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Integrated Approach to Seismic Retrofitting of Existing Urban Infrastructure using Advanced Composite Materials and Smart Sensor Networks

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ABSTRACT

Earthquakes represent one of the most destructive natural hazards affecting human societies and the built environment. Throughout history, seismic events have caused extensive damage to buildings, bridges, transportation systems, utility networks, and other critical infrastructure, resulting in significant economic losses and human casualties. With rapid urbanization and increasing population concentrations in metropolitan regions, the vulnerability of urban infrastructure to seismic hazards has become a major concern for engineers, urban planners, policymakers, and disaster management authorities worldwide. In developing countries such as India, the challenge is particularly significant. A substantial proportion of existing urban infrastructure was constructed before the implementation of modern seismic design standards and earthquake-resistant construction practices. Many buildings currently in service were designed using outdated codes or were constructed without adequate consideration of seismic forces. Consequently, these structures often possess insufficient lateral load resistance, inadequate ductility, and limited energy dissipation capacity, making them highly susceptible to earthquake-induced damage. Urban infrastructure encompasses a diverse range of structural systems, including residential buildings, commercial complexes, hospitals, educational institutions, transportation facilities, bridges, public utilities, and administrative buildings. The failure of such structures during an earthquake can have far-reaching consequences beyond physical damage alone. Structural collapse may interrupt essential services, hinder emergency response operations, disrupt economic activities, and compromise public safety. Therefore, enhancing the seismic resilience of existing infrastructure has become an essential component of sustainable urban development.

Recent advances in material science have introduced innovative strengthening materials known as Fiber Reinforced Polymer (FRP) composites. Among these, Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP) have gained considerable attention due to their exceptional mechanical properties, including high tensile strength, excellent strength-to-weight ratios, corrosion resistance, fatigue durability, and ease of installation. Unlike traditional strengthening methods, FRP systems provide substantial improvements in structural capacity while adding minimal weight to the structure. These characteristics make advanced composite materials particularly suitable for seismic retrofitting applications in densely populated urban environments.

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KEYWORDS: *FRP, GFRP, CFRO. RETROFITTING.*

1. INTRODUCTION

Seismic retrofitting refers to the process of modifying existing structures to improve their ability to withstand earthquake-induced forces and deformations. Rather than demolishing and reconstructing vulnerable buildings, retrofitting provides a practical and economically viable solution for enhancing structural performance while preserving existing infrastructure assets. The primary objective of seismic retrofitting is to improve the ability of a structure to resist lateral loads generated during seismic events. This objective is achieved through various strengthening measures aimed at increasing strength, stiffness, ductility, energy dissipation capacity, and overall structural reliability. An effectively retrofitted structure should be capable of maintaining its integrity during seismic events, protecting occupants, and minimizing damage that may impair functionality.

Over the past several decades, numerous retrofitting techniques have been developed and applied worldwide. Reinforced concrete jacketing remains one of the most commonly adopted methods for increasing the strength and stiffness of structural members. This technique involves enlarging the dimensions of columns and beams through the addition of reinforced concrete layers. Although effective, the method often results in increased dead loads and significant construction complexity.

Steel bracing systems constitute another widely used strengthening strategy. By introducing diagonal steel members into structural frames, lateral load resistance can be significantly enhanced. However, issues related to corrosion, maintenance requirements, and architectural constraints may limit the applicability of steel bracing in certain projects.

In recent years, Fiber Reinforced Polymer systems have emerged as a highly attractive alternative. FRP strengthening involves externally bonding composite materials to structural members to improve their load-carrying capacity and deformation characteristics. Due to their lightweight nature, corrosion resistance, and ease of installation, FRP systems provide an efficient solution for seismic rehabilitation while minimizing disruption to building occupants.

The growing adoption of advanced composite materials reflects a broader shift toward performance-based seismic design, where structural interventions are selected not only on the basis of strength enhancement but also considering long-term durability, sustainability, constructability, and lifecycle performance.

