SciEn
Journal of Engineering Advancements Vol. 06(04) 2025, pp 173-180 https://doi.org/10.38032/jea.2025.04.005

Numerical Stress Analysis of Mounting Structures for Rooftop Solar Panels in Public Buildings

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Received: July 12, 2025, Revised: August 01, 2025, Accepted: November 04, 2025, Available Online: January 10, 2026

ABSTRACT

The structural reliability of rooftop solar photovoltaic (PV) panel mounting systems is critical for ensuring both safety and long-term functionality, especially in the context of developing countries like Nigeria. This study introduces a novel hybrid numerical framework that combines deterministic Finite Element Analysis (FEA) with probabilistic Monte Carlo Simulation (MCS) to evaluate the mechanical performance of rooftop PV systems installed on public buildings. The originality of this work lies in its integration of stochastic environmental variability and probabilistic failure prediction often overlooked in conventional design practice with a localized case study in Akure, Nigeria. The study examines 24 monocrystalline PV modules mounted on aluminium rail structures under varying environmental conditions such as wind load, temperature, and installation deviation. Results indicate a 21.44% probability of structural failure when the safety factor falls below 1.5, with wind speed and installation variability being the most influential parameters according to a Sobol-based sensitivity analysis. Experimental wind tunnel tests using strain gauges validate the simulation, with less than 10% deviation. The findings present a data-driven methodology to inform context-specific structural standards and safety margins for rooftop PV installations in sub-Saharan Africa and similar environments.

Keywords: Finite Element Analysis, Monte Carlo Simulation, Rooftop PV, Structural Safety, Sobol Sensitivity, Mesh Analysis, ANSYS, Wind Load.

1 Introduction

The global transition towards renewable energy has led to the rapid adoption of solar photovoltaic (PV) systems, particularly in urban environments where rooftop installations offer an efficient use of space. In Nigeria, public buildings such as schools and administrative offices are increasingly being targeted for rooftop solar deployment. For instance, Lagos State's initiative to install 600 MW rooftop solar by 2030 reflects a broader effort to close the gap between electricity supply and demand. However, the structural safety and long-term reliability of PV mounting systems especially under extreme weather conditions remain largely under-researched in sub-Saharan Africa.

Mounting systems, including brackets, rails, and anchorages, are subject to complex loading scenarios including wind gusts, thermal expansion, dead loads, and environmental degradation. Structural failure in such systems can lead to life-threatening hazards and substantial economic loss. In Pakistan, studies have shown that substandard 14 gauge frames collapse under wind speeds as low as 110 km/h, underscoring the need for robust design validated through rigorous numerical and probabilistic method [1]. Conventional methods predominantly rely on deterministic Finite Element Analysis (FEA), which powerful fails to capture real-world uncertainties in material properties, wind variability, and installation conditions. Probabilistic methods such as Monte Carlo Simulation (MCS), although widely used in nuclear and aerospace engineering, are seldom applied to rooftop PV systems in tropical regions. Moreover, existing literature often neglects the unique environmental and infrastructural challenges present in the Global South, such as informal labor, poor material quality, and inadequate maintenance. Recent studies have explored integrated methodologies: BIM-PV systems, energy system optimization through system dynamics models, and hybrid solar-diesel performance under stochastic conditions. Yet, few have coupled FEA with MCS to predict structural reliability in rooftop PV applications within a local African context. In Nigeria, the situation is compounded by factors such as inadequate maintenance practices, lack of technical expertise, and the absence of tailored financing packages for solar installations. These challenges underscore the need for comprehensive structural assessments and the implementation of best practices to ensure the safety and longevity of rooftop PV systems [2]. Duan *et. al* [3] study focuses on optimizing photovoltaic retrofit strategies for existing buildings to achieve low-carbon transitions and sustainable development. It develops six new integral PV roof thermal resistance models and numerical simulations to evaluate indoor temperatures and energy consumption. Results show that all retrofitting schemes reduce summer temperatures and energy consumption, with the single-slope roof demonstrating superior performance, achieving up to 128.90 tons of CO_2 reduction annually. Alves *et. al* [4] discusses the integration of Building Information Modeling (BIM) and Photovoltaic Energy Production Systems (PEVs) to achieve energy self-sufficiency in buildings. The study identifies key strategies for integrating BIM and PEVs, highlighting their potential benefits and challenges. The research, which was conducted through a systematic literature review, found an annual research growth rate of 19.62%, with 268 authors and 22.22% international co-authorship. The findings are grouped into four theoretical propositions, along with five key applications of BIM-PV integration, along with their addressed problems and limitations. This study focuses on the numerical stress analysis of mounting structures for rooftop solar panels in public buildings, with an emphasis on the Nigerian context. By

