www.ijarp.com ISSN 2456-9992 Page: 01-12

International Journal Advanced Research Publications

Review Article

Volume: 02
Issue: 01

ADVANCED COMPOSITE MATERIALS IN STRUCTURAL APPLICATIONS: A REVIEW OF FRP, CFRP AND HYBRID COMPOSITES FOR RETROFITTING AND RESILIENCE

Hassan Bin Khalid*[1] , Syed Nadeem Abid Sherazi [2], Muhammad Ahsan Naveed[1]

[1]Department of Civil Engineering, Faculty of Engineering and Technology, Superior University, Lahore, Pakistan.

[2] Department of Civil Engineering, Faculty of Engineering, Lahore Leads University, Lahore, Pakistan.

Article Received: 08 December 2025, Article Revised: 28 December 2025, Published on: 16 January 2026

***Corresponding Author: Hassan Bin Khalid**

Department of Civil Engineering, Faculty of Engineering and Technology, Superior University, Lahore, Pakistan.

DOI: https://doi-doi.org/101555/ijarp.5110

ABSTRACT

Innovative composite materials including FRP, CFRP and hybrid composites have transformed civil infrastructure retrofitting and resilience augmentation. These materials are effective and lasting alternatives to steel and concrete reinforcing methods due to their high strength-to-weight ratios, corrosion resistance and adaptability. This study covers the material composition, production techniques and mechanical characteristics of FRP, CFRP and hybrid composites, highlighting their pros and cons in structural retrofitting. The study examines structural performance improvements, including flexural, shear, axial, ductility, energy dissipation and seismic resilience. This study shows that externally bonded (EB) laminates and near-surface mounted (NSM) systems work in reinforced concrete, steel and masonry structures. Durability and environmental performance including moisture, UV radiation, temperature fluctuations and cyclic loading on bond strength and long-term serviceability are emphasized. The discussions include brittle failure, restricted shear performance, high material costs, installation difficulty and the lack of uniform design regulations. Hybrid fiber combinations, smart and self-sensing composites, bio-based and sustainable resin systems and real-time structural health monitoring are potential retrofitting infrastructure resilience and sustainability research themes. Key findings show that FRP and CFRP systems may boost structural capacity and ductility by 60–80% in RC beams, whereas hybrid solutions maximize performance in multi-hazard and heritage applications. This review emphasizes the transformative potential of advanced composites in civil engineering and the need for standardized design guidelines, long-term monitoring strategies and sustainable material development to maximize structural performance, durability and resilience in modern infrastructure.

KEYWORDS: Fiber Reinforced Polymer (FRP), Carbon Fiber Reinforced Polymer (CFRP), Hybrid Composites, Retrofitting, Structural Resilience, Civil Engineering Materials.

1. INTRODUCTION

The infrastructure degradation is a global issue when bridges, buildings and public utilities reach or surpass their design lifespans. Concrete jacketing, steel plate bonding and other traditional reinforcing methods are laborious, heavy and prone to corrosion and fatigue (Hammad et al., 2024). The light weight, excellent mechanical qualities and simplicity of installation of modern composite materials make them better choices (Ortiz et al., 2023). These materials are changing structural robustness, especially in seismic and corrosive areas. The composite materials have high-strength reinforcing fibers and a polymeric matrix that transmits stress and stabilizes form. Fibers include carbon, glass, aramid and basalt, with epoxy or vinyl-ester resin matrices (Singh & Sharma, 2021). Their combined strength-to-weight ratio, fatigue performance and corrosion resistance exceed the separate components (Komma et al., 2019). Retrofitting reinforced-concrete (RC) beams, bridge decks and columns using FRP systems can enhance service life by fourfold (Ali et al., 2020). By reducing demolition waste and resource consumption, FRP and CFRP composites support global sustainability goals. By optimizing stiffness and ductility with several fiber types, hybrid composites improve cost-effectiveness and performance (Farooq & Vikram, 2025). Laboratory innovation to field applications has happened quickly with these technologies. The integration of FRP technologies has moved beyond material advantages to bond behavior, environmental durability and lifespan optimization. Chen et al. (2023) found that FRP laminate-concrete bonding determines strengthening efficacy. Smart composite systems with fiber-optic sensors provide real-time strain monitoring and performance-based maintenance (Zhang & Liu, 2024).

