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Impact Behavior of FRP-Strengthened Reinforced Concrete Members: A Systematic Review of Experimental and Numerical Advances (2016–2025)

Abdul Khyum

School of Civil Engineering, Southwest Jiaotong University, Chengdu 610031, China

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***Corresponding Author:** Abdul Khyum

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Abstract **Review Article**

Fiber-reinforced polymer (FRP) strengthening has become a widely adopted technique for retrofitting reinforced concrete (RC) structures, yet current design codes do not address impact loading despite the documented vulnerability of infrastructure to vehicle collisions, crane strikes, and debris impacts. This paper presents a systematic review of experimental, numerical, and analytical developments in the impact behavior of FRP-strengthened RC beams, columns, and slabs published between 2016 and 2025. The experimental evidence establishes that FRP strengthening improves impact resistance by 20 to 60 percent and reduces peak displacement by 25 to 40 percent, with full wrapping configurations consistently outperforming partial schemes and carbon FRP providing superior stiffness enhancement while glass and basalt FRP offer greater energy absorption capacity. Validated finite element simulations using ABAQUS/Explicit and LS-DYNA with concrete damaged plasticity and Hashin damage criteria reproduce experimental trends with sufficient accuracy to support parametric exploration beyond laboratory constraints. A critical mechanistic finding is that FRP strengthening shifts the failure hierarchy from brittle shear collapse toward ductile flexural responses, though debonding at the FRP-concrete interface remains the dominant performance limit. Parametric synthesis identifies two to three FRP layers and axial load ratios of 0.1 to 0.2 as optimal for impact applications. The absence of impact provisions in ACI PRC-440.2-23 and fib Bulletin 90 constitutes the most consequential gap between research knowledge and engineering practice, with repeated impact characterization, dynamic bond-slip quantification, and full-scale validation identified as priority research needs for future code development.

Keywords: FRP strengthening, impact loading, reinforced concrete, finite element simulation, debonding.

1. Introduction

Reinforced concrete structures serving as bridge piers, parking garage columns, and industrial building frames are routinely exposed to impact events that fall outside the scope of conventional design. Vehicle collisions with bridge substructures alone account for approximately 15,000 recorded incidents per year in the United States, imposing substantial repair costs and service disruptions across the national highway network (Agrawal et al., 2018). Beyond vehicular strikes, crane drops in construction zones, falling debris during adjacent demolition, and freight-handling accidents in warehouse facilities subject structural members to transient forces that develop over milliseconds rather than the quasi-static loading durations assumed in design codes. Unlike seismic or wind hazards, for which mature design provisions exist, impact loading remains largely unaddressed in current structural engineering practice.

Fiber-reinforced polymer (FRP) composites have gained considerable traction as a retrofitting solution for reinforced concrete (RC) members, offering high strength-to-weight ratios, corrosion immunity, and rapid field installation that minimizes operational downtime (Hollaway and Teng, 2008). Carbon FRP (CFRP) delivers high stiffness, glass FRP (GFRP) provides cost-effective ductility, and basalt FRP (BFRP) has emerged as an environmentally sustainable alternative with mechanical properties comparable to GFRP (Fiore et al., 2015). Over the past two decades, externally bonded and near-surface mounted FRP systems have been applied to thousands of structures worldwide under static design frameworks prescribed by ACI PRC-440.2-23 and fib Bulletin 90. Yet neither document addresses impact loading, creating a disconnect between practice and the growing body of evidence that impact scenarios demand distinct analytical treatment.

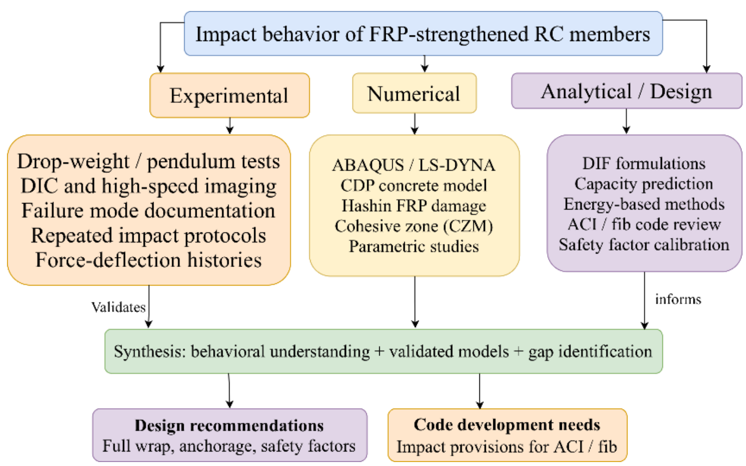

Figure 1 Conceptual framework of the review, illustrating the convergence of three research perspectives: experimental investigations (drop-weight tests, DIC measurement, failure documentation), numerical simulations (ABAQUS/Explicit, LS-DYNA, constitutive model calibration), and analytical/design considerations (DIF formulations, code provisions, capacity prediction).