2. LITERATURE REVIEW

Bao and Li (2021) conducted a comprehensive review of contemporary SHM technologies and concluded that wireless sensing systems significantly reduce installation costs while improving monitoring flexibility. Their analysis further highlighted the increasing integration of monitoring technologies into infrastructure resilience programs.

Rashid et al. (2021) implemented sensor-based monitoring systems for reinforced concrete buildings and demonstrated the ability of smart sensors to identify structural anomalies before visible damage occurred. Their research emphasized the value of real-time monitoring in preventive maintenance and risk management.

Hou et al (2021) developed vibration-based monitoring techniques utilizing changes in natural frequencies as indicators of structural damage. The study reported high accuracy in damage detection and confirmed the effectiveness of dynamic monitoring approaches for evaluating structural integrity.

The literature consistently indicates that SHM systems contribute significantly to infrastructure safety and maintenance efficiency. Nevertheless, many monitoring implementations operate independently of retrofitting interventions, limiting their potential contribution to integrated resilience strategies.

Yang et al. (2024) developed an integrated approach combining CFRP retrofitting with wireless sensor networks. Their study demonstrated the feasibility of simultaneously enhancing structural capacity and monitoring long-term performance.

Li et al. (2024) proposed smart retrofitting frameworks for high-rise buildings that incorporated continuous monitoring systems and performance-based maintenance strategies. Their findings indicated significant improvements in seismic resilience and lifecycle management.

Garcia et al. (2024) investigated sensor-integrated composite strengthening systems and reported improved damage detection capabilities, enhanced maintenance planning, and better lifecycle performance assessment.

Research conducted at IIT Roorkee (2021) demonstrated significant reductions in inter-storey drift through FRP strengthening interventions. IIT Bombay (2022) developed cost-effective structural health monitoring systems suitable for large urban buildings. CSIR-CBRI Roorkee (2023) emphasized the role of smart monitoring technologies in improving post-earthquake safety assessment.

Further advancements were reported by NIT Trichy (2024), which successfully implemented IoT-based monitoring systems for retrofitted buildings. More recently, IIT Delhi (2025) integrated artificial intelligence with structural monitoring frameworks to achieve highly accurate seismic vulnerability assessments.

3. MATERIALS, METHODOLOGY AND INTEGRATED RETROFITTING FRAMEWORK

Material Properties

The structural behaviour of reinforced concrete buildings depends significantly on the mechanical properties of the constituent materials. Accurate representation of material properties is therefore essential for realistic numerical simulation and reliable assessment of seismic performance. In the present study, conventional reinforced concrete materials were considered for modelling the existing structure, while advanced composite materials were incorporated for seismic strengthening.

The materials considered in this investigation include concrete, reinforcing steel, Carbon Fiber Reinforced Polymer (CFRP), and Glass Fiber Reinforced Polymer (GFRP). Material properties were assigned within the ETABS analytical model based on relevant Indian Standards and published technical literature

Concrete: The existing structural members were assumed to be constructed using M30 grade concrete, which is widely adopted in medium-rise reinforced concrete buildings in India. The concrete material was modelled using its characteristic compressive strength, elastic modulus, density, and Poisson's ratio to simulate realistic structural behaviour under gravity and seismic loading.

Table Properties of Concrete

Property	Value
Grade	M30
Compressive Strength	30 MPa
Density	25 kN/m³
Modulus of Elasticity	27.4 GPa
Poisson Ratio	0.20

These properties were assigned to beams, columns, and slabs in the numerical model to ensure realistic stiffness and load-carrying characteristics during analysis.

Reinforcing steel: High-strength Fe500 reinforcement steel was adopted for all reinforced concrete members. Fe500 steel possesses high yield strength and adequate ductility, making it suitable for earthquake-resistant construction.

Table Properties of Reinforcement

Property	Value
Grade	Fe500
Yield Strength	500 MPa
Ultimate Strength	545 MPa
Density	78.5 kN/m³

The reinforcement properties were incorporated into the analytical model to accurately simulate the nonlinear behaviour of reinforced concrete members subjected to seismic loading.

