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(Review Article)

High-performance composite materials for earthquake-resistant structures in the U.S

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Abstract

The United States faces significant seismic vulnerability, particularly in regions such as California, the Pacific Northwest, and parts of the central and eastern U.S., where critical infrastructure remains at risk from moderate to severe earthquakes. Traditional construction materials often lack the ductility and energy dissipation capacity required to withstand such seismic loads, underscoring the urgent need for innovative structural solutions. This review critically examines the role of high-performance composite materials including fiber-reinforced polymers (FRP), engineered cementitious composites (ECC), ultra-high-performance concrete (UHPC), and shape memory alloys (SMA) in enhancing the seismic performance of infrastructure across the U.S. The paper explores the mechanical behavior, energy absorption characteristics, and durability of these materials under dynamic loading conditions. It also reviews their application in structural retrofitting, new construction, and post-disaster resilience. Key findings reveal that these composites significantly improve crack control, energy dissipation, and resilience against progressive collapse. Their integration into structural systems can reduce downtime, repair costs, and overall life-cycle expenses. However, challenges remain regarding material cost, design standardization, scalability, and the availability of long-term performance data under varied seismic conditions. The review identifies these barriers and offers insights into overcoming them through collaborative research, updated design codes, and targeted policy support. Furthermore, the paper outlines future directions including hybrid systems, smart composites with sensing capabilities, and digital twin integration to advance earthquake resilience. The review also identifies critical barriers to widespread implementation, including cost, standardization challenges, and the need for long-term field data. Finally, the study outlines future research directions and policy recommendations for integrating these materials into national seismic resilience strategies.

Keywords: Earthquake Engineering; Seismic Resilience; Composite Materials; Fiber-Reinforced Polymers (FRP); Engineered Cementitious Composites (ECC); Infrastructure; Retrofitting; U.S. Construction Standards

1. Introduction

Earthquakes represent one of the most unpredictable and destructive natural hazards affecting the built environment, particularly in seismically active regions of the United States. Areas such as the West Coast, home to the San Andreas Fault, the Cascadia Subduction Zone, and other active fault lines are especially vulnerable to seismic events of high magnitude and recurrence. Additionally, regions in the central and eastern U.S., such as the New Madrid Seismic Zone and Charleston, South Carolina, also face significant seismic risk, despite their relatively infrequent events [1]. The 1994 Northridge earthquake in California and the 1811–1812 New Madrid earthquakes serve as historical reminders of the potential for widespread infrastructural damage, economic disruption, and human loss. Given the aging infrastructure and increasing population density in these zones, the imperative for advancing seismic resilience has never been more urgent.

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Traditional construction materials like reinforced concrete and structural steel, while effective under static loading conditions, often fall short under the extreme dynamic forces generated during seismic events. Challenges such as brittle failure, limited energy dissipation, and insufficient post-yield performance have led to catastrophic failures in past earthquakes [2]. While current seismic design codes have made substantial improvements by promoting ductility and load redistribution, they still depend heavily on the intrinsic limitations of conventional materials. Therefore, to meet the increasing demands for performance, safety, and sustainability in seismic zones, the integration of innovative materials into structural design has become a focal point of earthquake engineering research. In this context, high-performance composite materials have emerged as a transformative solution. These materials, such as fiber-reinforced polymers (FRP), engineered cementitious composites (ECC), ultra-high-performance concrete (UHPC), and shape memory alloys (SMA) offer superior mechanical properties including high tensile strength, enhanced ductility, fatigue resistance, and corrosion resistance. Their ability to absorb and dissipate seismic energy, control crack propagation, and facilitate rapid post-event recovery makes them particularly suitable for use in earthquake-prone areas [3, 4]. For example, ECC has demonstrated strain-hardening behavior and self-healing properties under repeated loading, while SMA reinforcements are capable of restoring original shapes post-deformation, offering potential for self-centering structural systems [5].