The distinction is rooted in material physics. Under quasi-static conditions, concrete and steel respond at strain rates near 10^{-5} s^{-1}, whereas low-velocity impact induces rates in the range of 10^0 to 10^2 s^{-1} (Bischoff and Perry, 1991). At these elevated rates, concrete compressive strength increases by factors of 1.2 to 2.0, and tensile strength by 1.5 to 6.0, as captured through dynamic increase factor (DIF) formulations developed from split Hopkinson pressure bar testing (Malvar and Crawford, 1998). Steel reinforcement exhibits more modest rate sensitivity, with DIFs between 1.1 and 1.3 (Malvar, 1998). FRP composites, by contrast, show limited rate dependence, with CFRP tensile strength increasing by only 5 to 20 percent across impact-relevant strain rates (Ou et al., 2016). This asymmetry in rate sensitivity alters the internal force distribution between concrete substrate, steel reinforcement, and external FRP, shifting failure mechanisms in ways that static-based design cannot predict. Inertial effects further complicate the response by redistributing shear forces along member lengths and activating higher vibration modes that static analysis does not consider.

Pham and Hao (2016) published the first comprehensive synthesis of FRP-strengthened concrete behavior under impact, consolidating experimental observations across beams, slabs, columns, and masonry walls. That review, now cited over 300 times, established that FRP strengthening consistently enhances impact resistance but identified critical uncertainties regarding failure modes, FRP rupture strains under dynamic conditions, and bond mechanisms at the FRP-concrete interface. Subsequent reviews have addressed adjacent topics: Siddika et al. (2020) examined FRP strengthening performance broadly across loading types, while Askar et al. (2022) focused on flexural and shear enhancement under static conditions. However, the research landscape has evolved substantially since 2016. High-speed digital image correlation now enables full-field strain mapping during millisecond-duration events. Finite element platforms, particularly ABAQUS/Explicit and LS-DYNA, have matured to achieve prediction errors below 10 percent when calibrated with appropriate constitutive models. The volume of published work has expanded correspondingly, yet no review has synthesized these developments into a unified assessment.

Several persistent gaps motivate the present study. First, repeated low-velocity impact, the scenario most relevant to parking structures and bridge piers along freight corridors, has been examined in fewer than fifteen dedicated experimental programs. Second, the dynamic bond-slip relationship between FRP and concrete, arguably the most failure-critical interface, lacks reliable characterization at elevated strain rates. Third, numerical modeling approaches vary widely in material model selection, mesh strategy, and contact definition, yet systematic comparison of their relative accuracy remains absent. Fourth, and most consequentially, current design codes offer no provisions for impact loading of FRP-strengthened members, leaving practitioners to extrapolate from static guidelines or rely on project-specific numerical analysis. The result is either conservative over-design that wastes resources, or unknowing under-design that accepts unquantified risk.

This review addresses these gaps through a systematic synthesis of experimental, numerical, and analytical developments reported between 2016 and 2025. The methodology follows a systematic narrative framework appropriate for fields encompassing heterogeneous research designs (Snyder, 2019), with documentation guided by the PRISMA 2020 reporting standards (Page et al., 2021). Literature was retrieved from Web of Science, Scopus, and Google Scholar using Boolean search strings combining FRP material terms, structural application terms, and impact loading descriptors, restricted to English-language peer-reviewed publications. Following duplicate removal and screening, the synthesis draws on studies spanning experimental drop-weight investigations, validated finite element simulations, and analytical modeling efforts.

The specific objectives are to: (1) synthesize experimental findings on FRP-strengthened beams, columns, and slabs under single and repeated impact loading; (2) evaluate numerical modeling approaches with emphasis on material model calibration and validation accuracy; (3) analyze damage mechanisms and failure mode transitions unique to dynamic conditions; (4) assess parametric effects of FRP configuration, impact velocity, and axial load ratio; (5) critically evaluate the absence of impact provisions in current design guidelines; and (6) identify prioritized research directions essential for future code development.

The remainder of this paper is organized as follows. Section 2 reviews FRP materials and strengthening configurations relevant to impact applications. Section 3 synthesizes experimental studies and damage mechanisms across member types. Section 4 evaluates numerical modeling approaches and parametric analysis findings. Section 5 discusses design considerations and persistent research gaps. Section 6 presents conclusions.