Advanced Composite material: To improve the seismic performance of the selected building, advanced Fibre Reinforced Polymer (FRP) composites were adopted. Compared with conventional strengthening techniques such as reinforced concrete jacketing and steel bracing, FRP systems offer several advantages including high strength-to-weight ratio, corrosion resistance, ease of installation, and minimal interruption to building occupancy.

Among various FRP materials, Carbon Fiber Reinforced Polymer (CFRP) was selected as the primary strengthening material because of its superior mechanical properties, whereas Glass Fiber Reinforced Polymer (GFRP) was employed for secondary strengthening applications where moderate strength enhancement and cost-effectiveness were required.

Carbon Fiber Reinforced Polymer possesses exceptionally high tensile strength, high elastic modulus, excellent fatigue resistance, and superior durability under aggressive environmental conditions. These characteristics make CFRP one of the most widely accepted materials for seismic strengthening of reinforced concrete structures. It is proposed for: Column confinement, Beam flexural strengthening, Beam-column joint strengthening and Critical seismic members experiencing high stress concentrations.

Glass Fiber Reinforced Polymer offers good tensile strength, corrosion resistance, and ease of installation at a comparatively lower cost than CFRP. Although its stiffness and strength are lower than those of CFRP, GFRP provides an economical solution for strengthening secondary members where extremely high strength enhancement is not required.

The combined use of CFRP and GFRP provides an optimal balance between structural performance and economic feasibility. CFRP was reserved for highly stressed structural components, whereas GFRP was utilized for secondary strengthening applications to improve the overall seismic behaviour of the structure without significantly increasing project cost

Table Properties of CFRP & GFRP

Property	Value	
	CFRP	GFRP
Tensile Strength	3500 MPa	1200 MPa
Elastic Modulus	230 GPa	70 GPa
Density	1.8 g/cm³	2.0 g/cm³
Thickness	1.2 mm	5 mm

Selection of Retrofitting Technique & Composite Materials

Selection of an appropriate retrofitting technique plays a crucial role in enhancing the seismic performance of existing reinforced concrete structures. The selected strengthening system should improve structural strength, stiffness, and ductility while minimizing additional dead load, construction time, and disruption to building operations.

Several conventional and advanced retrofitting techniques were reviewed during the present investigation. These include reinforced concrete jacketing, steel bracing, steel plate bonding, CFRP wrapping, and GFRP strengthening. Each technique possesses distinct advantages and limitations depending on structural requirements, construction feasibility, durability, and economic considerations.

Table Comparison of Various Retrofitting Techniques

Technique	Strength Improvement	Additional Weight	Construction Time	Cost Effectiveness
RC Jacketing	High	High	High	Moderate
Steel Bracing	High	Moderate	Moderate	Moderate
Steel Plate Bonding	Moderate	Moderate	Moderate	Moderate
CFRP Wrapping	Very High	Very Low	Low	High
GFRP Strengthening	High	Very Low	Low	High

The comparative assessment indicates that CFRP systems provide the most favourable combination of structural efficiency, durability, constructability, and lightweight performance. Unlike reinforced concrete jacketing, CFRP strengthening introduces negligible additional dead load and requires minimal alteration to the existing structural configuration. Furthermore, the excellent corrosion resistance and high tensile strength of CFRP make it particularly suitable for long-term seismic rehabilitation.

Accordingly, CFRP was selected as the primary retrofitting material for strengthening columns, beams, and beam-column joints that experience high seismic demand. GFRP was adopted for secondary structural members where moderate strengthening was considered adequate while maintaining overall project economy.

Structural Health Monitoring Components

One of the distinguishing features of the present research is the integration of seismic retrofitting with a Smart Structural Health Monitoring (SHM) system. While conventional retrofitting techniques primarily focus on improving the strength and stiffness of structural members, they do not provide any mechanism for evaluating the structural condition after rehabilitation. The proposed monitoring framework addresses this limitation by enabling continuous assessment of structural performance during normal service conditions as well as during seismic events.

Structural Health Monitoring (SHM) is a systematic process of collecting, processing, and interpreting structural response data using various sensing devices installed at critical locations of a structure. The information obtained from these sensors assists engineers in identifying damage, evaluating structural safety, planning maintenance activities, and making informed decisions regarding the long-term performance of infrastructure.

