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Advancing Seismic Resilience and Structural Performance of Reinforced Concrete Systems through Fibre-Reinforced Polymer Integration and Structural Health Assessment

Dr. Lucas André Moreau
Department of Civil and Environmental Engineering, Université de Sherbrooke, Canada

ABSTRACT: The accelerating deterioration of reinforced concrete infrastructure under increasing functional demands, environmental exposure, and seismic risk has intensified scholarly and professional interest in advanced materials and retrofit strategies capable of extending service life while enhancing structural resilience. Among these strategies, fibre-reinforced polymer systems have emerged as a transformative intervention, offering high strength-to-weight ratios, corrosion resistance, and adaptability to a wide range of structural deficiencies. This research article develops a comprehensive and critical examination of fibre-reinforced polymer applications within reinforced concrete buildings and infrastructure, with particular emphasis on seismic performance enhancement, structural auditing, damage detection, and performance-based rehabilitation. Grounded strictly in established scholarly literature, the study synthesizes theoretical foundations of structural health monitoring, non-destructive evaluation techniques, and damage-based retrofit philosophies to construct an integrated analytical framework for fibre-reinforced polymer-based interventions. The article elaborates extensively on the evolution of retrofit methodologies, contrasting traditional steel jacketing and conventional strengthening approaches with contemporary composite-based solutions. Special attention is devoted to the interaction between pre-damage states, material compatibility, confinement mechanics, and global seismic behavior, as discussed in the literature on substandard reinforced concrete members and non-ductile structures. Drawing upon recent academic discourse, including advanced discussions on fibre-reinforced polymer deployment in construction practice, the article interprets how composite systems influence load redistribution, energy dissipation, ductility enhancement, and failure mode transformation. Methodologically, the study adopts a qualitative, interpretive research design rooted in critical literature analysis, enabling an in-depth exploration of performance trends, limitations, and contextual dependencies without reliance on experimental datasets or numerical modeling. The results section articulates synthesized findings related to strength recovery, stiffness modification, and damage mitigation, while the discussion interrogates competing scholarly perspectives, unresolved challenges, and long-term durability considerations. Ultimately, the article argues that fibre-reinforced polymer systems, when embedded within rigorous structural assessment and damage-informed design frameworks, represent a pivotal advancement in sustainable seismic retrofit practice. The conclusions underscore the necessity of integrating material innovation with holistic evaluation methodologies to achieve resilient, economically viable, and performance-driven rehabilitation of aging concrete infrastructure (Bandela, 2025; Farrar et al., 2007).

Keywords: Fibre-reinforced polymer retrofit; seismic rehabilitation; reinforced concrete structures; structural health monitoring; non-destructive evaluation; damage-based design

INTRODUCTION

The global inventory of reinforced concrete structures constructed during the latter half of the twentieth century is increasingly characterized by aging materials, evolving loading demands, and exposure to environmental and seismic hazards that were not fully anticipated at the time of design. This condition has precipitated a critical reassessment of structural safety, serviceability, and resilience across both developed and developing regions, motivating extensive research into assessment methodologies and retrofit technologies capable of addressing systemic deficiencies (Mahadik et al., 2014). Reinforced concrete, once regarded as a durable and maintenance-light material, is now widely recognized as vulnerable to degradation mechanisms such as corrosion of reinforcement, fatigue, cracking, and cumulative damage from seismic events, necessitating proactive intervention strategies informed by rigorous structural auditing practices (Naik et al., 2017).

Within this evolving context, the conceptual foundations of structural health monitoring have gained prominence as a means of diagnosing damage states and informing decision-making regarding repair and strengthening. Structural health monitoring, as articulated in foundational literature, is not merely a collection of sensing technologies but a comprehensive paradigm integrating damage detection, localization, and prognosis within the lifecycle management of structures (Farrar et al., 2007). This paradigm shift has profound implications for retrofit design, as it enables engineers to tailor interventions to the specific performance deficits and damage patterns observed in existing buildings, rather than relying on prescriptive, one-size-fits-all solutions.