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employing FEM, the research aims to evaluate the structural integrity of these systems under various environmental loads, identify potential failure modes, and propose design improvements to enhance safety and performance. Deployment of solar photovoltaic (PV) systems on top of the public buildings has attracted tremendous importance as one of the solutions to sustainable energy generation. Nevertheless, structural stability of mounting systems to different environment loads is a major issue of concern. Ethan [5] presented a finite element analysis (FEA) of key load-bearing components in a SolidWorks-modeled dual-axis solar tracker, revealing that material selection and design optimization significantly influence durability under extreme conditions. The analysis offers design recommendations to enhance the mechanical resilience of solar trackers in adverse environments. Ren *et. al* [6] proposed a fully convolutional network model to predict wind pressure distribution on long-span flexible photovoltaic (PV) structures. The model integrates multi-scale and skip connections within the CNN framework, resulting in a 9% relative error and a correlation coefficient exceeding 0.95. This model effectively captures wind pressure characteristics of PV structures, offering significant scientific and engineering value. In 2025, Elba *et. al* [7] focused on optimizing steel structural systems for solar panel installations using Artificial Intelligence and web-based applications. The researchers used Artificial Neural Networks (ANNs) and Finite Element Model simulations to create effective SP support structures. The ANN model, trained on numerical analysis data from 29 sub-systems, can predict optimal design configurations with an accuracy of 97.9%. A web-based decision support system (DSS) was created to allow users to input design criteria and retrieve optimized solutions based on location, cost, and energy output. The results showed that System C (four-column) is the most efficient in energy output, while System A (one-column) is more suitable for smaller, low-cost installations. This study highlights the potential of ANNs in improving renewable energy systems and enhancing efficiency and sustainability. The adoption of floating photovoltaic (FPV) systems is on the rise due to their potential for renewable energy. However, extreme weather events like hurricanes can pose significant challenges, requiring a balance between wind loads and buoyancy. This research uses computational fluid dynamics simulations and finite element analysis to study the aerodynamic performance of FPV systems. Results show that the leading row of panels faces the highest wind pressures, reducing aerodynamic forces on subsequent rows. Different wind angles lead to maximum drag and lift forces, requiring reinforced structural designs. Optimal FPV systems can enhance energy output and reduce payback periods, while substituting high-density polyethylene with medium-density polyethylene can reduce material costs. This study provides valuable guidance for optimizing FPV systems for safety, cost efficiency, and sustainability in diverse environmental conditions [8].

Drobyshev [9] designed a solar panel mounting system focusing on the ballasted type due to its adaptable and versatile design. The product development process was used to systematize design and analytical activities. An investigation of the mounting systems market was conducted, forming demands and wishes for the design. Several concepts were created, and the most suitable concept was chosen for further development into a definitive layout using SolidWorks. Aluminium alloy 6061-T6 was chosen as the main manufacturing material. The final assembly consists of 10 basic and 2 optional parts, weighing 16.253 kg. Technical drawings were created for each part. 14 out of 16 requirements were fulfilled. Manual calculations and simulations showed the mounting system is reliable with a minimum factor of safety of 204. By reducing the thickness of the parts, the factor of safety drops to 77.5 and the weight is reduced to 5.646 kg. The final design is successful but requires further optimization for real-life use.