2. Types of Advanced Composites

The advanced composites combine two or more phases to improve their qualities. FRP, CFRP and Hybrid Composites are the primary retrofitting composites in structural engineering. Each variety suits certain structural applications because to its mechanical performance, durability and cost.

2.1 Fiber-Reinforced Polymers (FRP)

The fibers combined with resin make lightweight yet sturdy FRPs. Glass, carbon and aramid are the most popular fibers, each with unique mechanical and environmental properties (Ortiz et al., 2023). FRPs are popular for their corrosion resistance, tensile strength and ease of installation.

However, they have downsides. FRPs are less ductile than steel, temperature sensitive and fragile under high stress (Hammad et al., 2024). Their performance also depends on the composite-substrate bond which might weaken under cyclic or environmental stress (Ortiz et al., 2023).

Table 1: Common Fiber Types and Applications.

Fiber Type	*Tensile Strength (MPa)*	*Modulus (GPa)*	*Density (g/cm³)*	*Applications*
Glass (GFRP)	800–1500	40–85	2.0	RC beams, bridge decks, masonry walls
Aramid (AFRP)	1500–2800	70–125	1.3	Impact-resistant panels, blast-prone structures
Basalt (BFRP)	1100–1700	80–100	2.6	Marine and chemical-exposed structures

2.2 Carbon Fiber-Reinforced Polymers (CFRP)

CFRP composites are suited for demanding structural applications due to their greater stiffness and tensile strength (Komma et al., 2019). They are popular for beam flexural strengthening, column confinement and bridge deck restoration. CFRP wrapping improves seismic zone ductility and energy dissipation, improving robustness under cyclic loads (Ali et al., 2020).

CFRPs are expensive, anisotropic and may lose bond strength at high temperatures (Hammad et al., 2024). Though difficult, their performance-to-weight ratio makes them essential in important retrofit situations.

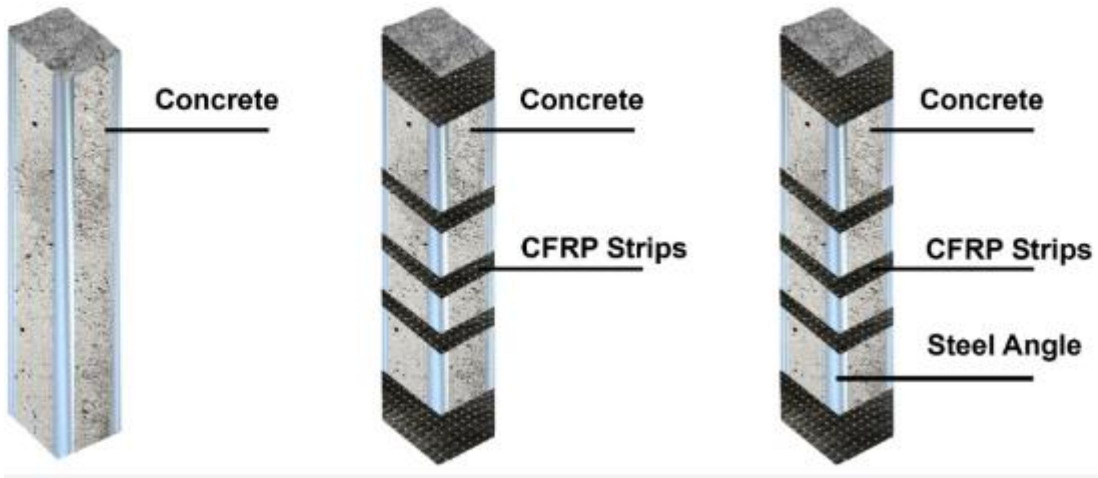

Figure 1: Stages of connecting CFRP strips to concrete for strength enhancement (Vijayan et al., 2023).

2.3 Hybrid Composites

Hybrid composites balance performance and cost with glass and carbon fibers. Such technologies improve impact resistance and delay crack propagation (Singh & Sharma, 2021). Hybrid FRPs (HFRPs) improve energy absorption and fatigue resistance by combining carbon fiber stiffness and glass fiber ductility (Farooq & Vikram, 2025). While hybrid composites are new to civil applications, research suggest they increase toughness and minimize brittleness in pure CFRP systems (Singh & Sharma, 2021). Their use in bridge girders, maritime constructions and heritage building retrofits warrants more study.