2. FRP Materials and Strengthening Configurations

2.1 Types of FRP Materials

The selection of fiber type governs much of the structural response under impact, since each fiber system brings a distinct combination of stiffness, strain capacity, and rate sensitivity. Carbon fiber-reinforced polymer (CFRP) dominates the impact literature, accounting for the majority of published studies, because its high elastic modulus produces immediate stiffness gains that limit transient deflections. At typical laminate fiber volumes of 40 to 60 percent, CFRP composites achieve tensile strengths of 1020 to 2410 MPa and elastic moduli of 100 to 270 GPa, though their ultimate strain remains limited to 0.5 to 1.5 percent (ACI Committee 440, 2023). Glass fiber-reinforced polymer (GFRP) offers greater deformation capacity, with ultimate strains reaching 1.5 to 3.0 percent at composite tensile strengths of 520 to 1400 MPa, making it particularly suitable for applications where energy absorption through controlled deformation is prioritized over peak load resistance. Basalt fiber-reinforced polymer (BFRP) has attracted growing attention as an environmentally sustainable alternative, produced from volcanic rock without synthetic chemical additives, with composite-level tensile strengths of 600 to 1500 MPa and moduli of 50 to 90 GPa that position it between GFRP and CFRP in stiffness (fib, 2019). Aramid fiber-reinforced polymer (AFRP) provides exceptional toughness and energy dissipation, which are advantageous under dynamic loading, although susceptibility to moisture degradation and ultraviolet exposure limits its long-term durability in exposed installations. Table 1 compares the composite-level mechanical properties of these systems alongside conventional steel reinforcement, with values drawn from laminate test data rather than bare-fiber specifications to ensure direct relevance to design practice.

It is worth noting that the distinction between fiber-level and composite-level properties has been a persistent source of confusion in the impact literature. Published property tables frequently report fiber tensile strengths exceeding 3500 MPa for carbon and 4500 MPa for basalt, values that are unattainable in finished laminates where the polymer matrix and fiber-volume fraction reduce the effective properties by 40 to 60 percent. The values presented in Table 1 correspond to typical wet-layup and precured laminate systems as documented in ACI PRC-440.2-23 and fib Bulletin 90, and should be used in preference to fiber-level data when assessing strengthening performance.

Table 1 Typical mechanical properties of FRP composite laminates and steel reinforcement

Property	CFRP	GFRP	BFRP	AFRP	Steel
Tensile strength (MPa)	1020–2410	520–1400	600–1500	700–1720	400–600
Elastic modulus (GPa)	100–270	20–40	50–90	40–85	200
Ultimate strain (%)	0.5–1.5	1.5–3.0	1.5–3.0	2.0–3.0	15–25
Density (g/cm³)	1.5–1.6	2.1–2.5	2.6–2.8	1.4–1.5	7.85

Note: Values represent composite laminate properties at fiber volumes of 40–60%. Sources: ACI PRC-440.2-23 (ACI Committee 440, 2023); fib Bulletin 90 (fib, 2019) for BFRP.

2.2 Strengthening Configurations

The geometric arrangement of external FRP reinforcement determines how forces are transferred between the composite and the concrete substrate during the brief, high-intensity loading that characterizes impact events. Full wrapping, in which the FRP sheet completely encloses the member cross-section, provides maximum lateral confinement and is the preferred configuration for columns subjected to lateral impact from vehicle collisions or pendulum tests (Hollaway and Teng, 2008). By preventing concrete spalling and redistributing hoop stresses uniformly, full wraps sustain confinement throughout the millisecond-duration contact phase when inertial effects generate localized stress concentrations far exceeding those observed under static loading. U-wrapping, which encases three sides of a beam while leaving the top compression face exposed, serves as a practical alternative when monolithic slab connections restrict full access. This configuration enhances shear resistance effectively but delivers lower confinement than full wraps, particularly at high impact energies where anchorage at the open edges becomes critical. Strip bonding allows targeted strengthening of specific flexural or shear zones with reduced material consumption, though careful attention to strip spacing and termination points is essential, since stress concentrations at strip ends can initiate premature debonding under transient dynamic loads.