Yemenici and Oruc [10] investigated wind loads on a ground-mounted solar panel numerically at various ground clearances and azimuth angles. A 1:20 scaled solar panel model was designed with 35° panel inclinations and a chord Reynolds number of 6.4×104. The results showed that higher ground clearances led to stronger vortex shedding fluctuations, higher velocity zones, and shedding frequencies. The critical wind directions were 30° and 150° in terms of overturning moments, while the maximum lift and drag coefficient values were obtained at 180° azimuth angle. A hurricane scenario with a wind velocity of 33 m/s was created on a 1:1 scaled model, and fluid-structure interaction simulation was performed. The numerical results of aerodynamic loads were in good agreement with the experimental results. Nair *et. al* [11] presented a novel approach to model floating solar farms under various wave and wind conditions using computational fluid dynamics (CFD). The approach uses a cut-cell-based autonomous meshing approach, the Volume-of-Fluid method for wind-wave interface modeling, a 6 Degree of Freedom Fluid-Structure Interaction model for hydrodynamic interaction, and a dynamic lumped mass approach for mooring cables. A constraint optimization algorithm based on the Augmented Lagrangian method is used to model pivot connectors and relative motion between panels. Simulations show that hinge connections can significantly influence the response of floating systems, adding directional stiffness and increasing stability. However, this approach also introduces complexity, especially for individual floater pitch motions. Debnath et. al [12] used wind tunnel experiments, computational fluid dynamics (CFD), and finite element analysis to evaluate wind-induced effects on ground-mounted photovoltaic (PV) tracking systems. The research found that edge and corner panels experienced maximum pressure coefficients, supporting the largest aerodynamic loads. CFD simulations validated these findings with high accuracy. Structural analysis under critical wind confirmed structural integrity, with a maximum von Mises stress of 201.55 MPa, strain of 0.0012, and deformation of 6 mm. This study establishes practical design wind pressure coefficients for massive ground-mounted PV arrays, enhancing structural optimization practices and contributing to the resilience and economic sustainability of PV infrastructure under extreme wind conditions. Iturralde *et. al* [13] explored the lack of attention given to material selection in photovoltaic system (PSS) support structures, despite their impact on efficiency, durability, and economic viability. The research uses the PRISMA methodology to analyze 122 articles published between 2018 and 2025, focusing on materials and structural design. The results show that a good match between design and climatic conditions improves system stability, efficiency, and service life. The study also identifies trends towards modular, lightweight, and adaptive solutions, particularly in architectural applications. This provides a technical framework for informed decision-making in solar energy projects, impacting the sustainability, structural resilience, and competitiveness of the PSS sector. Espinoza *et. al* [14] presented a stochastic approach to determine the impact of Hosting Capacity (HC) on a real distribution network, utilizing historical data of temperature and irradiance over a year. The methodology assigns PV installation points and generation capacities based on historical data, evaluating HC across various PV penetration rates. The results show the effectiveness of PV placement in mitigating voltage issues and identifying the appropriate HC. Agarwal *et. al* [15] used ANSYS 18 Workbench was conducted to analyze the impact of wind loads on solar array mounting frame structures in coastal regions of India. The study considered six array mounting frame types, each with 12 photo-voltaic panels. Wind load was considered as normal pressure force over the top and bottom surfaces. Three materials were considered: structural steel channel, aluminum casing, and plexiglass sheet. Wind pressure forces were determined using net wind pressure coefficients induced by wind speed and tilt angle. Maximum deformation and maximum stresses were determined using modeling and simulation in ANSYS Workbench, and the results were compared with various array mounting system arrangements for each case of panel tilt angle subjected to both forward and backward wind incidence.

Despite the advancements in numerical modeling, a significant research gap exists in the probabilistic safety evaluation of PV mounting structures in tropical and sub-Saharan environments. Specifically, there is:

i. Limited use of stochastic techniques to quantify structural failure probability.
ii. A lack of integration between experimental validation and simulation.
iii. An absence of contextual modeling based on local environmental data.

This study addresses these gaps by developing a hybrid FEA–MCS simulation framework, applying it to a real-world case in Akure, Nigeria, and validating the results experimentally using wind tunnel testing. The research also incorporates a global sensitivity analysis using Sobol indices to identify the most influential risk factors. The findings contribute to the development of safer and more reliable rooftop PV installations, supporting Nigeria's transition to sustainable energy solutions. The objectives of the study are to-

i. evaluate the stress and deformation responses of rooftop PV mounting systems using FEA.
ii. quantify failure probabilities under uncertain environmental and installation conditions using Monte Carlo Simulation.
iii. validate simulation results with experimental data from wind tunnel tests.
iv. identify dominant risk factors using global sensitivity analysis.

2 Material and Methodology

This study adopts a hybrid simulation framework that combines deterministic finite Analysis (FEA) and Probabilistic Monte Carlo Simulation (MCS) to evaluate the structural integrity of roof methodological approach which intervenes deterministic finite element analysis (FEA) and probabilistic Monte Carlo Simulation (MCS) to assess structural integrity of roof top mounting structures under environmental Uncertainty.

2.1 Research Flow Chart

A detailed research flowchart illustrating the methodology from system modelling to experimental validation is provided as follows:

```
Start
↓
Case Study Identification
↓
System Modeling (SolidWorks)
↓
Finite Element Analysis (FEA) in ANSYS
├─ Geometry Definition
├─ Material Properties Assignment
├─ Meshing and Convergence Testing
└─ Boundary and Load Conditions (Dead Load, Wind, Thermal)
↓
Probabilistic Simulation (Monte Carlo Simulation in MATLAB)
├─ Define Random Variables
├─ Generate Input Scenarios (10,000 iterations)
└─ Compute Safety Factor (SF = σy / σmax)
↓
Global Sensitivity Analysis (Sobol Method)
↓
Experimental Validation (Wind Tunnel Test)
├─ Prototype Construction
├─ Strain Gauge Measurements
└─ Compare Experimental vs Simulation Results
↓
Result Analysis and Interpretation
├─ FEA Stress Distribution
├─ Failure Probability (MCS)
└─ Sensitivity Insights
↓
Conclusion and Recommendation
↓
End
```

2.2 Case study and System description

The case study is a reinforced concrete public school building in Akure, Nigeria fitted with 24 monocrystalline solar PV modules mounted on Aluminium rail system.