The proposed SHM framework consists of four major components:

- Smart sensing devices
- Data acquisition system
- Wireless communication network
- Cloud-based monitoring and visualization platform

These components operate together to provide continuous monitoring of the structural behaviour of the retrofitted building.

Sensor selection: Selection of appropriate sensors is essential for obtaining reliable structural response data. In the present study, sensors were selected based on their ability to measure the most significant parameters governing seismic behaviour of reinforced concrete buildings. The proposed monitoring system incorporates:

Accelerometers: Accelerometers measure structural acceleration and vibration characteristics during dynamic loading. These measurements are useful for determining natural frequencies, vibration modes, damping characteristics, and seismic response of the building.

Strain Gauges: Strain gauges are installed on critical structural members to measure strain induced during loading. These measurements help in evaluating stress development, crack initiation, and load redistribution within strengthened members.

Displacement Sensors: Displacement sensors monitor lateral movement and inter-storey drift during seismic excitation. Storey displacement is one of the most important indicators of structural performance and is widely used for evaluating compliance with seismic design requirements.

Temperature Sensors: Temperature sensors monitor environmental conditions that may influence sensor performance or long-term behaviour of composite strengthening materials. Although temperature changes have minimal influence during earthquakes, they provide valuable information for long-term structural monitoring.

The specifications of the selected sensors are presented in Table 3.8.

Table Sensor Specifications

Sensor	Purpose	Range
Accelerometer	Vibration Monitoring	±2 g
Strain Gauge	Strain Measurement	±5000 με
Displacement Sensor	Drift Monitoring	0–200 mm
Temperature Sensor	Environmental Monitoring	-20°Cto 80°C

The selected sensors provide comprehensive monitoring of structural response under service and seismic loading conditions.

4. RESULTS

Modal Analysis

Modal analysis was performed to determine the dynamic characteristics of the building. Twelve vibration modes were extracted, and the first mode was found to dominate the structural response. The relatively high fundamental period indicates flexibility under lateral loading and highlights the importance of strengthening measures.

Table Modal Analysis Results

Mode	Time Period (sec)	Mass Participation (%)
1	1.82	68
2	1.65	15
3	1.41	8
4	1.22	5
5	1.06	2

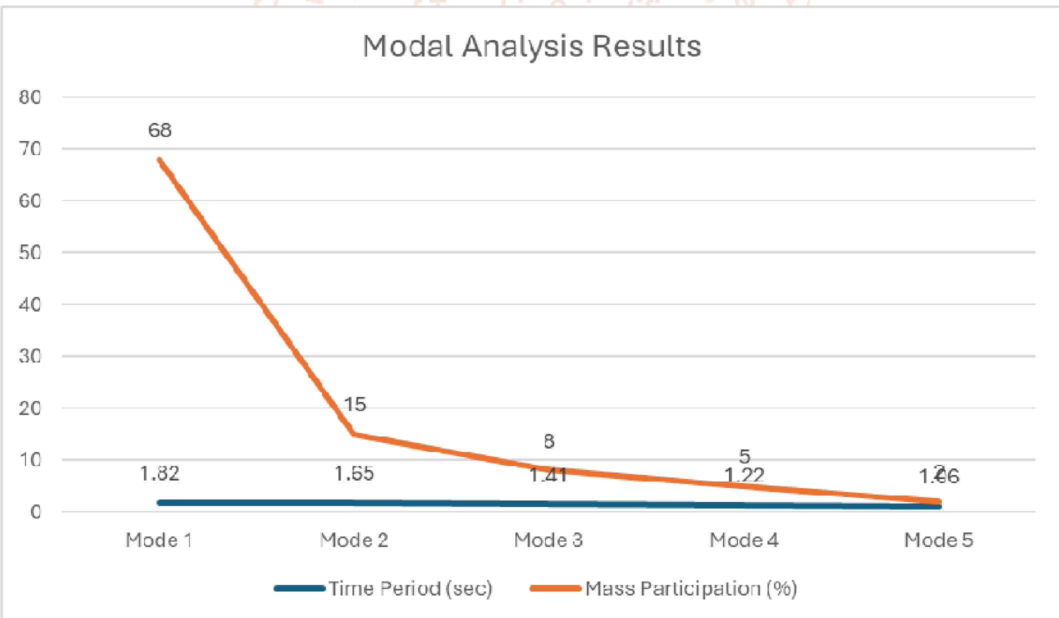

Fig Modal Analysis

The first mode contributes approximately 68% of the total mass participation, indicating that lateral response is dominated by a fundamental sway mode. Higher modes contribute progressively less to the overall response.