Parallel to advances in assessment methodologies, the development and deployment of fibre-reinforced polymer composites have redefined the landscape of structural rehabilitation. Fibre-reinforced polymers, encompassing systems based on carbon, glass, and aramid fibres embedded in polymeric matrices, offer mechanical and durability characteristics that contrast sharply with traditional strengthening materials. Their high tensile strength, low density, and resistance to corrosion render them particularly attractive for applications where added mass or intrusive construction must be minimized. Scholarly work has increasingly emphasized that the significance of fibre-reinforced polymer systems extends beyond their material properties, encompassing new design philosophies centered on confinement, ductility enhancement, and controlled failure mechanisms (Bandela, 2025).

The seismic vulnerability of existing reinforced concrete buildings represents one of the most critical drivers for fibre-reinforced polymer adoption. Many structures erected prior to the widespread incorporation of modern seismic design principles exhibit non-ductile detailing, inadequate confinement, and insufficient shear capacity, rendering them susceptible to brittle failure modes under earthquake loading. Studies examining repaired and retrofitted reinforced concrete columns have demonstrated that confinement-based strengthening can substantially alter seismic response characteristics, promoting more stable hysteretic behavior and delaying strength degradation (Youm et al., 2006). Fibre-reinforced polymer wraps, in particular, have been shown to provide effective external confinement, compensating for deficiencies in transverse reinforcement without the need for extensive demolition or section enlargement.

Despite these promising attributes, the scholarly discourse surrounding fibre-reinforced polymer retrofit is marked by ongoing debate regarding its effectiveness across varying damage states, structural typologies, and loading scenarios. Research on pre-damaged columns retrofitted with composite materials suggests that the initial condition of the structure plays a decisive role in determining post-retrofit performance, challenging assumptions that composite strengthening can uniformly restore or enhance capacity (Bedirhanoglu et al., 2019). This insight underscores the necessity of integrating damage-based assessment frameworks into retrofit design, aligning with broader movements toward performance-based engineering and resilience-oriented practice.

Another dimension of this discourse concerns the relationship between fibre-reinforced polymer systems and traditional retrofit techniques such as steel jacketing. While steel jacketing has a well-established track record in seismic rehabilitation, it introduces challenges related to corrosion, constructability, and increased mass, which can adversely affect seismic demand. Comparative analyses have highlighted that fibre-reinforced polymer solutions can achieve comparable or superior performance enhancements while mitigating these drawbacks, though questions remain regarding long-term durability and fire resistance (Hoshikuma & Unjoh, 1997). These comparative considerations are central to informed decision-making in retrofit projects, particularly in regions with constrained resources or complex architectural constraints.

Beyond reinforced concrete frames, the application of fibre-reinforced polymer systems to masonry and hybrid structures further illustrates the versatility of composite materials in seismic strengthening. Investigations into the in-plane strengthening of unreinforced masonry walls using fibre-based coatings and shotcrete systems have demonstrated significant gains in shear capacity and deformation tolerance, suggesting transferable principles applicable to reinforced concrete rehabilitation (Facconi et al., 2015; Lin et al., 2014). These studies contribute to a broader understanding of how fibre reinforcement interacts with brittle substrates to modify failure mechanisms and energy dissipation characteristics.

The present research article seeks to contribute to this multifaceted scholarly conversation by developing an extensive, integrative analysis of fibre-reinforced polymer-based retrofit strategies within the broader framework of structural assessment and seismic resilience. Rather than focusing narrowly on experimental outcomes or design equations, the study emphasizes theoretical elaboration, historical evolution, and critical interpretation of existing literature to illuminate underlying mechanisms, assumptions, and implications. In doing so, it addresses a persistent gap in the literature: the need for a holistic, conceptually grounded synthesis that connects material innovation with assessment methodologies, damage characterization, and performance objectives (Bandela, 2025).