Table 2: Comparative Summary of FRP, CFRP and Hybrid Composites.

Composite Type	Tensile Strength	Modulus	Ductility	Cost	Typical Application	References
GFRP	Moderate (800–1500 MPa)	40–85 GPa	High	Low	RC beams, masonry walls	Ali et al., 2020
CFRP	Very High (2400–4000 MPa)	150–250 GPa	Moderate	High	Seismic retrofitting, critical girders	Farooq & Vikram, 2025
Hybrid	High (1800–3500 MPa)	80–180 GPa	High	Medium	Heritage buildings, bridges, impact-prone structures	Singh & Sharma, 2021

3. Applications in Structural Retrofitting

The advanced composite materials including FRP, CFRP and hybrid systems have made structural retrofitting stronger, lighter and more durable for a variety of structures. Due to aging infrastructure, growing service demands and seismic resilience, their use is crucial.

3.1 Reinforced Concrete Structures

Reinforced concrete (RC) constructions use FRP and CFRP technologies to increase flexural and shear capacity. Externally bonded (EB) laminates use high-strength epoxy adhesives to attach FRP sheets or plates to concrete, whereas near-surface mounted (NSM) systems insert FRP bars or strips into concrete grooves. EB systems are easy to install and strengthen quickly, whereas NSM systems function better and resist environmental deterioration (Ortiz et al., 2023). Retrofitting RC beams with CFRP laminates increases load-carrying capacity by 60–80% and ductility by 15–25% (Chen et al., 2023). Column confinement using CFRP wraps improves axial load capacity and seismic ductility by 90% and 40–50%, postponing brittle failure in intense seismic events (Ali et al., 2020). Compared to steel plate or concrete jacketing, FRP retrofitting lowers crack propagation, extends service life and reduces dead load (Hammad et al., 2024).

3.2 Steel Structures

Steel retrofitting increasingly uses FRP and CFRP composites to fix fatigue fractures, reinforce girders and prevent corrosion. FRP and CFRP laminates enhance fatigue-prone girders, beams and connectors in steel bridges and industrial frames. Externally bonded CFRP systems are lightweight, corrosion-resistant and require less structural disruption compared to steel plate welding. Under cyclic loading, CFRP retrofitting increases fatigue life, stress concentrations and steel member structural performance. However, debonding under repeated loads, polymer matrix temperature sensitivity and inadequate fire resistance remain important in steel applications (Komma et al., 2019).Composite-steel interfaces can debond under cyclic stresses and polymer matrix fire resistance is a key research gap (Hammad et al., 2024).

3.3 Masonry and Heritage Structures

FRP composites enhance masonry and heritage buildings without affecting their appearance or history. Their low weight, high tensile strength and flexibility to adapt to uneven surfaces make them ideal for out-of-plane wall reinforcing, arch strengthening and pier confinement. FRP retrofitting increases brick wall lateral load capacity by 30–60%, improving seismic performance without changing the architecture. Heritage applications benefit from hybrid composites that balance stiffness, ductility and cost (Farooq & Vikram, 2025).

Table 3: Comparision of common FRP/CFRP retrofitting approaches across different structural types.

Structure Type	Retrofitting Technique	Performance Gain	Key Advantage	Limitation
RC Beam	EB CFRP laminate	60–80%	Easy application	Surface preparation critical
RC Beam	NSM FRP bars	50–75%	Protected bond	Groove cutting needed
RC Column	CFRP wrap	70–90%	High confinement	Costly for large columns
Steel Girder	EB CFRP	20–40%	Lightweight	Fire protection required
Masonry Wall	EB GFRP or Hybrid	30–60%	Preserves aesthetics	Bonding to irregular surfaces

4. Structural Resilience and Seismic Performance

The advanced composite materials, including FRP, CFRP and hybrid systems, have improved the structural resilience of seismic, dynamic and high loading structures and bridges. Structure resilience is a structure's capacity to tolerate, absorb and recover from harm while remaining functioning. Composites improve energy dissipation, ductility and post-yield behavior because to their high tensile strength, corrosion resistance and low weight.