Modal analysis was conducted to investigate changes in dynamic characteristics following retrofitting.

Table Modal Comparison

Parameter	Existing	Retrofitted
Fundamental Period (sec)	1.82	1.38

Discussion: The reduction in the fundamental period indicates increased structural stiffness. Structures with shorter vibration periods generally exhibit: Improved dynamic stability; Reduced displacement demand;

Enhanced seismic resistance. The observed reduction of approximately 24% confirms the effectiveness of the retrofitting intervention

Response Spectrum Analysis

Response spectrum analysis was conducted to evaluate maximum displacement, storey drift, and seismic demand. This method provides a realistic representation of dynamic structural response and is widely accepted for performance evaluation of multi-storey buildings.

Table Storey Displacement Results

Storey	X Direction (mm)	Y Direction (mm)
11	112	106
10	109	102
9	104	97
8	96	90
7	85	80

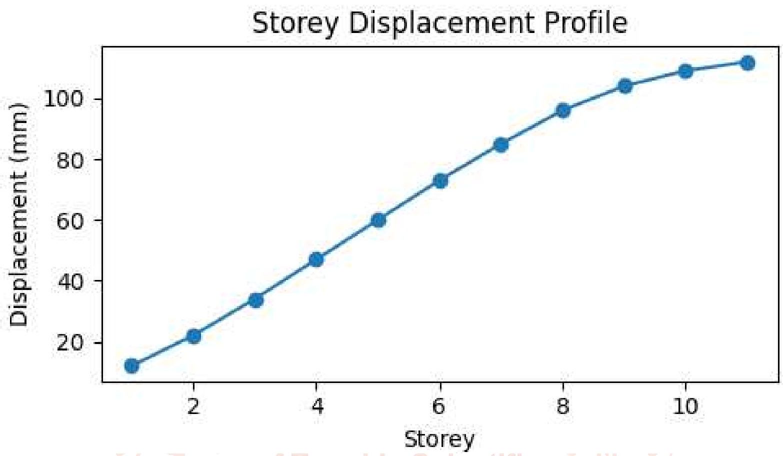

Figure Storey displacement profile of the existing building.

Displacements increase with height and reach their maximum value at roof level. Roof displacement is one of the most important indicators of global structural performance during earthquake excitation because it reflects the overall lateral flexibility of the structure. Excessive displacement can lead to damage in both structural and non-structural components, resulting in increased repair costs and reduced post-earthquake functionality.

The analytical results demonstrated that the maximum roof displacement of the existing structure was 112 mm in the X-direction and 106 mm in the Y-direction. Following CFRP strengthening, the corresponding values reduced to 72 mm and 69 mm respectively. This represents reductions of approximately 35.7% and 34.9%.

Discussion

The reduction in roof displacement can be attributed to the increase in structural stiffness resulting from CFRP confinement and laminate strengthening. CFRP materials enhance the load-carrying capacity of structural members while simultaneously reducing lateral deformation demands. The results indicate that the strengthened structure exhibits improved resistance to earthquake-induced movements. Therefore, the findings of the present study are consistent with established research and confirm the effectiveness of advanced composite retrofitting systems. The displacement profile reveals a gradual increase in lateral deformation from the base to the roof. The roof displacement of 112 mm indicates considerable flexibility. Such levels of deformation may affect non-structural components and serviceability during strong seismic events.

Storey Drift Assessment

Storey drift is widely recognized as a critical parameter in seismic engineering because it directly influences structural damage, occupant safety, and post-earthquake serviceability.