Table 2 Comparison of FRP strengthening configurations for impact applications

Configuration	Advantages	Limitations	Best application
Full wrap	Maximum confinement; prevents spalling; highest impact resistance	Higher material cost; requires full member access	Columns under lateral impact
U-wrap	Good shear enhancement; practical for beam applications	Lower confinement than full wrap; open-edge anchorage required	Beams in shear-critical regions
Strip bonding	Material-efficient; targeted strengthening	Limited confinement; debonding risk at strip ends	Flexural strengthening of beams and slabs
NSM system	Superior bond; protected from surface damage	Requires groove cutting; limited to adequate concrete cover	Environments with durability concerns
EBR + mechanical anchors	Enhanced debonding resistance; improved ductility	Complex installation; increased design effort	High-energy impact scenarios

Near-surface mounted (NSM) systems follow a fundamentally different load-transfer mechanism. Rather than relying on external adhesive bonds, NSM bars or strips are embedded within grooves cut into the concrete cover, creating mechanical interlock that provides superior bond performance and protects the reinforcement from environmental exposure and surface damage (De Lorenzis and Teng, 2007). For impact applications, this embedded configuration offers the additional advantage of shielding the FRP from direct contact with the impactor, reducing the risk of localized fiber rupture at the point of strike.

Fiber orientation further influences the structural response. Longitudinal fibers aligned at 0° to the member axis primarily enhance flexural capacity, while transverse fibers at 90° improve shear resistance and lateral confinement. Inclined orientations at ±45° provide balanced performance under the combined flexural-shear demands that commonly arise during impact events, where load redistribution through inertial effects generates simultaneous bending and shearing across multiple cross-sections.

2.3 Bonding and Anchorage Systems

The performance of any externally bonded FRP system under impact loading is ultimately governed by the integrity of the bond interface between the composite and the concrete substrate. Under quasi-static conditions, adhesive bonds can redistribute stress gradually through shear-lag mechanisms, allowing the FRP to develop a substantial fraction of its tensile capacity before debonding initiates. Impact loading eliminates this gradual redistribution. Stress concentrations develop rapidly at plate termination points and at locations where flexural or shear cracks widen suddenly, and the available time for stress transfer is measured in milliseconds rather than seconds. Chen and Teng (2001) established the foundational anchorage strength models that quantified the relationship between bond length, concrete tensile strength, and maximum transferable force for externally bonded plates, providing the analytical basis that subsequent dynamic studies have extended.

Mechanical anchorage devices supplement adhesive bonding by providing alternative load paths that remain active even after partial debonding has occurred. Kalfat et al. (2013) classified the principal anchorage techniques into six categories, including FRP U-wraps, FRP spike anchors, metallic anchor plates, patch anchors, and substrate strengthening through chases, and assessed their relative effectiveness for different strengthening applications. A subsequent efficiency framework by Kalfat et al. (2018) quantified the performance of each category and identified spike anchors and patch anchors as the most effective systems for flexural applications, with bidirectional patch anchors achieving the highest normalized efficiency among all tested configurations. For impact-prone structures, hybrid systems that combine externally bonded reinforcement with mechanical anchorage are increasingly recommended, since the redundant load path ensures that sudden stress redistributions during the contact phase do not trigger progressive collapse of the bond interface.

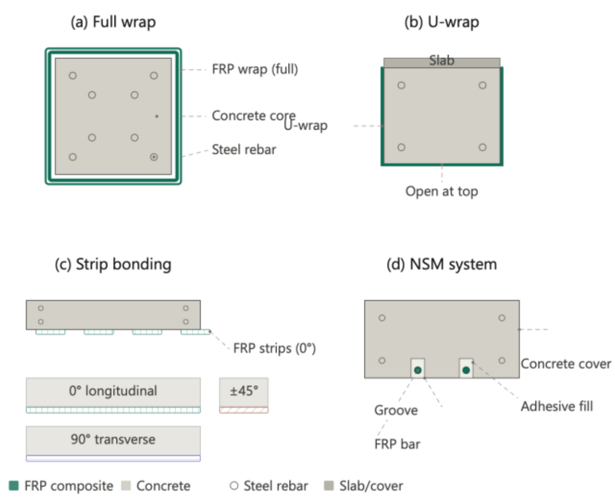

Figure 2 Schematic diagrams of FRP strengthening configurations for reinforced concrete members: (a) full wrap for columns, (b) U-wrap for beams, (c) strip bonding with fiber orientations (0°, 90°, ±45°), and (d) near-surface mounted (NSM) bar installation showing groove geometry and adhesive fill.

3. Experimental Studies on Impact Behavior and Damage Mechanisms

3.1 Testing Methods and Instrumentation

Drop-weight testing remains the predominant experimental technique for investigating FRP-strengthened RC members under impact. In a typical configuration, a guided steel mass falls from a controlled height onto a specimen supported on a rigid frame, producing impact velocities between 1 and 10 m/s and impact energies that can be varied precisely through adjustment of drop height and impactor mass. Instrumentation has advanced considerably since early studies relied solely on load cells and displacement transducers. Contemporary programs routinely employ high-speed cameras operating at frame rates of 10,000 to 100,000 per second, paired with digital image correlation (DIC) systems capable of resolving full-field strain distributions across the specimen surface during events lasting only a few milliseconds. Despite these advances, no universally accepted protocol governs specimen geometry, support conditions, or impact parameters, which complicates direct comparison across studies and underscores the need for standardization as the field matures.