This integrative perspective is particularly timely given the increasing emphasis on sustainability and lifecycle performance in the construction industry. Fibre-reinforced polymer systems, when judiciously applied, have the potential to extend the service life of existing structures, reduce demolition waste, and minimize the environmental footprint associated with new construction. However, realizing this potential requires a nuanced understanding of both the capabilities and limitations of composite materials, as well as their interaction with existing structural systems under complex loading conditions.

In framing the problem statement, this article posits that the effectiveness of fibre-reinforced polymer retrofit cannot be fully understood in isolation from the processes of structural auditing, damage detection, and performance evaluation that precede and follow intervention. Non-destructive evaluation techniques such as ultrasonic pulse velocity testing and rebound hammer assessments play a crucial role in characterizing material condition and informing retrofit design, yet their integration into composite-based rehabilitation strategies remains uneven across practice and research (Petro et al., 2011; Kazemi et al.). By situating fibre-reinforced polymer applications within this broader assessment context, the study advances a more comprehensive understanding of retrofit efficacy and reliability.

Accordingly, the objectives of this research are threefold. First, it aims to trace the theoretical and historical development of fibre-reinforced polymer systems in structural rehabilitation, highlighting key milestones and paradigm shifts. Second, it seeks to synthesize findings from diverse strands of literature on seismic performance, damage-based retrofit, and structural health monitoring to articulate common themes and points of contention. Third, it endeavors to critically assess the implications of these findings for future research and practice, identifying avenues for methodological refinement and interdisciplinary integration. Through this expansive and critical approach, the article aspires to serve as a foundational reference for researchers, practitioners, and policymakers engaged in the advancement of resilient, performance-driven construction systems (FEMA-547, 2006).

METHODOLOGY

The methodological approach adopted in this research is grounded in qualitative, interpretive analysis of peer-reviewed scholarly literature and authoritative technical guidelines related to structural assessment, seismic retrofit, and fibre-reinforced polymer applications. This approach is deliberately selected to align with the study’s objective of developing an extensive theoretical and critical synthesis rather than generating new experimental or numerical data. In the domain of civil engineering research, such literature-based methodologies are particularly valuable for elucidating conceptual linkages, contextual dependencies, and emergent trends that may not be readily apparent within isolated empirical studies (FIB, 2003).

At the core of the methodology lies a structured yet flexible process of literature engagement, encompassing thematic categorization, comparative interpretation, and critical reflection. The initial phase involves the identification of foundational works addressing structural health monitoring, non-destructive evaluation, and structural auditing, which collectively establish the diagnostic framework within which retrofit decisions are made (Farrar et al., 2007; Mahadik et al., 2014). These sources are examined not merely for their technical content but for their underlying assumptions regarding damage, safety, and performance, which inform subsequent stages of analysis.

The second phase of the methodology focuses on the examination of seismic retrofit strategies for reinforced concrete structures, with particular emphasis on the evolution from traditional techniques such as steel jacketing to composite-based interventions. Key studies on the seismic performance of repaired and retrofitted reinforced concrete columns, beam-column joints, and short columns are analyzed to extract insights into confinement mechanics, failure mode modification, and hysteretic behavior (Youm et al., 2006; Pohoryles et al., 2019). Within this phase, special attention is given to research addressing the influence of pre-damage on retrofit effectiveness, as this theme intersects directly with damage-based assessment paradigms (Bedirhanoglu et al., 2019).

The third methodological phase centers on fibre-reinforced polymer systems themselves, encompassing material properties, application techniques, and performance outcomes as reported in the literature. The analysis draws extensively on contemporary discussions of fibre-reinforced polymer integration in construction projects, which situate composite materials within broader trends of innovation, sustainability, and performance-based design (Bandela, 2025). Rather than treating these discussions as prescriptive guidance, the methodology interrogates their implications, limitations, and areas of uncertainty, thereby fostering a critical stance toward prevailing narratives.

Throughout the methodological process, comparative analysis serves as a key analytical tool. Studies addressing different structural typologies, loading conditions, and retrofit configurations are juxtaposed to identify convergent findings and divergent conclusions. For example, research on fibre-reinforced polymer strengthening of reinforced concrete elements is compared with studies on masonry wall strengthening to explore the transferability of confinement and reinforcement concepts across materials (Kalali & Kabir, 2012; Facconi et al., 2015). This comparative lens enables a more nuanced understanding of how fibre-based systems interact with diverse substrates and structural systems.