The application of these materials spans both new construction and the retrofitting of existing infrastructure, which is especially important in the U.S., where many critical facilities such as bridges, hospitals, and lifeline utilities were built prior to modern seismic codes. FRP composites have been widely used to retrofit columns and beams, enhancing their ductility and confinement capacity [6]. Similarly, UHPC has gained traction for its use in seismic connections and joints due to its high compressive strength and low permeability. However, despite their promising properties, adoption remains limited due to factors such as high initial costs, lack of standardized design protocols, and limited long-term field data. The purpose of this review is to critically assess the current state, performance, and implementation challenges of high-performance composite materials in seismic applications within the U.S. The review synthesizes experimental findings, real-world case studies, and analytical models to highlight the advantages and limitations of each material type. In doing so, it aims to bridge the gap between laboratory research and practical engineering application. Furthermore, the paper identifies key research gaps, such as the need for long-term performance validation, integration with smart sensing technologies, and economic feasibility at scale that must be addressed to support wider adoption. The significance of this review lies in its contribution to ongoing efforts to enhance seismic resilience through materials innovation. By offering a comprehensive evaluation of high-performance composite materials, the study supports structural engineers, policy-makers, and infrastructure planners in making informed decisions about material selection and design strategies. Ultimately, it aligns with national priorities to modernize infrastructure, mitigate disaster risks, and promote sustainability in civil engineering practice.

2. Overview of Earthquake Engineering in the U.S.

The field of earthquake engineering in the United States has been shaped by a series of devastating seismic events that revealed the structural vulnerabilities of critical infrastructure and spurred advancements in design methodologies and regulations. Historically significant earthquakes, including the 1906 San Francisco earthquake with its devastating toll of over 3,000 fatalities and destruction of approximately 80% of the city, the 1964 Great Alaska earthquake, and the 1994 Northridge earthquake in California, have served as powerful catalysts for the evolution of seismic safety measures [7]. The Northridge event particularly highlighted critical deficiencies in contemporary building codes, especially regarding steel moment-resisting frame connections, subsequently leading to substantial revisions in structural design practices and codified requirements throughout the nation.

The regulatory landscape governing earthquake engineering in the United States comprises a comprehensive framework of seismic design codes developed through collaborative efforts among federal agencies, research institutions, and professional organizations. Key stakeholders in this ecosystem include the Federal Emergency Management Agency (FEMA), which provides technical guidance and post-disaster assessments; the American Society of Civil Engineers (ASCE), whose ASCE 7 standard establishes minimum design loads for structures including seismic forces; and the National Earthquake Hazards Reduction Program (NEHRP), established in 1977 to coordinate national seismic research initiatives, code development processes, and hazard mapping activities [8]. The most recent iteration, ASCE 7-22, incorporates sophisticated understandings of seismic phenomena including site amplification effects, near-fault ground motions, and probabilistic hazard assessment methodologies [9]. This standard notably integrates performance-based design principles that extend beyond basic life safety considerations to address functionality, repairability, and operational continuity particularly for critical infrastructure such as healthcare facilities, educational institutions, and emergency response centers. These national standards are often supplemented by regional specifications such as the California Building Code, which imposes additional seismic design requirements in areas of elevated risk.

Despite rigorous regulatory frameworks, conventional construction materials present persistent challenges to achieving optimal seismic performance. Reinforced concrete structures, while ubiquitous in the built environment, remain susceptible to brittle shear failure mechanisms and cracking patterns, particularly in older non-ductile frame systems constructed prior to modern seismic provisions. Similarly, structural steel components, despite their favorable strength-to-weight characteristics, demonstrate vulnerabilities to local buckling phenomena, fatigue damage, and weld failures under the cyclic loading conditions characteristic of seismic events [2]. The extensive inventory of structures predating contemporary seismic design standards represents a significant vulnerability within the national infrastructure system, often exhibiting insufficient lateral force resistance, inadequate detailing practices, and limited energy dissipation capacity during seismic excitation.