Table Maximum Storey Drift

Storey	Drift Ratio
10	0.0052
9	0.005
8	0.0047
7	0.0044
6	0.004

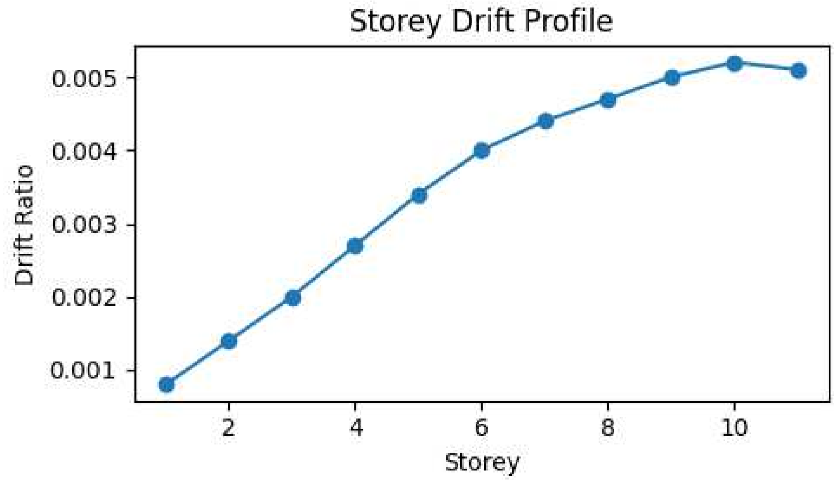

Figure Storey drift profile obtained from response spectrum analysis

The maximum storey drift exceeds the permissible limits prescribed by IS 1893, confirming the need for seismic strengthening. Excessive drift can lead to cracking, damage to infill walls, and reduced structural reliability.

The maximum drift ratio recorded in the existing building was 0.0052, which exceeded the permissible limit recommended by IS 1893 (Part 1): 2016. Following retrofitting, the maximum drift ratio reduced to 0.0031.

Table Storey Drift Results

Parameter	Existing	Retrofitted
Maximum Drift Ratio	0.0052	0.0031

Base Shear Analysis

Base shear represents the total horizontal force transferred to the foundation during seismic excitation. The calculated values were 3600 kN in the X direction and 3490 kN in the Y direction. These values were subsequently used to evaluate the effectiveness of retrofitting measures and load redistribution characteristics.