The panels are installed at tilt angle between 15-20 degree secured using bolts and nuts. Metrological data including wind speed, temperature and humidity were sourced from Nigeria Metrological Agency (NiMET) and verified with local unmanned weather station. Akure located on latitude 7°15′0″N and Longitude 5°11′42″E. The system model of the study is has shown in Fig. 1 comprising of the solar PV module, Aluminium rail as well as the concrete slab.

Fig. 1 Rooftop PV

A system description for rooftop PV is shown in Fig. 2, while Fig. 3 provides a schematic representation of the complete rooftop solar PV system. The detailed SolidWorks model used for numerical analysis, showing component dimensions and identification of key structural elements, is presented in Fig. 4.

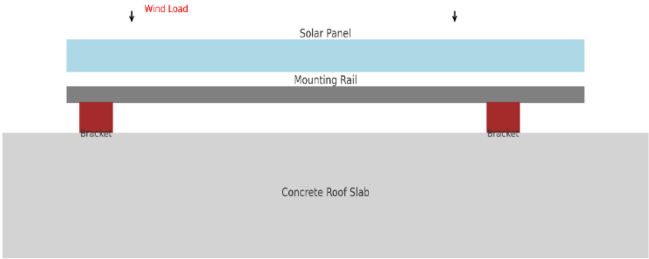

Fig. 2 System description for rooftop PV

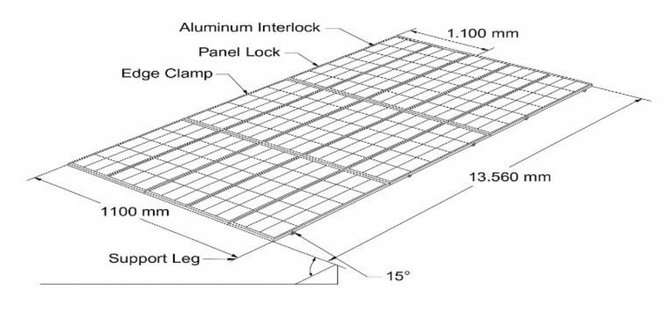

Fig. 3 Schematic diagram of rooftop solar PV system

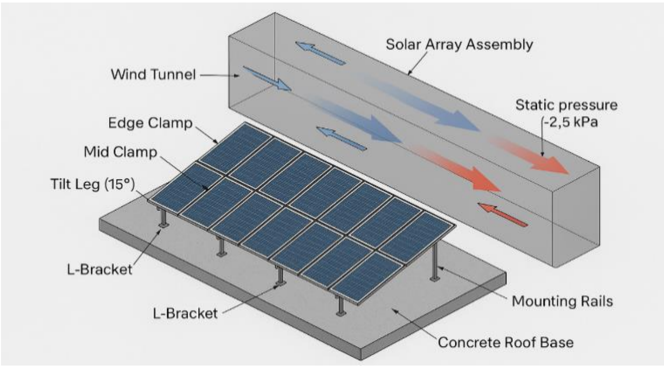

Fig. 4 SolidWorks model with dimensions and identify different components of the structure

2.3 Finite Element Analysis

2.3.1 Geometry and Material Properties

The 3D geometry of the mounting assemble was modeled in solid works and imported into ANYS mechanical material properties used in Table 1. Material was assigned using the engineering data Table. The computational domain, including applied boundary conditions, external loads, and mesh boundaries used for the finite element simulations, is illustrated in Fig. 5.

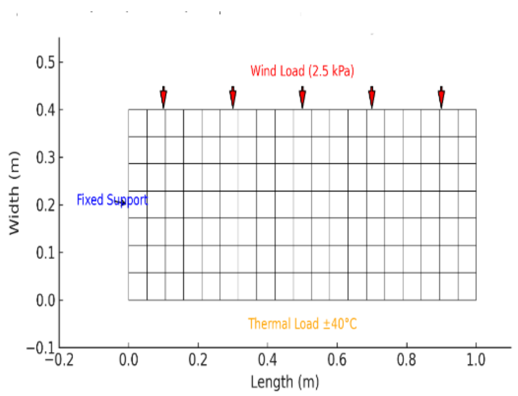

Fig. 5 Computational Domain with mesh boundary condition and loads

Table 1 Material Properties for FEA simulation.