3.2 FRP-Strengthened RC Beams

Beams constitute the most extensively studied member type, and the accumulated evidence establishes several consistent trends. Pham and Hao (2016b) tested seven beams strengthened with longitudinal CFRP strips and U-wraps under drop-weight impact, demonstrating that combining flexural and shear FRP reinforcement is essential because strengthening only for flexure shifts the failure mode toward brittle shear, a transition that is particularly dangerous under dynamic loading. That study also introduced a modified beam section with a curved soffit designed to reduce stress concentrations at the FRP U-wrap corners, a technique that significantly improved FRP utilization compared to conventional sharp-cornered sections. Kishi et al. (2020) extended these findings through a systematic program on beams strengthened in flexure with bonded CFRP and AFRP sheets, confirming that bond quality and end anchorage are the primary factors governing whether the predicted dynamic capacity is realized in practice.

Table 3 Summary of verified experimental studies on FRP-strengthened RC beams under impact (2016–2025)

Reference	FRP type	Key parameters	Principal findings
Pham and Hao (2016b)	CFRP	Flexure + shear FRP; curved soffit	Combined strengthening essential; curved section improves FRP utilization
Kishi et al. (2020)	CFRP/AFRP	Bonded sheets; low-velocity	Bond quality and end anchorage govern dynamic capacity
Saleh et al. (2020)	GFRP bars	Overload damage mechanisms	Lower residual deflection; higher stability than steel RC
Huang et al. (2021)	BFRP bars	Static + impact comparison	BFRP comparable to GFRP; improved durability
Zhang et al. (2023)	CFRP	Multi-impact; pre-damaged beams	Stiffness retention over repeated cycles; anchored CFRP effective
Çalışkan (2025)	CFRP strips	Shear-deficient beams	Failure mode shift from diagonal shear to flexural

The choice of fiber type influences the balance between stiffness gain and energy absorption. Huang et al. (2021) conducted combined static and impact tests on concrete beams reinforced with basalt FRP bars, reporting performance broadly comparable to GFRP systems while offering improved alkaline resistance. At the opposite end of the stiffness spectrum, Saleh et al. (2020) investigated overload damage mechanisms in GFRP-reinforced beams under high-intensity low-velocity impact, finding that GFRP beams exhibited lower residual deflections and higher overall stability than steel-reinforced counterparts despite larger peak displacements, a result attributable to the elastic recovery capacity of the FRP bars. More recently, Çalışkan (2025) examined shear-deficient beams strengthened with externally bonded CFRP strips, demonstrating through both experiment and finite element analysis that CFRP strip bonding effectively shifts the failure mode from catastrophic diagonal shear to a more controlled flexural response, even when the original beam lacks any internal shear reinforcement.

Repeated impact loading on beams has received limited but growing attention. Zhang et al. (2023) tested pre-damaged RC beams strengthened with CFRP under multiple successive impacts, quantifying the progressive stiffness degradation cycle by cycle and demonstrating that CFRP strengthening maintains structural integrity over a significantly greater number of impact cycles than unstrengthened controls. Their results showed that properly anchored CFRP systems retain effective load transfer even after visible matrix cracking develops in the composite, because the continuous fiber architecture bridges localized damage zones and redistributes stress to intact regions.

3.3 FRP-Strengthened RC Columns Under Lateral Impact

Column studies have gained momentum since 2020, driven by the practical relevance of vehicle collision scenarios and the recognition that columns present fundamentally different mechanics than beams due to the presence of sustained axial compression. Xu et al. (2020) conducted the first detailed experimental program on cantilever circular RC columns wrapped with CFRP and subjected to lateral low-velocity impact, establishing that CFRP confinement prevents concrete spalling and significantly reduces lateral displacement, with the strengthening mechanism activating primarily in the second stage of the impact response after the initial peak contact force has subsided. Swesi et al. (2022) investigated square RC columns under combined axial and transverse loading, reporting that CFRP wrapping with layers applied in both longitudinal and transverse directions reduces lateral displacement by 25 to 40 percent, though the benefit is sensitive to the axial load level and the wrapping configuration.

The interaction between axial load and impact response has emerged as a central research question. AL-Bukhaiti et al. (2023) performed asymmetrical-span impact tests on both circular and square RC columns with and without CFRP wrapping while varying the axial compression ratio, demonstrating that moderate axial loads enhance impact resistance by activating confinement mechanisms, but excessive compression precipitates brittle failure by limiting the column's capacity to accommodate lateral deformation. Sun et al. (2023) and Sun et al. (2024) systematically mapped the failure mode transition from flexural to shear as impact mass and velocity increase, providing the parametric boundaries that define when CFRP shear strengthening becomes critical for preventing catastrophic collapse under high-energy collisions.