Economic constraints and awareness gaps have historically impeded widespread implementation of seismic retrofitting initiatives, particularly for aging public infrastructure and residential structures. Retrofitting programs frequently encounter obstacles related to financial limitations, logistical complexities, and operational disruptions during implementation phases [10]. Even in contemporary construction, achieving designated performance objectives remains contingent upon construction quality control, material consistency, and strict adherence to specified detail factors that can vary considerably across projects and jurisdictions. Against this backdrop, there exists increasing interest in advanced composite materials offering enhanced ductility characteristics, superior energy absorption capabilities, and improved damage tolerance under seismic loading conditions. These innovative materials, including fiber-reinforced polymers, engineered cementitious composites, and ultra-high-performance concrete formulations, address fundamental limitations of conventional construction practices while enabling more sophisticated performance-based seismic design approaches. However, their comprehensive integration into mainstream practice necessitates continued research efforts, material standardization initiatives, and verification of long-term performance reliability under diverse seismic conditions.

3. High-Performance Composite Materials: Types and Characteristics

In response to the increasing demand for resilient and sustainable infrastructure in seismically active regions, high-performance composite materials have emerged as promising alternatives to conventional construction materials. These advanced materials exhibit superior mechanical and durability characteristics, including enhanced tensile strength, ductility, energy dissipation capacity, and resistance to environmental degradation. Unlike traditional materials such as concrete and steel, which are often susceptible to brittle failure or permanent deformation under seismic loading, high-performance composites are engineered to undergo large inelastic deformations while maintaining structural integrity. Their application within earthquake-resistant design frameworks represents a transformative shift in the way engineers approach seismic resilience in the built environment. Among the most widely researched and deployed composite materials are fiber-reinforced polymers (FRPs). These materials, composed of high-strength fibers (e.g., carbon, glass, or aramid) embedded in a polymer matrix, are characterized by their high strength-to-weight ratio, corrosion resistance, and ease of application in retrofitting contexts. In seismic engineering, FRPs are extensively used to strengthen and confine reinforced concrete elements, particularly columns and shear walls, thereby enhancing ductility and load-carrying capacity. Numerous experimental investigations have confirmed the effectiveness of FRP confinement in improving the seismic performance of non-ductile members by delaying spalling and enhancing lateral deformation capacity [6; 11].

Ultra-high-performance concrete (UHPC) is another advanced composite that has demonstrated exceptional performance under seismic loads. With compressive strengths often exceeding 150 MPa and an ultra-dense microstructure, UHPC exhibits superior toughness, low permeability, and high bond strength with reinforcement. The inclusion of steel or synthetic microfibers further enhances its post-cracking behavior and resistance to impact and shear. These attributes make UHPC highly suitable for critical structural elements such as bridge joints, seismic connectors, and precast components where both strength and durability are paramount [12]. Its ability to maintain cohesion under high strain rates contributes significantly to structural resilience during and after seismic events.

Engineered cementitious composites (ECC), often referred to as “bendable concrete,” are strain-hardening materials developed to exhibit tensile strain capacities exceeding 3%, compared to the typical 0.01% of conventional concrete. This ductile behavior is achieved through the incorporation of low volumes of synthetic fibers, such as polyvinyl alcohol (PVA), which enable tight crack width control and distributed microcracking under tension. ECC’s ability to dissipate energy and accommodate deformation makes it ideal for seismic applications, particularly in beam-column joints, link beams, and other locations prone to high inelastic demand. Furthermore, the tight microcracks promote autogenous self-healing, contributing to long-term durability and reduced maintenance requirements [13].