An important methodological consideration in this study is the deliberate exclusion of quantitative modeling, equations, and tabulated data. This exclusion is not a limitation but a strategic choice aligned with the research objective of conceptual elaboration. By relying exclusively on descriptive and interpretive text, the methodology emphasizes reasoning, theoretical coherence, and critical discourse over numerical precision, thereby complementing the extensive body of quantitative research already available in the field (Uang, 1991).

Nevertheless, the methodology acknowledges inherent limitations associated with literature-based research. The reliance on published studies introduces potential biases related to publication trends, regional research priorities, and methodological conventions. Furthermore, the interpretive nature of the analysis means that conclusions are contingent upon the quality and scope of existing literature, rather than being empirically validated within the present study. These limitations are explicitly recognized and addressed through transparent reasoning and cautious extrapolation, consistent with best practices in scholarly synthesis (FEMA-

547, 2006).

In sum, the methodology employed in this research is designed to facilitate an in-depth, critical exploration of fibre-reinforced polymer-based seismic retrofit within the broader ecosystem of structural assessment and resilience engineering. By integrating diverse strands of literature through systematic interpretation and comparison, the study seeks to generate insights that are both theoretically robust and practically relevant, laying the groundwork for future empirical and interdisciplinary investigations (Bandela, 2025).

RESULTS

The interpretive synthesis of the reviewed literature yields a set of interrelated findings that collectively illuminate how fibre-reinforced polymer systems function as a transformative mechanism in the seismic upgrading and long-term performance enhancement of reinforced concrete structures. These results do not emerge from experimental replication within this study, but rather from the systematic interpretation of converging scholarly evidence across assessment methodologies, retrofit strategies, and material performance discussions, as consistently reported in prior research (Farrar et al., 2007; Bandela, 2025).

A central result evident across the literature is that fibre-reinforced polymer retrofitting fundamentally alters the damage progression trajectory of reinforced concrete members. Structural audit studies emphasize that many existing buildings exhibit latent deficiencies such as insufficient transverse reinforcement, poor detailing, and material degradation, which predispose them to brittle failure under seismic loading (Mahadik et al., 2014; Naik et al., 2017). When fibre-reinforced polymer confinement is applied to such members, the dominant failure mode shifts from sudden shear or compression failure toward more ductile, deformation-controlled behavior. This transition is repeatedly identified as a critical indicator of seismic performance improvement in retrofitted columns and beam-column joints (Youm et al., 2006; Pohoryles et al., 2019).

Another prominent result concerns the interaction between pre-existing damage and retrofit effectiveness. Research examining pre-damaged reinforced concrete columns demonstrates that fibre-reinforced polymer wraps do not merely restore original capacity, but instead establish a new equilibrium of stiffness, strength, and ductility that depends strongly on the initial damage state (Bedirhanoglu et al., 2019). Columns with moderate pre-damage show substantial gains in energy dissipation and deformation capacity after retrofitting, whereas severely damaged members exhibit more limited improvements. This finding underscores the necessity of integrating detailed damage assessment, often informed by non-destructive evaluation techniques, into retrofit decision-making processes (Petro et al., 2011).

The literature further reveals that fibre-reinforced polymer systems consistently enhance confinement efficiency compared to traditional steel jacketing, particularly in terms of uniform stress distribution and corrosion resistance. While steel jacketing has historically been effective in increasing axial and shear capacity, it introduces additional mass and long-term durability concerns that may exacerbate seismic demand (Hoshikuma & Unjoh, 1997). Fibre-reinforced polymer confinement, by contrast, achieves comparable or superior improvements in load-bearing behavior without significantly altering global mass or stiffness characteristics, a result emphasized in contemporary construction innovation studies (Bandela, 2025).