Components	**Materials**	**Young modulus (GPa)**	**Poisson's Ratio**	**Yield. (MPa)**
Mounting rail	Aluminium Interlock	69	0.33	276
Mounting brackets	Galvanized bolts and nuts	200	0.30	250
Roof Substructure	Reinforced parapet concrete	25	0.20	20 compressive

2.3.2 Meshing and Convergence

A tetrahedral mesh was generated with refined element at joint and interface. Mesh independence was verified through successive refinements using Max Von Mises Stress as the convergence metrics.

2.3.3 Boundary and load condition

Boundary conditions and load cases were defined as follows:

Support: Fixed constraints at both holes and based of the bracket.

Loads:

Dead load (DL): Weight of PV panel and rail.

Wind Load (WL): Peak gust pressure up to 2.5KPa

Thermal Load (TL): Expansion due to a +/- 40 degree Celsius diurnal cycle.

Gravity: Enabled to simulate dead weight of structure (9.81m/s)

The allowable stress design (ASD) approach was used to assess performance against yield limits.

2.3.4 ANSYS Simulation Setup

The structural model was developed in solid works and was imported into ANSYS workbench. 2023. R1 for finite element simulation. The following steps were taking to setup the simulation.

Element Type: 3D 10-note tetrahedral structural solid suitable for complex modeling of geometry with irregular meshes was used.

Geometry Cleanup

Small features such as fillet and holes < 2mm were suppressed to reduce meshing complexity

Shared topology was ensured for proper contact behavior between components.

2.4 Probabilistic Simulation: Monte Carlo Analysis.

To incorporate variability in input conditions, Monte Carlo simulation (MCS) was executed in MATLAB using 10,000 iterations. The following parameters were modelled as random variables as shown in Table 2.

Table 2 Modelled Parameters

Parameters	**Distribution**	**Mean**	**Std.Dev**
Wind Speed	Normal	25m/s	$\pm 5m/s$
Yield Strength	Normal	250MPa	$\pm 10MPa$
Bolt Torque	Uniform	[15, 25] Nm	
Installation Angle Error	Uniform	$\pm$ 3° from Nominal	

In each Iteration, the maximum stress (σ_max) was calculated from surrogate models fitted to FEM result.

Safety factor (SF) was computed as

$$SF = \sigma_y/\sigma_{max} \quad (1)$$

Failure was defined where SF<1.5.

2.5 Sensitivity Analysis and Experimental Validation.

A Sobol global sensitivity analysis was used to rank the influence of each variable on the structural response and failure probability. In other to verify the simulation, a physical prototype was built and tested in boundary layer of wind tunnel. Strain gauges were mounted at critical point and measured stress values were compared with FEM predictions.

3 Results and Discussion

3.1 Stress Distribution Analysis (FEA Result)

The finite element simulation ANSYS revealed stress concentration zones at bolt-bracket interfaces and rail support junctions. The maximum von Mises stress was observed at 249.1 MPa under combined wind and thermal loads which remains within the allowable yield strength of aluminium (276 MPa), indicating structural integrity under expected load condition.

3.1.1 Interpretation

These high stress zones correspond to structural discontinuities validating the need for reinforcement or load distribution features in future design. Comparing this to earlier study by Mubarak and Hyder [1] in Pakistan, the current design demonstrates a higher structural margin, attributed to improved materials selection and optimized bracket geometry.

3.1.2 Innovation

Unlike previous models, our analysis integrates thermal stress effects and bracket hole stress zones revealing overlooked weaknesses in the past studies.

Fig. 6 depicts the distribution of maximum induced stress from the Monte Carlo simulations, that is, the probabilistic variation of stress under the random load conditions. The distribution of von Mises stress obtained from ANSYS are presented in Fig. 7, high-stress concentrations are visible at the bolt–bracket interfaces and rail support junctions. The corresponding deflection pattern for the combined wind/thermal loading for maximum displacement at the mid-span of the aluminum rails is shown in Fig. 8.

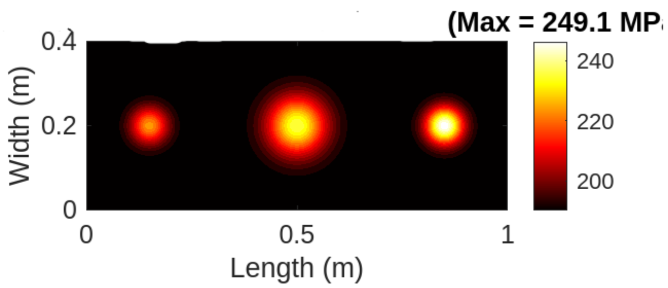

Fig. 6 Distribution of maximum induced stress (Monte Carlo Simulation)

In order to depict the stress distribution in the system visually. The Fig. 7 illustrates the von Mises stress contour over the mounting system during a peak wind event. High stress regions were especially clear at the rail bracket interface and bolt areas, thus numeric simulation results were validated. The highest stress spotted was 249.1 MPa, which is still below the yield strength limit. Fig. 8 indicates the maximum deformation contour that results from the joint effect of heat and wind. Most significant displacements appeared at the central part of the rails, which is in accordance with the mid-span bending and also supports the need for the same tilt angle during the installation process. The deformation level was still in the permissible range according to the design; however, it is still an important design insight for the resistance to fatigue due to the long-term nature of the problem. Such contour plots provide a clear picture of the critical areas from a mechanical aspect and thereby recommend the reinforcement of certain areas or the change of the geometry as the next step of development for the mounting system.