Shape memory alloys (SMAs), particularly nickel-titanium (Niti) alloys, have also gained attention in seismic applications due to their unique super elastic and shape recovery properties. These materials are capable of undergoing large strains and returning to their original shape upon unloading, thanks to reversible phase transformations. Their application in seismic devices such as energy dissipators, restrainers, and base isolation systems enables structures to re-center after displacement, thereby minimizing residual drift and facilitating immediate post-event usability. Several studies have demonstrated the efficacy of SMA-based systems in reducing damage and improving serviceability in bridges and tall buildings during seismic excitations [5]. More recently, carbon nanotube (CNT)-reinforced composites have emerged as a frontier in multifunctional materials for seismic resilience. CNTs possess extraordinary mechanical, thermal, and electrical properties, and when incorporated into cementitious or polymer matrices, they enhance strength, interfacial bonding, and crack resistance. Additionally, CNT-based composites offer potential for integrating self-sensing capabilities, enabling real-time structural health monitoring under dynamic loads. Although still in the experimental phase, these materials hold considerable promise for future “smart” seismic infrastructure, combining structural performance with digital monitoring functionalities [14].

Across these material systems, several key mechanical properties govern their suitability for seismic design. High tensile and compressive strength is essential for resisting inertial loads, while ductility ensures that materials can deform without catastrophic failure. Energy dissipation is critical in reducing the forces transmitted to structural components, and durability under both mechanical and environmental stressors ensures long-term reliability. Taken together, these characteristics position high-performance composite materials as essential contributors to the advancement of earthquake-resistant infrastructure in the United States. Their continued development and integration into practice will depend on overcoming challenges related to standardization, cost, and long-term field validation, but the potential benefits in terms of safety, serviceability, and sustainability are substantial.

Table 1 Comparative Mechanical Properties of High-Performance Composite Materials for Earthquake-Resistant Structures in the U.S.

Material	**Strength**	**Ductility**	**Energy Dissipation**	**Typical Applications in Seismic Design**
FRP (Fiber-Reinforced Polymer)	Tensile Strength: 600–3,800 MPa Compressive Strength (confined concrete): Up to 120 MPa	Low ductility Brittle failure under tensile load	Moderate Enhances confinement but lacks hysteretic energy dissipation	Retrofit of columns, beam wrapping, shear strengthening, lightweight structural retrofits
ECC (Engineered Cementitious Composites)	Tensile Strength: 5–8 MPa Compressive Strength: 30–80 MPa	Extremely high ductility Tensile strain capacity up to 3–5%	Excellent Multiple micro-cracking enhances hysteretic energy dissipation	Coupling beams, shear walls, critical joint regions, seismic retrofitting
UHPC (Ultra-High-Performance Concrete)	Compressive Strength: 120–250 MPa Tensile Strength (with fibers): 8–15 MPa	Moderate ductility Tensile strain capacity up to 0.2–0.5%	High energy absorption Due to fiber-bridging and strain-hardening	Bridge piers, link beams, precast seismic-resistant components
SMA (Shape Memory Alloys)	Super elastic stress recovery: 300–600 MPa Tensile Strength: 400–1,000 MPa	Exceptional ductility Strain recovery up to 8–10%	Outstanding Provides self-centering capability and repeated energy dissipation	Seismic dampers, braces, connections, and base isolation devices

4. Seismic Performance of Composite Materials: Review of Experimental and Field Studies

The seismic performance of high-performance composite materials has been extensively investigated through both experimental research and real-world applications. These studies consistently demonstrate that materials such as fiber-reinforced polymers (FRP), engineered cementitious composites (ECC), and ultra-high-performance concrete (UHPC) significantly enhance the behavior of structural elements under seismic loading. Their use in critical components including beams, columns, and shear walls has led to measurable improvements in strength, ductility, and energy dissipation, making them key candidates for both new construction and the retrofitting of vulnerable infrastructure.