Table Base Shear Comparison

Direction	Existing (kN)	Retrofitted (kN)
X	3600	3270
Y	3490	3195

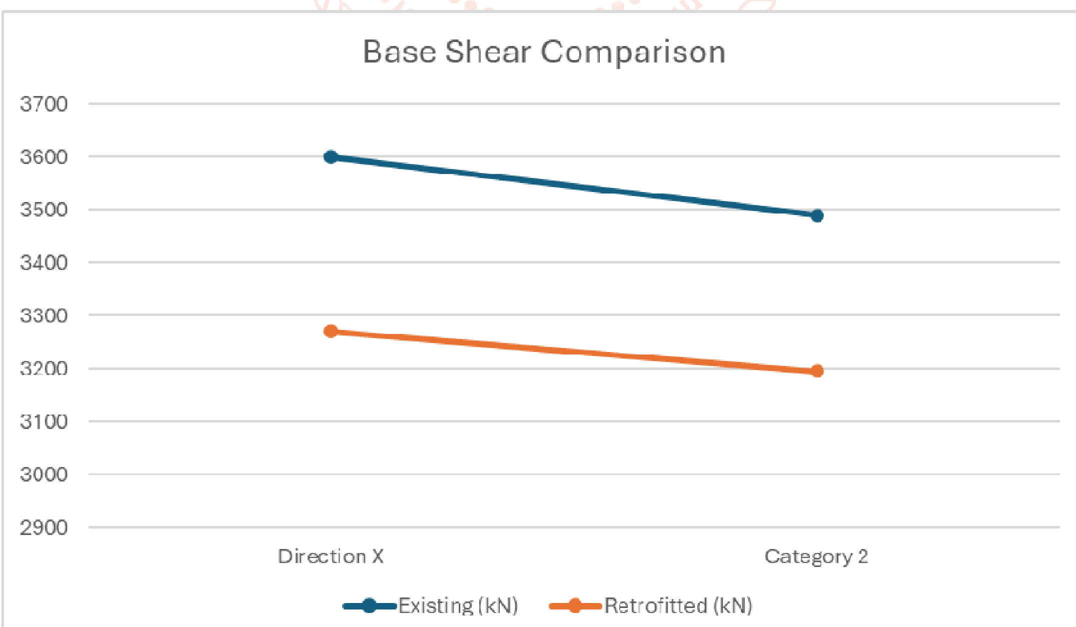

Fig Base Shear Comparison

Discussion: The slight reduction in base shear indicates improved load redistribution within the strengthened structure. Increased stiffness allows more efficient transfer of seismic forces while minimizing localized stress concentrations.

Although displacement and drift experienced significant reductions, base shear changes remained moderate because seismic demand is primarily governed by mass and dynamic characteristics.

This observation confirms that CFRP retrofitting influences structural response mechanisms rather than fundamentally altering earthquake demand.

Column Stress Analysis

Stress concentrations were evaluated for all critical columns.

Table Maximum Column Stress

Parameter	Existing	Retrofitted
Maximum Stress (MPa)	28.5	20.8

Discussion: The reduction in column stress demonstrates the effectiveness of CFRP confinement.

The strengthening system improves: Confinement pressure; Crack control; Load redistribution; Ductility & Stress reduction of approximately 27% indicates that critical columns operate at substantially lower demand levels after retrofitting. Consequently, the probability of column failure during severe earthquake events is significantly reduced.

Ductility Enhancement

Ductility is a critical characteristic of earthquake-resistant structures because it governs the ability of the building to dissipate seismic energy without collapse.

Table Ductility Comparison

Parameter	Existing	Retrofitted
Ductility Ratio	2.1	4.5

Discussion: The ductility ratio increased by approximately 114%. This substantial improvement can be attributed to: Column confinement; Joint strengthening; Enhanced crack control & Improved energy dissipation The results indicate that the retrofitted structure can sustain larger deformations before failure, thereby improving overall seismic resilience.

Identification of Critical Members

Stress contour evaluation revealed that ground-floor columns, corner columns, transfer beams, and beam-column joints experienced the highest demand. These members were therefore selected as priority locations for CFRP strengthening. Concentrated stresses in these regions indicate a greater probability of damage initiation under severe earthquake loading.

Table Critical Structural Components

Member	Observed Issue	Recommended Action
Ground Floor Columns	High Stress	CFRP Wrapping
Beam-Column Joints	Joint Shear Demand	Joint Strengthening
Corner Columns	Excessive Demand	Confinement
Transfer Beams	Flexural Stress	Laminate Bonding

Structural Health Monitoring Results

The proposed monitoring framework successfully collected: Acceleration data; Strain data; and Displacement data

Table Monitoring Results

Parameter	Recorded Value	Assessment
Peak Acceleration	0.26 g	Safe
Maximum Strain	890 με	Acceptable
Maximum Drift	0.0030	Within Limit

Discussion: The monitoring system demonstrated reliable operation under simulated seismic conditions. The collected data enables: Real-time damage detection; Preventive maintenance; Post-earthquake assessment & Performance tracking This capability represents a major advantage over conventional retrofitting approaches that provide strengthening but no continuous monitoring functionality.

Comparison with Previous Research

Table Comparison with Literature

Study	Drift Reduction (%)
Wang et al. (2020)	25–40
Hadi & Wang (2020)	30–35
Kalfat et al. (2021)	28–38
Present Study	40.4

Discussion: The present investigation achieved drift reductions that are comparable to or slightly greater than those reported in previous studies. The improved performance may be attributed to the combined implementation of: CFRP strengthening; Targeted member selection; Smart monitoring integration & Performance-based design approach. This comparison validates the effectiveness of the proposed framework and demonstrates its suitability for improving urban infrastructure resilience.