Table 4 Summary of verified experimental studies on FRP-strengthened RC columns under lateral impact (2020–2025)

Reference	Column type	Key parameters	Principal findings
Xu et al. (2020)	Circular, CFRP wrap	Cantilever; low-velocity	CFRP prevents spalling; activates in Stage-II response
Swesi et al. (2022)	Square, CFRP wrap	Axial load + impact; 20 specimens	25–40% displacement reduction; sensitive to wrap configuration
AL-Bukhaiti et al. (2023)	Circular + square, CFRP	Axial ratio variation; asymmetrical span	Moderate axial load beneficial; excessive compression detrimental
Sun et al. (2023)	RC columns	Axial + lateral; failure mode mapping	Failure mode transition boundaries identified
Sun et al. (2024)	RC columns	Impact mass and velocity variation	High velocity triggers shear-dominated failure

3.4 FRP-Strengthened RC Slabs and Repeated Impact

Impact studies on slabs remain comparatively limited, though the available data reveal distinct behavioral patterns that differ from beam and column responses. Chen et al. (2020) investigated two-way RC slabs strengthened with basalt FRP strips under drop-weight impact, testing various strengthening layouts and anchoring schemes across eleven specimens. Their results indicated that bidirectional strip configurations outperform unidirectional arrangements because the two-way load distribution inherent to slab behavior requires reinforcement in both principal directions to prevent localized punching failure.

Repeated impact loading on slabs has produced some of the field's most informative datasets. Batarlar et al. (2021) tested five 1.5 × 1.5 m RC slabs strengthened with carbon textile-reinforced concrete (TRC) at three different textile reinforcement ratios under successive drop-weight impacts at TU Dresden. The strengthened slabs sustained four to five impact cycles before perforation, compared to two cycles for unstrengthened controls, with the improvement attributed to post-cracking load redistribution rather than raw strength gain. This distinction is significant because it suggests that for repeated impact scenarios, the continuity and crack-bridging capacity of the strengthening system matter more than its peak tensile strength. Daneshvar et al. (2021) extended this understanding to corroded RC slabs under multi-impact conditions, demonstrating that FRP strengthening can partially compensate for the capacity loss caused by reinforcement corrosion, a finding with direct practical implications for aging infrastructure subjected to both environmental degradation and accidental loading.

3.5 Damage Mechanisms and Failure Mode Transitions

Table 5 Summary of observed failure mode transitions in FRP-strengthened RC members

Member type	Without FRP	With FRP	Dominant transition
Beams (low energy)	Flexural	Flexural with debonding	Flexure → Flexure + debonding

Member type	**Without FRP**	**With FRP**	**Dominant transition**
Beams (high energy)	Shear	Flexural or mixed	Shear → Flexure
Columns	Shear/flexure	Flexure dominant	Shear → Flexure
Slabs	Punching shear	Flexural punching	Brittle → Ductile

Note: Low energy defined as <500 J; high energy as >1500 J. Transitions based on experimental observations from the studies reviewed in Sections 3.2–3.4.

Across all member types, a consistent pattern emerges from the experimental evidence. FRP strengthening fundamentally alters the failure hierarchy of RC members under impact. Unstrengthened beams subjected to increasing impact energy transition from flexural failure at low energies to brittle shear failure at high energies, a particularly dangerous shift because shear failure occurs without warning and offers minimal energy dissipation. FRP-strengthened beams, by contrast, maintain flexural or mixed flexural-debonding responses across a broader energy range, with the dominant failure mechanism shifting to debonding at the FRP-concrete interface rather than sudden shear collapse. In columns, the transition follows a similar logic: unstrengthened columns develop combined shear-flexure damage, while CFRP-wrapped columns exhibit predominantly flexural responses with controlled concrete damage confined within the FRP shell.

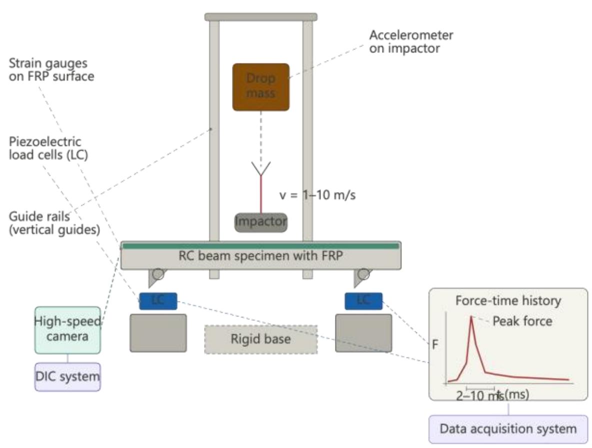

Figure 3 Typical drop-weight impact test setup showing instrumentation arrangement: load cells beneath supports, accelerometers on impactor, high-speed camera with DIC system, and strain gauges on reinforcement and FRP surfaces.