Findings related to seismic retrofit philosophy indicate a broader shift toward damage-based and performance-oriented approaches. Traditional prescriptive retrofit methods often target strength enhancement alone, whereas fibre-reinforced polymer interventions are frequently designed to optimize ductility, energy dissipation, and post-elastic behavior. This shift aligns with damage-based seismic retrofitting frameworks that prioritize controlled damage mechanisms and predictable performance under extreme loading (Vui Van Cao et al., 2020). The results suggest that fibre-reinforced polymer systems are particularly well suited to such frameworks because their effectiveness is closely tied to confinement mechanics rather than reliance on internal reinforcement continuity.

The reviewed literature also highlights consistent improvements in structural reliability assessment when fibre-reinforced polymer retrofit is combined with structural health monitoring concepts. Structural health monitoring research emphasizes the importance of baseline condition assessment and post-intervention performance tracking to ensure long-term safety (Farrar et al., 2007). When composite retrofits are implemented following comprehensive audits and non-destructive testing, the resulting systems demonstrate more predictable performance and reduced uncertainty in capacity estimation, according to synthesized interpretations of audit-based studies (Kazemi et al.).

Beyond reinforced concrete frames, results from masonry strengthening studies reveal analogous performance enhancements attributable to fibre-based reinforcement concepts. Research on unreinforced masonry walls strengthened with fibre-reinforced mortars or polymer systems reports substantial gains in shear resistance and deformation capacity, reinforcing the broader applicability of fibre confinement and crack-bridging mechanisms (Facconi et al., 2015; Lin et al., 2014). These findings support the interpretation that fibre-reinforced polymer systems function as a cross-material retrofit strategy grounded in fundamental mechanics rather than material-specific behavior alone.

Finally, a recurring result across multiple sources is the recognition of unresolved challenges related to durability, fire resistance, and long-term bond behavior between fibre-reinforced polymer composites and concrete substrates. While short- and medium-term performance gains are well documented, scholars caution that environmental exposure, ultraviolet radiation, and sustained loading may influence composite effectiveness over extended service periods (FIB, 2003). These concerns do not negate the benefits observed but rather contextualize them within a broader lifecycle perspective increasingly emphasized in modern construction discourse (Bandela, 2025).

DISCUSSION

The synthesized results invite a deeper theoretical and critical discussion of fibre-reinforced polymer integration within reinforced concrete systems, particularly when examined through the lenses of seismic resilience, structural assessment, and evolving engineering philosophy. At its core, the discussion revolves around a fundamental shift in how structural safety and performance are conceptualized, moving away from purely strength-based criteria toward holistic, damage-tolerant frameworks that emphasize adaptability and resilience (FEMA-547, 2006).

One of the most significant theoretical implications of fibre-reinforced polymer retrofit lies in its redefinition of confinement mechanics. Classical reinforced concrete theory treats confinement as a secondary effect provided by transverse steel reinforcement, primarily intended to delay buckling and enhance compressive strength. Fibre-reinforced polymer systems, however, externalize confinement, creating a continuous restraint that fundamentally modifies stress-strain relationships within the concrete core. Scholars argue that this external confinement introduces a more uniform triaxial stress state, which explains the observed improvements in ductility and energy dissipation (Youm et al., 2006). This theoretical reinterpretation challenges conventional design assumptions and necessitates revised analytical frameworks capable of capturing composite-concrete interaction without relying solely on empirical calibration.

The discussion also engages with the longstanding debate between traditional steel-based retrofit methods and composite alternatives. Steel jacketing has been historically favored for its familiarity and predictable behavior, yet its limitations are increasingly scrutinized in light of sustainability, constructability, and durability concerns (Hoshikuma & Unjoh, 1997). Fibre-reinforced polymer systems, as emphasized in contemporary construction literature, represent not merely a material substitution but a paradigm shift toward lightweight, minimally invasive interventions that align with modern performance objectives (Bandela, 2025). Critics, however, caution that the long-term behavior of polymer matrices under environmental exposure remains less well understood than that of steel, highlighting an area where further empirical research is essential.

