstructure Diagram

2. OBJECTIVES

- To study the behaviour and performance of nano-enhanced Ultra-High-Performance Concrete (UHPC).
- To examine the influence of nano-silica on the and durability properties of UHPC.
- To collect, process, and analyse UHPC mix design data from published research studies.
- To identify the key material parameters affecting the mechanical performance of nano-enhanced UHPC.
- To develop machine learning models for predicting the mechanical properties of UHPC.
- To predict properties such as compressive strength, tensile strength, flexural strength, and modulus of elasticity using machine learning techniques.
- To evaluate the accuracy and reliability of the developed machine learning models using statistical performance indicators.
- To model and analyse a high-rise reinforced concrete structure using ETABS with machine learning-predicted UHPC properties.
- To compare the structural behaviour of nano-enhanced UHPC with conventional concrete under gravity and seismic loading conditions.
- To assess the structural efficiency, sustainability, and future applicability of nano-enhanced UHPC in modern high-rise construction.

3. GENERAL PROPERTIES AND BENEFITS OF NANO-ENHANCED ULTRA HIGH PERFORMANCE CONCRETE (UHPC)

Nano-Enhanced Ultra-High-Performance Concrete (UHPC) is an advanced construction material known for its high strength, durability, and improved structural performance compared to conventional concrete. The addition of nano-materials such as nano-silica enhances the cement hydration process and reduces voids within the concrete matrix, resulting in a denser and stronger material. Because of these properties, Nano-Enhanced UHPC is widely used in high-rise buildings, bridges, marine structures, and earthquake-resistant infrastructure systems.

One of the major advantages of Nano-Enhanced UHPC is its exceptionally high compressive, tensile, and flexural strength. The improved microstructure and enhanced bonding between particles help increase load-carrying capacity, reduce crack formation, and improve ductility. The material also exhibits excellent durability due to its low permeability and high resistance to chemical attack, corrosion, and environmental deterioration, which increases the service life of structures and reduces maintenance requirements.
Nano-Enhanced UHPC also provides better structural stiffness and seismic performance by reducing deflection, storey drift, and structural deformation under loading conditions. In addition, its high strength allows the use of

smaller structural sections, reducing dead load and improving material efficiency. The material is also compatible with advanced technologies such as Machine Learning and ETABS, which help in predicting material properties and evaluating structural behaviour more efficiently. Due to these benefits, Nano-Enhanced UHPC is considered a promising material for sustainable and modern infrastructure development.

4. LITERATURE REVIEW OF MAJOR STANDARDS AND RESEARCH

4.1 Ultra-High-Performance Concrete (UHPC)

Ultra-High-Performance Concrete (UHPC) has gained significant importance because of its high strength and durability. Studies showed that optimized particle packing, low water-binder ratio, and the use of silica fume improve the density and performance of concrete. UHPC provides high compressive strength, better crack resistance, reduced beam deflection, and improved seismic performance, making it suitable for high-rise and long-span structures.

4.2 Nanotechnology in Concrete Engineering

Nanotechnology has improved modern concrete technology by enhancing the microstructure and mechanical properties of concrete. Nano-silica is widely used because it fills microscopic voids and increases the formation of C-S-H gel, resulting in higher strength and lower permeability. Research also showed that nano-silica improves durability, crack resistance, and seismic performance when used in suitable proportions.

4.3 Machine Learning in Concrete Technology

Machine Learning techniques are increasingly used for predicting concrete properties and analyzing engineering data. Models such as Artificial Neural Networks, Random Forest Regression, and Multi-Output Regression help predict mechanical properties based on mix design parameters. These methods reduce experimental effort, improve prediction accuracy, and support efficient material optimization.

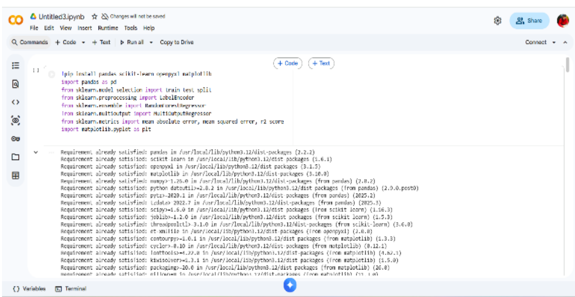


Fig. No.2: -Machine Learning Workflow Diagram

4.3 Structural Analysis Using ETABS

ETABS is widely used for modelling and analyzing high-rise structures under seismic loading. Previous studies showed that parameters such as storey drift, displacement, stiffness, and time period are important for evaluating structural stability. Research also indicated that high-performance materials improve stiffness and reduce lateral deformation during earthquake loading.