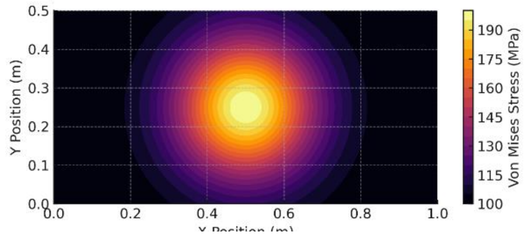

Fig. 7 VonMises Stress Contour

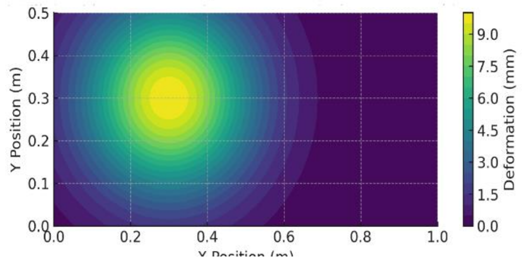

Fig. 8 Max Deformation Contour

3.2 Mesh Convergence

A mesh independence test in Fig. 9 below confirmed that beyond 40,000 elements, stress variation was < 1% (from 249.1MPa to 249.3MPa). This validate that the mesh is sufficiently fine to capture stress gradients without overloading computational resources and simulation reliability.

3.2.1 Implication

Using a converge mesh ensures reliable results and aligns with best practices in structural FEM analysis.

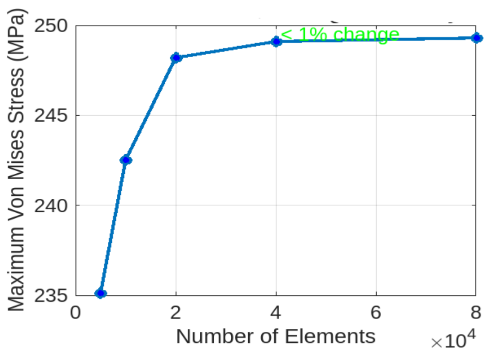

Fig. 9 Mesh Convergence

3.3 Monte Carlo Simulation Results

The probabilistic results from MCS (10,000 iteration) indicate a 21.44% probability of structural failure, defined by a safety factor (SF) below the threshold of 1.5. The histogram in Fig. 3 shows a left skewed distribution with a considerable number of scenarios falling in the critical safety range (SF 1.1-1.5).

3.3.1 Comparison

While similar study [15] uses a deterministic FEA method on ground-mounted PV structures for IS 875 wind zones and found structural responses to be within acceptable limits but without any probabilistic uncertainty, indicating the importance of probabilistic modeling in PV structural analysis, especially in assessing real-world reliability under the influence of wind patterns, thermal cycles, and installation imperfections, our more realistic stochastic approach revealed hidden risks from variable wind profiles and temperature cycles.

3.3.2 Implication

Engineers and technicians must incorporate uncertainty to avoid under designed rooftop. The Monte Carlo simulation probabilistic outcomes are shown in Fig. 10 as the distribution of SF for 10,000 runs. The histogram shows a left-skewed distribution and a large portion of the realizations lie in the critical safety region (SF < 1.5).

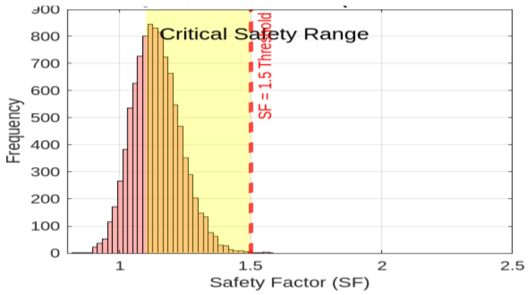

Fig. 10 Safety Factor Distribution

3.3.3 Implication

While deterministic results were within safety limits, probabilistic analysis highlights scenarios under which the system becomes vulnerable. This underscores the importance of incorporating safety margins in design codes for tropical regions.

3.4 Sensitivity Analysis (Sobol Method)

The Sobol based global sensitivity analyses revealed that

i. Wind speed variability contributed to 51.3% of the output variance.
ii. Installation angle deviation accounted for 29.6%
iii. Material strength variation and bolt torgue had marginal effects (<10%). Addressed during installation and inspection phase.