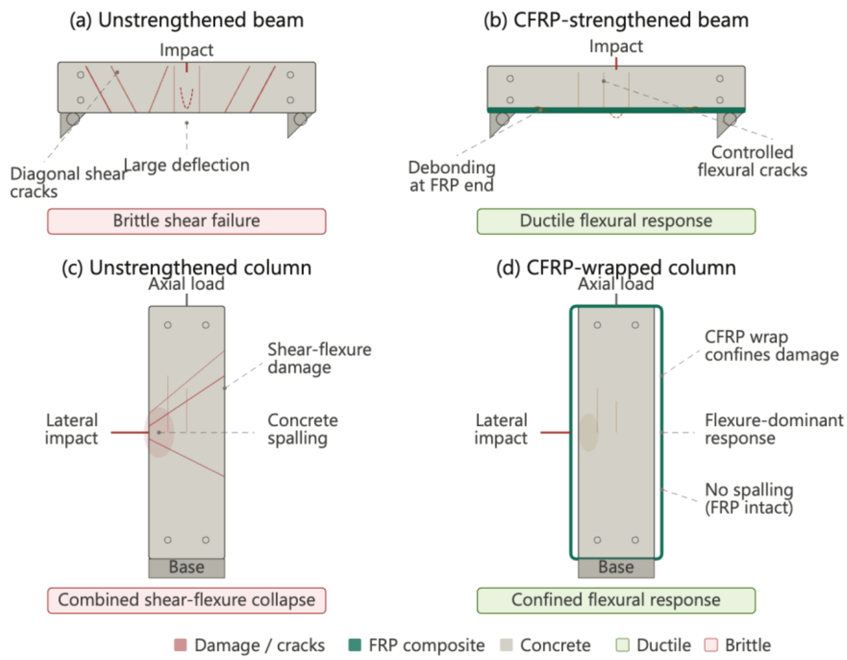

Figure 4 Failure mode comparison in FRP-strengthened RC members: (a) unstrengthened beam showing large deflection and severe shear cracking; (b) CFRP-strengthened beam demonstrating reduced deflection with controlled debonding; (c) unstrengthened column with combined shear-flexure damage; (d) CFRP-wrapped column exhibiting flexure-dominant response with confined concrete damage.

Interface failure remains the governing performance limit. Three debonding mechanisms recur across the literature: plate-end debonding initiating at FRP termination points, intermediate-crack debonding propagating from widening flexural cracks, and critical diagonal crack debonding along shear planes. Under impact loading, these mechanisms develop more rapidly and at lower strain levels than under static conditions because the millisecond-duration contact phase does not allow the gradual stress redistribution that enables adhesive bonds to develop their full capacity. Mechanical anchorage, as discussed in Section 2.3, mitigates this limitation by providing redundant load paths that remain active even after partial debonding.

4. Numerical Modeling and Parametric Analysis

4.1 Finite Element Modeling Approaches

The experimental evidence reviewed in Section 3 establishes clear behavioral trends, but laboratory programs are inherently constrained by specimen availability, cost, and the practical difficulty of systematically isolating individual parameters. Numerical simulation addresses this limitation by enabling controlled variation of impact velocity, FRP configuration, axial load level, and material properties within validated computational frameworks. Two explicit dynamics platforms dominate the published literature: ABAQUS/Explicit and LS-DYNA, each offering constitutive models suited to the three material domains that interact during an impact event on an FRP-strengthened RC member.

Concrete behavior under impact is most commonly represented through the Concrete Damaged Plasticity (CDP) model, which combines isotropic damage mechanics with plasticity theory to capture both the tensile cracking and compressive crushing that develop simultaneously during the millisecond-duration contact phase. The CDP model requires calibration of five plasticity parameters, including the dilation angle, which governs volumetric response under confinement, and the damage evolution curves that control stiffness degradation in tension and compression. For impact applications, the selection of dynamic increase factor (DIF) formulations embedded within the constitutive model exerts a strong influence on predicted peak forces and deflections. Hao and Hao (2014) demonstrated that different DIF models applied to the same RC wall geometry produced substantially different predicted responses under blast loading, a finding that extends directly to impact scenarios and highlights the importance of DIF model selection as a source of inter-study variability.