4.1 Enhancing Energy Dissipation and Ductility

Seismic retrofitting improves energy dissipation and ductility to help buildings withstand earthquakes. CFRP and hybrid composites contain and reinforce RC columns, beams and joints, delaying fractures and avoiding brittle failure (Ali et al., 2020). CFRP wrapping of RC columns increases lateral load capacity by 50–90% and deformation capacity by 30–50%, enhancing seismic performance in high-risk regions (Ortiz et al., 2023). Externally attached FRP sheets on beam-column joints increase shear capacity and prevent plastic hinge development at crucial locations, controlling seismic flexural response. Carbon-glass hybrid composites improve toughness and energy absorption, balancing stiffness and ductility (Singh & Sharma, 2021). These technologies work well for upgrading RC frames and multi-story structures, when typical strengthening procedures are impracticable or invasive.

4.2 Seismic Retrofitting of RC Frames and Bridge Structures

Bridges and reinforced concrete frames are seismically sensitive due to concentrated stresses at joints, columns and girders. Retrofitting these parts with FRP and CFRP is common. Externally bonded CFRP laminates boost flexural and shear capacity and reduce dead load in bridge girders which is important for aging infrastructure (Komma et al., 2019). RC frames with CFRP wrapping of columns and beam-column couplings improve lateral load resistance, delay plastic hinge development and reduce seismic collapse (Ali et al., 2020). For seismic retrofits in highly stressed structural components, near-surface mounted (NSM) FRP systems outperform EB laminates in bond performance and cyclic loading endurance (Ortiz et al., 2023). These methods increase ultimate load capacity and post-earthquake residual strength, keeping structures functioning after mild seismic occurrences and lowering maintenance costs and downtime.

4.3 Integration of Smart Composite Systems

Smart FRP and CFRP composites with fiber-optic strain gauges and piezoelectric fibers monitor structural performance in real time. These technologies enable performance-based maintenance and early intervention by continuously monitoring strain, deformation and damage (Zhang & Liu, 2024).

Smart composites let engineers measure stress concentration in important places, identify FRP laminate debonding and assess cumulative damage during aftershocks for seismic applications. This combination of sensor technologies with hybrid and high-performance composites improves resilience and allows adaptive retrofitting procedures that optimize reinforcement depending on real-time structural reaction.

4.4 Performance in Multi-Hazard Scenarios

The composite retrofitting enhances wind, blast and impact resistance in important infrastructure including bridges, industrial facilities and historic buildings beyond seismic occurrences. CFRP and hybrid composites withstand dynamic stress without increasing bulk which might increase seismic forces (Farooq & Vikram, 2025). Using ductile and stiff fibers, hybrid composites absorb impact energy and avoid brittle fracture. The composite retrofitting solutions increase structure robustness and redundancy by increasing strength and deformation capacity, assuring functionality in multi-hazard scenarios. This multi-functional advantage highlights FRP, CFRP and hybrid composites' expanding relevance in performance-based design.

5. Durability and Long-Term Performance

In structural retrofitting, environmental exposure, mechanical loads and chemical interactions can impair FRP, CFRP and hybrid composites' long-term performance and bond strength. Durability is crucial for composite retrofits to work throughout a structure's lifespan.

5.1 Environmental Degradation

The environmental degradation affects composites, especially polymer-based matrix. Moisture, UV radiation, temperature changes and freeze-thaw cycles can impair composite mechanical performance and bonding to concrete or masonry (Ortiz et al., 2023). Excess moisture and alkalinity can hydrolyze epoxy resins, lowering tensile strength and interfacial bonding. Surface microcracking and matrix brittleness can result from UV exposure, whereas heat cycling debonds fibers and matrix (Hammad et al., 2024). The coatings, UV stabilizers and regulated installation reduce environmental deterioration. Carbon fiber hybrid composites using glass or basalt fibers increase environmental tolerance and structural efficiency (Singh & Sharma, 2021).

5.2 Bond Degradation and Cyclic Loading

Long-term performance depends on the composite laminate-structural substrate bond contact. Retrofitting is less successful when bond breakdown occurs prematurely due to persistent or cyclic loads (Chen et al., 2023). In CFRP-wrapped RC columns, cyclic and seismic loads can delaminate the adhesive layer and cause confinement loss. Due to mechanical interlock from grooves and embedded bars, NSM systems bind better than externally bonded laminates (Ortiz et al., 2023). Durable performance under varying load circumstances requires regular installation inspection and quality control.