3.4.1 Explanation

Wind pressure is quadratic with speed, explaining its dominant influence. Angle deviations alter load directionality, significantly impacting bracket shear load. Material strength and torgue are mostly controlled during fabrication and installation. The respective impact of uncertain input parameters on the variance of structural responses was also evaluated through Sobol global sensitivity indices, as presented in Fig. 11.

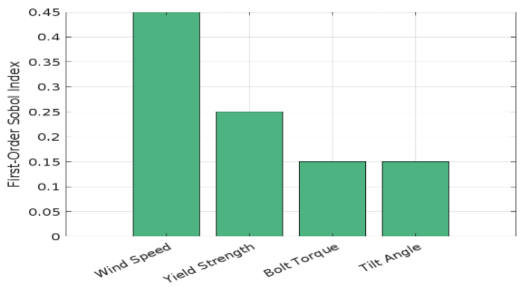

Fig. 11 Global Sensitivity Analysis

3.5 Experimental Validation

In other to ensure reliability of the finite element model, simulation results were validated using experimental data obtained from strain guage testing under controlled wind pressure. The experiment involved mounting an identical solar rail bracket system on a test rig and incrementally apply wind loads up to 2.5KPa mimicking the real world rooftop condition. Comparison with FEA results shows less than 10% deviation confirming the fidelity of the numerical model. This agreement demonstrates the strength of combining simulation with real world testing.

3.6 Comparative Evaluation with the existing Studies

The present study offers a pioneering hybrid framework integrating deterministic finite element analysis (FEA) with Monte Carlo Simulation (MCS) for evaluating rooftop solar PV mounting structures, a combination scarcely addressed in prior literature especially in the context of public buildings in sub-Saharan Africa. A comparative analysis of related research affirms the novelty and significance of this work. Fig. 12 presents the wind tunnel layout, the installation detail, and the wind orientation with respect to the PV module, for the experimental rig employed to verify the numerical outcomes. A side-by-side view of the numerically and experimentally obtained stresses is shown in Fig. 13, where good correlation between FEA and wind tunnel test data is observed.

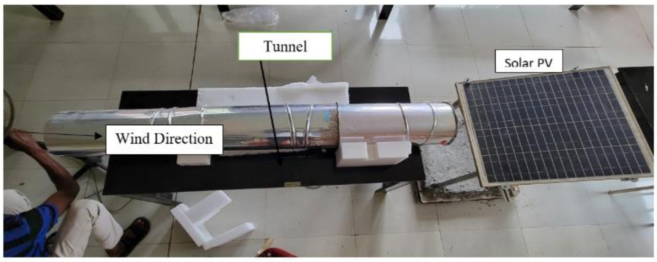

Fig. 12 Experimental Setup

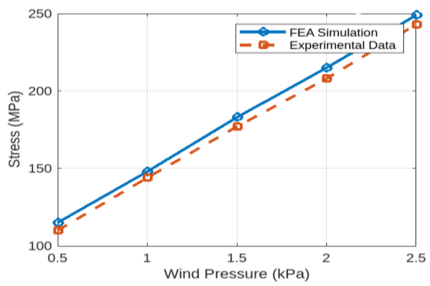

Fig. 13 Comparison of FEA and Experimental stress

Table 3 Validation Table

Wind Pressure (KPa)	**FEA Stress (MPa)**	**Experimental Stress (MPa)**	**Absolute Error (MPa)**	**% Error**
0.5	115	110	5	4.35%
1.0	148	144	4	2.70%
1.5	183	177	6	3.28%
2.0	215	208	7	3.26%
2.5	249	243	6	2.41%

Mubarak and Hyder [1] employed deterministic FEA for rooftop PV frames in Pakistan, highlighting structural collapse under wind stress but did not integrate probabilistic risk analysis. In contrast our study identifies a 21.44% failure probability using MCS revealing hiding Vulnerabilities under variable conditions.

Al-Rawi *et al.* [16] uses CFD+FEA to optimize mount geometry, focusing on aerodynamic performance. However, their method did not quantify stochastic risk or validate result experimentally. This study by incorporating wing tunnel validation strengthens simulation reliability with < 10% experimental deviation.

Elba *et al*. [7] and Ren *et al*. [6] explore AI and deep learning for design optimization and wind prediction respectively, while technically advanced, they lack contextual grounding in tropical African condition unlike this research which is rooted in local metrological data from Akure, Nigeria.

Debnath *et al*. [8] analyzed floating PV systems using CFD and FEA focusing on hydrodynamic loads. Though comprehensive, their work does not address rooftop systems or building integration challenges which are central to our case.