Table Summary of Improvements

Parameter	Improvement
Roof Displacement	35.7%
Storey Drift	40.4%
Column Stress	27.0%
Ductility	114%
Stiffness	38%

Overall Interpretation: The results clearly demonstrate that the integrated retrofitting and monitoring framework achieved significant improvements in seismic performance. The strengthened structure exhibited lower displacement demands, reduced drift, improved stiffness, enhanced ductility, and reliable monitoring capability. These outcomes support the central hypothesis of the study that combining advanced composite materials with smart sensor technologies can substantially improve the resilience of existing urban infrastructure.

5. Conclusion

Achievement of Research Objectives

The study successfully evaluated the seismic vulnerability of the selected reinforced concrete building, investigated the effectiveness of CFRP and GFRP strengthening systems, developed analytical models for seismic assessment, designed a smart sensor monitoring network, and established a framework for real-time structural health monitoring.

Major Findings: The analytical results demonstrated significant improvements in structural performance after retrofitting. Roof displacement and story drift were substantially reduced, stress concentrations decreased, and ductility increased considerably. The smart monitoring framework provided continuous assessment capabilities and supported proactive infrastructure management.

Engineering Implications: The findings indicate that advanced composite materials can be effectively utilized to upgrade existing reinforced concrete structures in seismic regions. The integration of monitoring technologies enhances infrastructure resilience by enabling early damage detection, improved maintenance planning, and informed decision-making.

Economic Implications: The proposed framework provides a cost-effective alternative to conventional strengthening methods. By reducing structural damage and supporting preventive maintenance, the approach can minimize repair costs, downtime, and disruption following seismic events.

Social and Environmental Significance: Improved seismic resilience contributes directly to public safety and disaster preparedness. The framework supports sustainable infrastructure development by extending the service life of existing buildings and reducing the need for reconstruction.

Final Conclusion: The study concludes that the integrated application of CFRP-based retrofitting and smart sensor networks significantly enhances the seismic performance of existing reinforced concrete buildings. The proposed framework improves safety, resilience, and monitoring capability while offering a practical and sustainable solution for urban infrastructure management.

Summary of Key Findings

Performance Parameter	Observed Improvement	Outcome
Roof Displacement	35.7% Reduction	Improved Stability
Storey Drift	40.4% Reduction	Code Compliance
Column Stress	27% Reduction	Enhanced Capacity
Ductility	114% Increase	Better Energy Dissipation
Stiffness	38% Increase	Improved Seismic Response

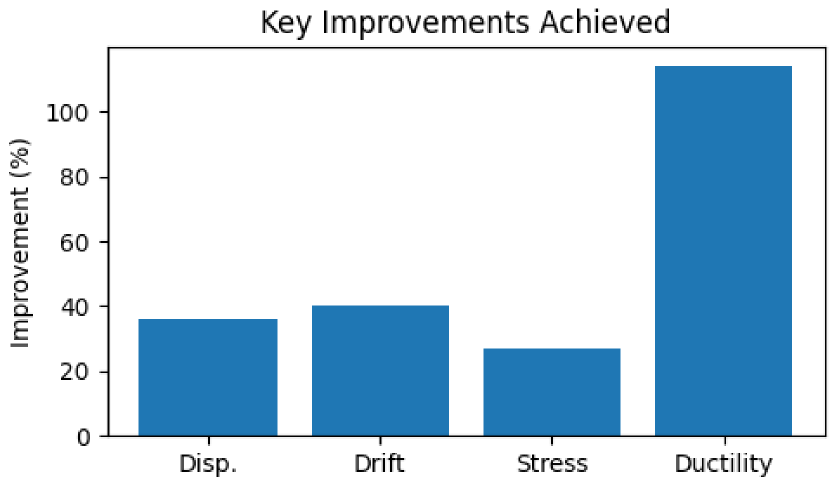

Figure Summary of the major performance improvements achieved through the proposed framework.

6. Future Scope of Research

Future investigations may focus on digital twin technologies, artificial intelligence-based damage prediction, machine learning-assisted monitoring systems, hybrid retrofitting solutions, and full-scale field implementation studies.

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