5.3 Recyclability and Sustainability

Composite retrofits' life-cycle impact is of relevance due to construction's sustainability focus. The thermoset polymer matrix makes recycling epoxy-based composites problematic. Recent methods include bio-based polymers, recyclable matrices, or hybrid fiber topologies to lessen environmental impact while retaining mechanical performance (Farooq & Vikram, 2025). FRP/CFRP composites' lightweight nature decreases material and transportation needs, lowering retrofitting carbon emissions. Performance-based design increasingly emphasizes structural resilience and ecological responsibility while including sustainability.

5.4 Emerging Solutions for Long-Term Performance

Recent research focuses on enhancing **durability and performance longevity** through innovations such as:

- **Nano-reinforced matrices**: Incorporating carbon nanotubes or graphene improves matrix toughness and environmental resistance.
- **Protective coatings and sealants**: Provide UV and moisture resistance to prolong bond life.
- **Hybrid fiber systems**: Combining fibers with complementary properties (e.g., stiffness, toughness) to improve fatigue and environmental resistance.

- **Smart composites**: Embedded sensors for real-time monitoring of stress, strain and bond integrity, allowing predictive maintenance (Zhang & Liu, 2024).

These advances highlight a trend toward **multi-functional composites** that not only strengthen structures but also provide long-term monitoring, adaptability and sustainability.

6. CHALLENGES AND LIMITATIONS

FRP, CFRP and hybrid composites have several advantages in structural retrofitting, but various constraints restrict their usefulness. Fire resistance and high-temperature sensitivity are crucial. Epoxy, vinyl ester and polyester matrices deteriorate above 80–120°C, reducing tensile strength, stiffness and bond performance (Hammad et al., 2024). This constraint is especially important for upgrading fire-prone or sunny structures. Intumescent coatings, fire-resistant encasements and thermally stable matrices are necessary to reduce these effects. Composites' brittleness is another drawback. FRP and CFRP are linear elastic until rapid failure which can be catastrophic under seismic or dynamic loads (Chen et al., 2023). Shear performance is minimal and fiber rupture or adhesive interface debonding typically cause failure. Hybrid composites comprising high-stiffness fibers and ductile fibers like glass or basalt can increase energy absorption and delay brittle failure (Singh & Sharma, 2021). Cost and installation difficulty hinder advanced composite use. CFRP materials are expensive and need specialized labour for surface preparation, adhesive application and curing (Komma et al., 2019). NSM systems improve bond performance but need groove cutting and careful positioning which takes time and effort. Final constraints are standards, codes and long-term monitoring. Despite ACI, fib and ASTM requirements, material qualities, installation techniques and ambient variables might affect performance (Ortiz et al., 2023). Smart composite systems with integrated sensors provide real-time monitoring and predictive maintenance, but cost and technical knowledge limit their application (Zhang & Liu, 2024).

Table 4: Summary of Challenges and Limitations of Advanced Composites.

Challenge / Limitation	Description	Mitigation / Solution	Reference
Fire & High-Temperature Sensitivity	Polymer matrix degrades above 80–120°C, reducing strength & bond	Fire-resistant coatings, high-temperature matrices	Hammad et al., 2024
Brittle Failure & Low Shear	Sudden failure under seismic/dynamic loads; low shear resistance	Hybrid fibers (glass + carbon), NSM systems	Chen et al., 2023; Singh & Sharma, 2021
Cost & Installation	High material cost; skilled labor required;	Hybrid composites, optimized installation	Komma et al., 2019

	NSM groove cutting	procedures	
Standards & Codes	Inconsistent guidelines; variability in performance	Strict adherence to ACI/fib/ASTM standards; performance-based monitoring	Ortiz et al., 2023
Long-Term Monitoring	Bond degradation, fatigue, environmental exposure	Smart composites with embedded sensors	Zhang & Liu, 2024