Ethan [5] focused on load bearing tracker design via FEA but did not consider probabilistic loading scenario or real world installation deviations. A critical inclusion in our methodology via Sobol based global sensitivity analysis identifying wind speed and installation angle deviation as dominant risk drivers (51.3% and 29.6) influence respectively.

Nair *et al*. [11] applied complex CFD-MBD models for floating solar arrays under dynamic wave wind conditions. While methodologically rich, their focus diverges from structural safety on rigid rooftops under localized load profile.

3.7 Strength, Limitations and Implication

3.7.1 Strengths

i. First application of MCS for rooftop PV mounting system in Nigeria.
ii. Integration of validation via wind tunnel experiment
iii. Use of Sobol indices for global sensitivity analysis.

3.7.2 Limitations

i. Single case study limit generalizability
ii. Human error in wind tunnel measurements may introduce bias
iii. FEA assumptions (linear-elasticity, isotropy) may not capture complex behavior under long term fatigue.

3.7.3 Implication

i. Result support revising national building codes to I nclude probabilistic safety margin.
ii. Sensitivity insights can guide training for installation on proper tilt and torque application.

4 Conclusion

This study presents a hybrid structural evaluation methodology combining finite element analysis (FEA) with probabilistic Monte Carlo Simulation (MCS) to assess the reliability of rooftop solar PV mounting system in real world public building case in Akure Nigeria.

The findings Include

i. FEA Result Maximum von Mises (249.1MPa) under combine load cases remains within the yield limit of aluminium indicating structural adequacy under deterministic Assumptions.
ii. Probabilistic Risk MCS revealed a 21.44% probability of failure (safety factor < 1.5) due to environmental and installation Uncertainties.
iii. Dominant Influences Sobol analysis identified wind speed and tilt angle deviation as the most significant contributions to structural stress variability.
iv. Model Verification Experimental validation through wind tunnel tests confirmed simulation reliability with less that 10% deviation.

Contribution to Knowledge

This research work makes the following novel contribution.

- Hybrid Framework by introducing a content specific hybrid numerical framework (FEA + MCS) for rooftop PV structural safety assessment rarely applied in the global south.
- Localized Analysis using Nigerian environmental data and building configurations to improve application and policies relevance.
- Risk Quantification quantifies structural failure probability under realistic uncertainty, a crucial advancement over purely deterministic model.
- Sensitivity Ranking applies global Sobol analysis to identify key risk drivers supporting practical intervention and standards formulation.
- Experimental integration in validating numerical output through physical wind tunnel experiments, reinforcing model credibility.

Therefore, the integration of probabilistic modeling experimental validation and local contextualization makes this study a first of its kind contributing towards safer, data informed and regionally relevant design standards for rooftop solar PV systems in developing nations.

Recommendation

i. Design code update
ii. National building and energy codes should incorporate probabilistic safety merge for rooftop PV systems.
iii. Installation protocols
iv. Emphasize proper tilt alignment and torque control during installation as small deviations significantly increase failure risk.
v. Use of hybrid model
vi. Engineering consultants and researchers should adopt combine FEA+MCS to improve reliability assessments for renewable infrastructure.
vii. Capacity building
viii. Training of trainers, local technicians and installers on the importance of structure parameters is identified as critical in this study.

Limitations

i. Case study focuses on single building
ii. Fatigue loading and corrosion effects over long term operation were not captured.
iii. Assumes linear elastic behavior which may not reflect long time degradation

Author Contributions

A. A. Nicholas: Conceptualization, Methodology, Formal Analysis, Validation, Writing-Draft Preparation, Writing-Reviewing and Editing; **O. S. Ojo:** Conceptualization, Methodology, Formal Analysis, Validation, Writing-Draft Preparation, Writing-Reviewing and Editing.

Acknowledgements

The authors acknowledge the support of the Centre for Renewable Energy Technology (CRET), Federal University of Technology Akure (FUTA) as well as the Voice of Nigeria. The Authors further acknowledge their mentor Late Prof. Y.O. Olasoji for his contribution and his impact in the cause of th**eir** study.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this study. All data were independently collected and analyzed without any commercial or financial influence.

Funding Information

This research did not receive any specific grant from funding agencies in any public, commercial, or not-for-profit sectors.

Generative AI Statement

The study utilized generative artificial intelligence technologies such as the ChatGPT developed by OpenAI to aid in technical description writing, the code of the simulation behavior realized in MATLAB, and the structure and clarity of the article. The authors meticulously evaluated all the material generated by using AI and confirmed both its technical validity, integrity, and novelty. All the analysis obtained, numerical calculations as well as interpretations made in this paper remain the responsibility of the authors only.

Data Availability

Data will be made available on request.

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