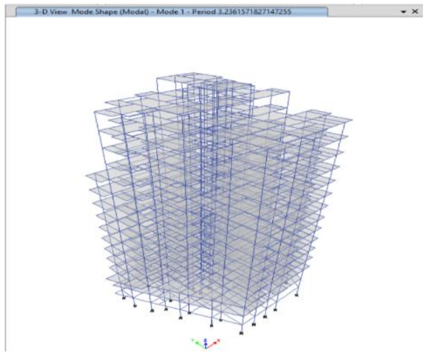


Fig No. 3: - ETABS Structural Model

4.5 Research Gap

Previous studies mainly focused on UHPC, nanotechnology, Machine Learning, and structural analysis separately. Very limited research has combined Machine Learning-based prediction of Nano-Enhanced UHPC properties with ETABS structural analysis. Therefore, the present study aims to develop an integrated framework for predicting material properties and evaluating the structural performance of Nano-Enhanced UHPC structures. Therefore, the present study aims to bridge this research gap by developing an integrated Machine Learning and ETABS-based framework for evaluating Nano-Enhanced UHPC structures.

5. RESULT AND DISCUSSION

5.1 Validation of Machine Learning Models

The developed machine learning models demonstrated high prediction accuracy for estimating the mechanical properties of Nano-UHPC. Random Forest Regression produced better performance compared with conventional regression techniques because of its ability to capture nonlinear relationships between input variables.

The predicted compressive strength values showed strong agreement with experimental results. The model achieved high R^2 values with comparatively lower MAE and MSE values, indicating reliable prediction capability.

The Actual vs Predicted Strength graph further confirmed the effectiveness of the developed model. Most data points were closely distributed around the regression line, demonstrating strong correlation between predicted and actual values.

The improved prediction accuracy can be attributed to efficient feature selection and proper preprocessing of the dataset. Parameters such as nano-silica dosage, silica fume content, and water-binder ratio were found to significantly influence compressive strength and stiffness.

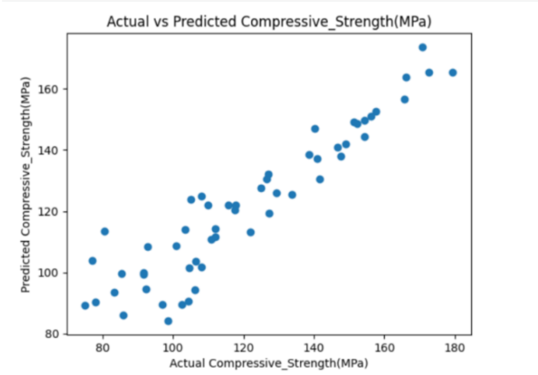


Fig No. 4: - Actual vs Predicted Strength Graph

5.2 Storey Displacement Analysis

Storey displacement is one of the most important parameters for evaluating the lateral stability of high-rise structures. The analysis results indicated that Nano-UHPC structures exhibited lower lateral displacement compared with conventional concrete structures under seismic loading.

The reduction in displacement was mainly due to the higher modulus of elasticity and increased stiffness of Nano-UHPC. The dense microstructure of the material reduced structural flexibility and improved resistance against lateral forces.

As the building height increased, the difference in displacement between conventional concrete and Nano-UHPC models became more significant. This indicates that advanced materials provide greater benefits in taller structures subjected to dynamic loading.
Lower storey displacement improves structural safety, reduces non-structural damage, and enhances occupant comfort during earthquake excitation.

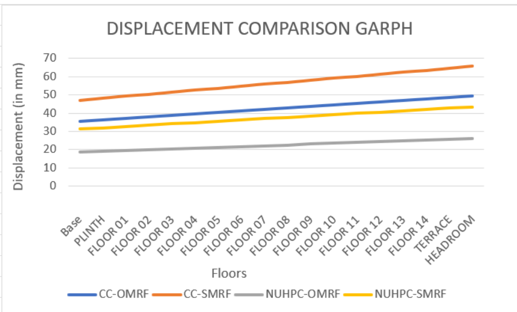


Fig No. 5: - Storey Displacement Comparison Graph

5.3 Storey Drift Analysis

Storey drift plays a critical role in seismic design because excessive drift may lead to structural instability and damage to non-structural components.

The analysis demonstrated that Nano-UHPC structures showed considerably lower storey drift compared with conventional concrete buildings. The reduction in drift occurred because of the improved stiffness and higher load resistance of Nano-UHPC structural members.

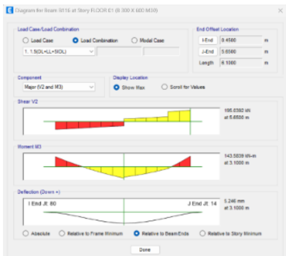
The improved bond strength and crack resistance of Nano-UHPC also contributed to enhanced seismic performance by limiting deformation under cyclic loading.

Reduced storey drift indicates better lateral stability and improved earthquake resistance, making Nano-UHPC suitable for seismic-prone regions.