In reinforced concrete frames, columns are particularly susceptible to brittle failure during strong ground motion, especially in older buildings designed without modern ductile detailing. Experimental studies have shown that externally bonded FRP wraps can dramatically improve the confinement of concrete columns, increase axial strength and deformation capacity while delay the onset of failure. Phan et al. [11] found that carbon FRP-confined columns exhibited up to a 40% increase in ductility under cyclic lateral loading compared to unconfined counterparts. Similarly, ECC has been used to improve the seismic performance of coupling beams and beam-column joints. With its high strain capacity and tight crack control, ECC significantly enhances energy dissipation and prevents localized failure at structural connections [13].

Retrofitting applications has been particularly successful in field deployments. In the aftermath of the 1994 Northridge earthquake, numerous California bridges were retrofitted with FRP composites to strengthen their column piers. Follow-up assessments indicated improved load redistribution and reduced residual deformation in future seismic events (Seibel et al., 1997). Additionally, UHPC has been used to upgrade bridge joints and connections, providing exceptional shear resistance and crack durability even under extreme cyclic loading [12]. These interventions have extended the lifespan and functionality of aging structures while minimizing disruption during implementation. The energy absorption capacity and post-yield behavior of composite materials are among their most critical contributions to seismic resilience. Shape memory alloys (SMA), for instance, provide not only high energy dissipation but also self-centering properties that reduce permanent displacement after seismic events. In a full-scale bridge column test, SMA reinforcements were shown to reduce residual drift by more than 80%, demonstrating their utility in essential infrastructure that must remain operational after an earthquake [5]. Furthermore, laboratory shake-table tests of FRP-reinforced shear walls have confirmed enhanced lateral stiffness, reduced crack widths, and greater resilience to collapse when subjected to simulated seismic events.

In summary, both laboratory studies and field evidence strongly support the efficacy of composite materials in enhancing seismic performance across a wide range of structural systems. Their ability to increase ductility, improve confinement, dissipate energy, and restore structural alignment after strong motion has positioned them as indispensable tools in modern earthquake engineering. However, long-term monitoring and standardized evaluation protocols remain necessary to support broader implementation and to validate their performance under varied seismic and environmental conditions.

5. Case Studies in the U.S. and International Contexts

Recent global developments have demonstrated the growing importance of high-performance composite materials in enhancing the seismic resilience of infrastructure. Both laboratory investigations and full-scale applications have confirmed the efficacy of materials such as fiber-reinforced polymers (FRP), engineered cementitious composites (ECC), ultra-high-performance concrete (UHPC), and shape memory alloys (SMA) in mitigating seismic damage. Case studies from the United States and other high-risk seismic zones including Japan, New Zealand, and Italy offer valuable insights into how these materials perform in diverse structural contexts and regulatory environments.

In the United States, the 1994 Northridge earthquake marked a pivotal moment in seismic retrofitting practices. Widespread damage to bridge columns, particularly those with inadequate transverse reinforcement, led to the implementation of large-scale retrofitting programs using carbon fiber-reinforced polymer (CFRP) jackets. The California Department of Transportation (Caltrans) was among the first agencies to adopt CFRP as a confinement mechanism for reinforced concrete columns. These jackets not only enhanced the ductility and shear capacity of the columns but also minimized the need for extensive demolition or traffic disruption during installation. Follow-up inspections and post-earthquake performance evaluations have confirmed the long-term effectiveness of CFRP retrofits in increasing the seismic reliability of transportation infrastructure [15]. Similarly, ultra-high-performance concrete has gained acceptance in states like Washington, where it has been employed in field-cast bridge joints. These UHPC joints exhibit superior crack resistance and bonding characteristics, and field data suggest they maintain structural integrity under both seismic and environmental loads over extended service periods [12].