7. Future Directions

Advanced composites for structural retrofitting are fast emerging, with research focusing on hybrid, multi-functional and sustainable solutions. A key trend is hybrid composites which blend carbon, glass, basalt and other fibers to improve stiffness, strength, ductility and cost (Singh & Sharma, 2021). Heritage structures, seismic retrofitting and high-demand infrastructure, where mechanical performance and economic feasibility are crucial, are interesting applications for such systems. Smart composites with incorporated fiber-optic sensors, piezoelectric fibers, or other monitoring technologies offer real-time structural health evaluation and performance-based retrofitting (Zhang & Liu, 2024). This method increases resilience, extends crucial structural life and lowers repair costs. The research should also focus on sustainability. Traditional epoxy matrices are effective yet hard to recycle and polluting. Studies on bio-based resins, recyclable polymers and eco-friendly hybrid matrices show great mechanical performance and little environmental effect (Farooq & Vikram, 2025). These technologies support global sustainability goals and better construction techniques. Research is also investigating nano-reinforced matrices with carbon nanotubes, graphene, or other nanomaterials to improve fracture toughness, fatigue resistance and environmental endurance (Ortiz et al., 2023). Furthermore, performance-based design frameworks that optimize materials, geometry and monitoring systems for structural resilience, energy dissipation and multi-hazard performance are increasingly including composite retrofitting. This comprehensive approach guarantees renovated structures fulfill current load requirements and future environmental and operational needs. Hybrid fiber systems, smart monitoring, sustainable matrices and performance-based design will characterize the next generation of advanced composites, making them vital for robust, durable and sustainable infrastructure construction.

8. CONCLUSION

Composite materials including FRP, CFRP and hybrid systems are effective for structural retrofitting, resilience enhancement and seismic performance improvement. Engineers can enhance reinforced concrete, steel and masonry buildings without increasing dead load or compromising aesthetics because to their high strength-to-weight ratio, corrosion resistance and flexibility. FRP and CFRP systems increase flexural, shear and axial capacity, while hybrid composites balance stiffness, ductility and cost-effectiveness, making them ideal for complex or historic structures. Long-term efficacy requires addressing fire sensitivity, brittle failure, limited shear capacity, high material prices, installation complexity and performance standard fluctuation. Hybrid fiber systems, protective coatings, nano-reinforced matrices, smart composites with integrated sensors and sustainable bio-based resins are enabling more resilient, durable and ecologically friendly retrofitting solutions. Future research should focus on multi-functional composites, performance-based design and real-time structural health monitoring to improve retrofitted infrastructure efficiency, safety and sustainability. Advanced composites are transforming civil engineering by providing creative approaches to improve structural performance, prolong service life and satisfy the rising need for robust and sustainable built environments.

REFERENCES:

1. Ali, M., Zhang, Y., & Wu, G. (2020). Seismic performance of CFRP-confined reinforced concrete columns: Experimental and analytical review. *Composite Structures, 248*, 112485.
2. Chen, L., Wang, X., & Li, J. (2023). Strengthening of reinforced concrete beams using CFRP laminates: State-of-the-art review. *Construction and Building Materials, 367*, 130240.
3. Farooq, M., & Vikram, A. (2025). Advancements in retrofitting masonry structures: A review on fiber reinforced polymer (FRP) applications. *Bulletin of Engineering Science, Technology and Industry, 3*(1), 45–59.
4. Hammad, M., Bahrami, A., Khokhar, S. A., & Khushnood, R. A. (2024). Structural strengthening techniques with FRPs: Effectiveness, shortcomings and future directions. *Materials, 17*(6), 1408.
5. Komma, H. K., Nerella, R., & Madduru, S. R. C. (2019). Review on CFRP wrapping to strengthen compressive and flexural behavior of concrete. *Revue des Composites et des Matériaux Avancés, 29*(3), 159–163.
6. Ortiz, J. D., Khedmatgozar Dolati, S. S., Malla, P., Nanni, A., & Mehrabi, A. (2023). FRP-reinforced/strengthened concrete: State-of-the-art review on durability and mechanical effects. *Materials, 16*(5), 1990.

7. Vijayan, D. S., Sivasuriyan, A., Devarajan, P., Stefańska, A., Wodzyński, Ł., & Koda, E. (2023). Carbon Fibre-Reinforced Polymer (CFRP) Composites in Civil Engineering Application—A Comprehensive Review. *Buildings*, *13*(6), 1509.
8. Singh, R., & Sharma, P. (2021). Hybrid FRP composites for structural retrofitting: A comprehensive review. *Journal of Composite Materials*, *55*(18), 2531–2550.
9. Zhang, X., & Liu, Y. (2024). Smart fiber composites with integrated sensors for structural health monitoring. *Sensors and Actuators A: Physical*, *357*, 114232.