Another critical dimension of the discussion concerns damage-based seismic retrofitting. Research consistently demonstrates that the effectiveness of fibre-reinforced polymer systems is contingent upon the initial damage state of the structure, reinforcing arguments for assessment-driven design (Bedirhanoglu et al., 2019). From a theoretical standpoint, this finding aligns with damage mechanics principles, which posit that material history influences future response. The implication is that retrofit strategies cannot be decoupled from diagnostic processes; instead, they must be conceived as adaptive interventions informed by detailed understanding of existing damage patterns (Petro et al., 2011).

Structural health monitoring literature further enriches this discussion by framing fibre-reinforced polymer retrofit as part of a continuous lifecycle management strategy rather than a discrete corrective action. Structural health monitoring emphasizes feedback loops between assessment, intervention, and monitoring, enabling engineers to refine performance expectations over time (Farrar et al., 2007). Within this framework, fibre-reinforced polymer systems are particularly advantageous because their installation can be precisely targeted and subsequently evaluated through non-destructive techniques, enhancing confidence in long-term performance predictions.

The discussion must also address the broader implications for seismic design philosophy. Damage-based and performance-oriented approaches advocate for controlled damage and rapid post-event functionality, especially in critical infrastructure. Fibre-reinforced polymer retrofits align well with these objectives by promoting ductile behavior and reducing the likelihood of catastrophic collapse, even when some damage occurs (Vui Van Cao et al., 2020). However, skeptics argue that overreliance on external confinement may mask underlying deficiencies in load paths or global system behavior, underscoring the need for holistic structural evaluation rather than component-level optimization alone (Uang, 1991).

Interdisciplinary considerations further complicate the discussion. Sustainability discourse increasingly influences material selection and retrofit strategies, with fibre-reinforced polymer systems often cited for their potential to reduce demolition waste and extend service life (Bandela, 2025). Yet the environmental impact of polymer production and end-of-life disposal remains a topic of debate, suggesting that sustainability assessments must consider full lifecycle impacts rather than focusing solely on operational performance.

Limitations identified in the literature warrant explicit discussion. Variability in installation quality, sensitivity to surface preparation, and dependence on bond integrity introduce uncertainties that challenge standardized design approaches (FIB, 2003). Moreover, fire resistance and high-temperature behavior of polymer matrices pose concerns in certain occupancy types, necessitating complementary protective measures or hybrid retrofit solutions. These limitations highlight that fibre-reinforced polymer systems are not universal solutions but context-dependent tools whose effectiveness hinges on informed application and rigorous quality control.

Looking forward, the discussion points toward several avenues for future research. Greater integration between structural health monitoring technologies and composite retrofit design could enable real-time performance tracking and adaptive maintenance strategies. Long-term field studies examining environmental durability and post-seismic performance would address persistent uncertainties and refine design guidelines. Additionally, comparative research exploring hybrid systems that combine fibre-reinforced polymer confinement with traditional strengthening methods may yield optimized solutions balancing reliability, durability, and sustainability (Bandela, 2025).

CONCLUSION

This research article has developed an extensive, theoretically grounded examination of fibre-reinforced polymer integration within the seismic rehabilitation and performance enhancement of reinforced concrete structures. Through critical synthesis of established literature on structural health monitoring, non-destructive evaluation, and retrofit methodologies, the study demonstrates that fibre-reinforced polymer systems represent a significant advancement in contemporary construction practice when applied within assessment-driven and damage-based frameworks. The findings underscore that the true value of fibre-reinforced polymer retrofitting lies not solely in material strength augmentation but in its capacity to reshape failure mechanisms, enhance ductility, and support resilient performance objectives. At the same time, the analysis acknowledges persistent challenges related to durability, environmental exposure, and lifecycle assessment, emphasizing the need for continued research and interdisciplinary integration. Ultimately, fibre-reinforced polymer systems, as articulated in recent construction innovation discourse, emerge as a critical component of future-oriented seismic resilience strategies grounded in rigorous assessment and holistic engineering judgment (Bandela, 2025).

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