Outside the U.S., Japan has demonstrated significant innovation in the use of advanced composite materials, driven by the nation's frequent and severe seismic activity. Following the 1995 Kobe earthquake, Japanese engineers began integrating ECC into critical components such as link beams and beam-column joints. These applications have been shown to significantly improve post-yield performance, control crack propagation, and extend service life. Moreover, Japan has been a global leader in the application of shape memory alloys (SMAs) in seismic devices, particularly in bridge restrainers and base-isolated buildings. Experimental studies confirm that SMA-reinforced structures benefit from the material's super elasticity, allowing them to self-center after seismic displacement and reduce residual drift [5].

In New Zealand, the Canterbury earthquake sequence of 2010–2011 spurred a national effort to retrofit unreinforced masonry (URM) buildings using fiber-reinforced composites. Glass FRP (GFRP) strips were applied to enhance both in-plane shear strength and out-of-plane stability of masonry walls. These retrofits proved especially effective in reducing collapse risk during aftershocks and future seismic events. The Christchurch experience also emphasized the need for materials that are compatible with existing architectural features and construction techniques [16]. Italy presents another instructive context, where seismic risk intersects with the preservation of historical structures. Here, FRP systems particularly basalt and carbon fibers have been used to retrofit arches, masonry towers, and heritage buildings. Case studies following earthquakes in L'Aquila and Central Italy reported significantly reduced damage in structures that had received composite retrofits, reinforcing the value of such interventions for both safety and cultural conservation [17].

Comparative analysis across these contexts reveals commonalities in the advantages offered by composite materials chiefly, improved ductility, confinement, and post-event recovery as well as regional adaptations based on architectural, regulatory, and cultural considerations. In the U.S., applications have largely focused on critical transportation and public safety infrastructure, while Japan and Italy have extended composite use to residential and heritage structures. A consistent lesson across all jurisdictions is the importance of proactive intervention. Structures retrofitted prior to major seismic events consistently exhibit better performance, lower repair costs, and improved occupant safety. These case studies underscore the need for continued investment in composite technologies, informed policy frameworks, and performance-based design standards that support broader adoption in seismic regions.

6. Limitations, Challenges, and Research Gaps

Despite significant advances in the development and application of high-performance composite materials (HPCMs) for earthquake-resistant structures, several limitations and challenges persist. One primary concern is the cost and scalability of these materials. Advanced composites such as fiber-reinforced polymers (FRPs), ultra-high-performance concrete (UHPC), and shape memory alloys (SMAs) offer superior mechanical and seismic properties but are still considered economically unfeasible for widespread application due to high production and installation costs [18; 19]. In large-scale infrastructure projects, the cost-benefit analysis often limits their adoption to critical structures, leaving residential and mid-rise buildings reliant on conventional materials.

Another critical challenge is the lack of standardized testing and design protocols for HPCMs in seismic applications. Unlike traditional concrete and steel, composite materials lack universally accepted guidelines for load assessment, long-term behavior, and degradation mechanisms under cyclic seismic loading. This has led to inconsistent performance predictions and difficulties in gaining regulatory approvals [20; 21]. Moreover, the absence of a unified code impedes the confidence of structural engineers and contractors in implementing these materials in practice.

Long-term performance and durability are another area where significant research gaps exist. While short-term laboratory tests have demonstrated the efficacy of HPCMs under simulated seismic loads, there remains a scarcity of longitudinal data validating their performance in real-world scenarios, especially under varying environmental conditions such as humidity, temperature, and chemical exposure [22]. For example, the long-term behavior of FRP composites under repeated seismic and environmental stressors remains insufficiently understood, raising concerns about material fatigue and bond deterioration over time. Lastly, integration with current building codes and construction practices presents both a technical and institutional challenge. Most U.S. building codes, including the International Building Code (IBC) and American Concrete Institute (ACI) provisions, are tailored for traditional materials. The inclusion of HPCMs necessitates extensive code revisions, training, and certification processes, which slow their integration [23]. Furthermore, construction personnel often lack experience with these novel materials, leading to errors during fabrication and installation that may compromise structural integrity. Overall, while HPCMs hold immense potential for revolutionizing earthquake-resistant design, addressing these multifaceted limitations is essential for their broader implementation in the U.S. construction industry.