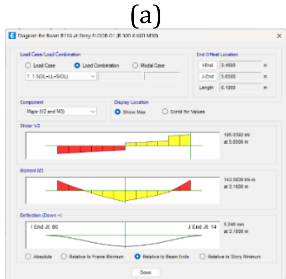
5.4 Beam Deflection Analysis

Beam deflection analysis showed that Nano-UHPC structures experienced lower deformation under applied loading conditions. The higher compressive strength and improved modulus of elasticity of Nano-UHPC increased the stiffness of beam elements and reduced bending deformation.

Lower beam deflection improves serviceability performance and reduces the possibility of cracking and long-term structural damage. The reduction in beam deflection also indicates improved load distribution and enhanced structural efficiency.



(a)



(b)

Fig No. 6: - ETABS Beam Deflection Output
(a) CC-SMRF (b) NUHPC-SMRF

5.5 Base Shear Analysis

Base shear represents the total lateral force transferred to the foundation during earthquake loading.

The results indicated slight variations in base shear values between conventional concrete and Nano-UHPC models. The reduction in self-weight due to smaller structural member sizes influenced the overall seismic response of Nano-UHPC structures.

Although the higher stiffness of Nano-UHPC increased lateral load resistance, the reduced dead load helped control the seismic forces acting on the structure.
This balance between stiffness and reduced self-weight contributed to improved structural efficiency under dynamic loading.

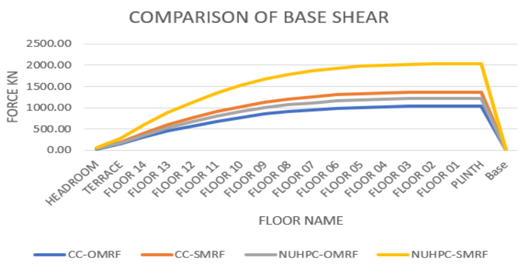


Fig No. 7: - Base Shear Comparison Graph

5.6 Structural Stiffness and Time Period

Structural stiffness significantly influences the dynamic behaviour of high-rise buildings.

Nano-UHPC structures exhibited higher stiffness values due to the improved modulus of elasticity and dense internal matrix of the material. Increased stiffness reduced lateral deformation and improved overall seismic performance.

The natural time period of Nano-UHPC structures was lower compared with conventional concrete structures. Reduced time period indicates increased rigidity and improved resistance against dynamic excitation.
The results clearly demonstrate that advanced high-performance materials can effectively improve structural behaviour under earthquake loading.

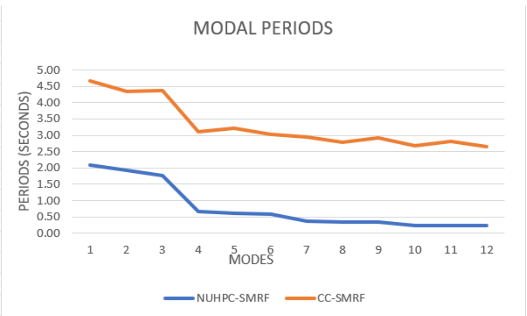


Fig No. 8: - Natural Time Period Graph

5.7 Reinforcement Requirement Analysis

The reinforcement requirement analysis showed that Nano-UHPC structures required comparatively lower reinforcement quantities due to their higher load-carrying capacity and improved strength characteristics.

The use of smaller structural sections combined with higher material strength improved overall material efficiency and reduced reinforcement congestion.

Reduced reinforcement requirement contributes toward faster construction, improved workability, and lower overall project cost.

6. CONCLUSION

The present study successfully developed an integrated framework combining machine learning techniques and ETABS-based structural analysis for evaluating the performance of Nano-Enhanced Ultra-High-Performance Concrete in high-rise buildings.

Machine learning models including Random Forest Regression and Multi-Output Regression demonstrated high prediction accuracy for estimating important mechanical properties of Nano-UHPC. The developed models effectively captured nonlinear relationships between mix design parameters and material behaviour.

The structural analysis results clearly indicated that Nano-UHPC significantly improved the seismic performance of high-rise buildings compared with conventional concrete structures.

The major conclusions obtained from the study are summarized as follows:

1. Nano-UHPC exhibited superior compressive strength, stiffness, and durability characteristics compared with conventional concrete.

2. The incorporation of nano-silica improved hydration efficiency and refined the concrete microstructure, resulting in enhanced mechanical performance.

3. Nano-UHPC structures demonstrated lower storey displacement and reduced storey drift under earthquake loading.

4. Beam deflection was considerably reduced because of the higher modulus of elasticity and improved stiffness of Nano-UHPC.

5. The improved strength characteristics enabled reduction in reinforcement requirement and structural member dimensions.

6. The integration of machine learning and structural analysis provided an efficient and reliable framework for rapid evaluation of advanced construction materials.

7. Nano-UHPC proved to be highly suitable for high-rise and seismic-resistant structures due to its superior structural efficiency and durability.

Overall, the study demonstrates that Nano-UHPC combined with machine learning-assisted structural analysis can contribute significantly toward the development of sustainable, intelligent, and high-performance infrastructure systems.

7. REFERENCES

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