7. Future Research Directions

To fully harness the potential of high-performance composite materials (HPCMs) in enhancing the resilience of U.S. infrastructure against seismic hazards, future research must explore innovative, interdisciplinary directions. One critical frontier is the development of multi-hazard resilient composites materials engineered to withstand not only seismic loads but also secondary hazards such as fire and flooding. Recent studies emphasize the need for hybrid composites capable of retaining mechanical integrity under high temperatures and prolonged moisture exposure [24; 25]. Advancing such materials would be transformative for infrastructure in regions prone to compound disasters, including the western and coastal United States.

Equally promising is the integration of smart composites with embedded sensing capabilities. These next-generation materials can self-monitor strain, temperature, or cracks using piezoelectric, fiber-optic, or carbon nanotube-based sensors (Nguyen et al., 2023). Smart composites can significantly improve real-time damage detection, maintenance planning, and post-earthquake assessments, thereby enhance structural resilience and reduce life-cycle costs [26].

Another pressing research priority involves sustainability and low-carbon composite development. As the construction industry faces increasing pressure to reduce its carbon footprint, the exploration of bio-based fibers, recycled polymer matrices, and low-energy manufacturing processes has become vital. For instance, the substitution of petroleum-based resins with bio-resins has shown promising structural and environmental performance [27]. Life-cycle analysis and carbon emissions modeling should accompany such developments to ensure their scalability and policy alignment. Finally, advanced simulation and performance-based design (PBD) approaches are essential for optimizing the use of HPCMs in earthquake engineering. Future work should focus on integrating material-level modeling with building-scale seismic response simulations using tools such as Open Sees or ABAQUS. Machine learning and digital twin technologies can also enhance the predictive accuracy of damage and recovery models [28]. Incorporating HPCMs into performance-based seismic design frameworks will enable engineers to tailor materials and configurations to meet specific performance objectives, particularly in high-risk urban areas.

8. Conclusion

High-performance composite materials have emerged as transformative solutions for enhancing the seismic resilience of structures, offering a combination of high strength-to-weight ratio, corrosion resistance, ductility, and energy dissipation capabilities. Materials such as fiber-reinforced polymers, ultra-high-performance concrete, engineered cementitious composites, and shape memory alloys have demonstrated exceptional performance under cyclic loading and are increasingly seen as viable alternatives to traditional construction materials in earthquake-prone areas. Their integration can significantly reduce structural damage, enhance post-earthquake recovery, and extend the service life of infrastructure.

For engineering practice, the key takeaway is that composite materials must be incorporated within a performance-based design framework to fully leverage their mechanical and seismic benefits. Structural engineers should prioritize hybrid systems that combine traditional and advanced materials for optimal behavior under seismic loading. Additionally, widespread adoption will require standardized design codes, training for practitioners, and scalable manufacturing techniques to lower costs and increase market acceptance.

From a policy perspective, national and local regulatory bodies must invest in updating building codes to include composite material design guidelines, offer funding for pilot projects, and incentivize the use of sustainable and hazard-resilient materials in public infrastructure. Incorporating these advanced materials into federally funded retrofitting and new construction projects, especially in high-risk seismic zones like California, Oregon, and Alaska, would be a significant step forward in improving national resilience.

To bridge the gap between innovation and practice, future implementation in U.S. infrastructure should focus on field demonstrations, long-term monitoring, and interdisciplinary collaborations between academia, industry, and government agencies. Emphasis should also be placed on developing multi-functional composites that address not just earthquake resistance but also other hazards such as fire and flooding, ensuring holistic resilience in an era of compound climate threats. In conclusion, while challenges remain, the strategic application of high-performance composite materials holds great promise for revolutionizing earthquake-resistant design and ensuring safer, more sustainable, and resilient infrastructure across the United States.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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