FRP composite behavior is typically captured using Hashin damage criteria, which distinguish among four failure modes: fiber tension, fiber compression, matrix tension, and matrix compression. This differentiated treatment is critical for impact simulations because FRP failure under dynamic loading rarely follows a single mode. Matrix cracking may initiate at concrete crack locations while fibers remain intact, and the progressive interaction between these modes determines whether the FRP contribution degrades gradually or terminates abruptly through catastrophic rupture. The FRP-concrete interface, where debonding initiates and propagates as described in Section 3.5, is modeled using cohesive zone formulations that define a traction-separation relationship governing damage initiation, evolution, and complete separation. Calibrating these interface parameters against dynamic single-lap shear tests remains one of the most challenging aspects of impact simulation, since the available experimental data at elevated strain rates is limited.

The accuracy of validated models is generally encouraging. Jin et al. (2021) used ABAQUS/Explicit with CDP to simulate impact-damaged RC beams subsequently strengthened with CFRP, achieving close agreement between predicted and measured midspan deflection histories, impact force plateaus, and crack patterns. Liu et al. (2023) employed LS-DYNA to model CFRP-wrapped RC columns under lateral impact, demonstrating that the numerical framework captures the two-stage dynamic response observed experimentally, where the CFRP strengthening mechanism activates only after the initial peak contact force subsides. Zhou et al. (2022) adopted a Continuous Surface Cap Model for ECC-confined columns, extending the modeling toolkit beyond conventional concrete to include high-performance cementitious composites. Çalışkan (2025) validated an ABAQUS model for shear-deficient beams strengthened with CFRP strips, confirming that the coupled CDP-Hashin-CZM framework reproduces the experimentally observed failure mode shift from diagonal shear to controlled flexure. Across these studies, mesh sensitivity remains a recognized limitation: because strain-softening in the CDP model introduces element-size dependence, predicted peak forces and damage localization can vary with mesh refinement unless fracture energy regularization is carefully implemented.

4.2 Parametric Effects on Impact Performance

Validated numerical models enable parametric exploration that would be impractical through experimentation alone. Three parameters consistently emerge as dominant influences on the impact response of FRP-strengthened RC members.

a) Impact velocity governs the loading regime. Sun et al. (2024) systematically varied both impactor mass and velocity on RC columns, establishing that deflection increases nonlinearly with velocity while the failure mode transitions from flexural at low velocities to shear-dominated at high velocities, regardless of whether CFRP strengthening is present. This velocity-dependent transition determines the type of FRP reinforcement needed: longitudinal FRP suffices at low velocities where flexural response dominates, whereas transverse wrapping becomes essential at high velocities where shear failure governs.
b) FRP layer count exhibits a characteristic diminishing-return pattern. Xu et al. (2020) and Swesi et al. (2022) both

reported that adding CFRP layers progressively reduces lateral displacement, with initial layers delivering the most substantial gains and efficiency declining beyond two to three layers. This saturation arises because interfacial shear stresses accumulate between successive FRP plies, increasing the risk of interlaminar delamination before the outer layers can develop their full tensile capacity. For practical design, two to three layers represent the optimal balance between performance improvement and material efficiency.

c) Axial load ratio introduces a non-monotonic effect in columns. AL-Bukhaiti et al. (2023) demonstrated through tests on CFRP-wrapped columns at varying axial compression ratios that moderate axial loads enhance impact resistance by activating the confinement mechanism of the FRP wraps, while excessive axial compression reverses this benefit by driving the column toward a compression-dominated failure that the FRP cannot arrest. Multiple studies converge on an optimal range of approximately 0.1 to 0.2 for the axial load ratio, beyond which the risk of brittle failure increases sharply (Swesi et al., 2022; AL-Bukhaiti et al., 2023).

Table 6 Summary of parametric effects on impact performance of FRP-strengthened RC members

Parameter	**Range studied**	**Effect on deflection**	**Effect on capacity**	**Optimal range**
Impact velocity	2–15 m/s	Increases nonlinearly	Decreases with velocity	Design-dependent
FRP layers	1–4	Decreases 25–40%	Increases per layer	2–3 layers
Axial load ratio	0–0.4	Decreases then increases	Increases then decreases	0.1–0.2
Concrete strength	25–80 MPa	Decreases with strength	Increases with strength	Project-specific

Note: Effects synthesized from parametric studies by Xu et al. (2020), Swesi et al. (2022), AL-Bukhaiti et al. (2023), and Sun et al. (2024). Deflection reduction percentages refer to CFRP-wrapped specimens relative to unstrengthened controls.

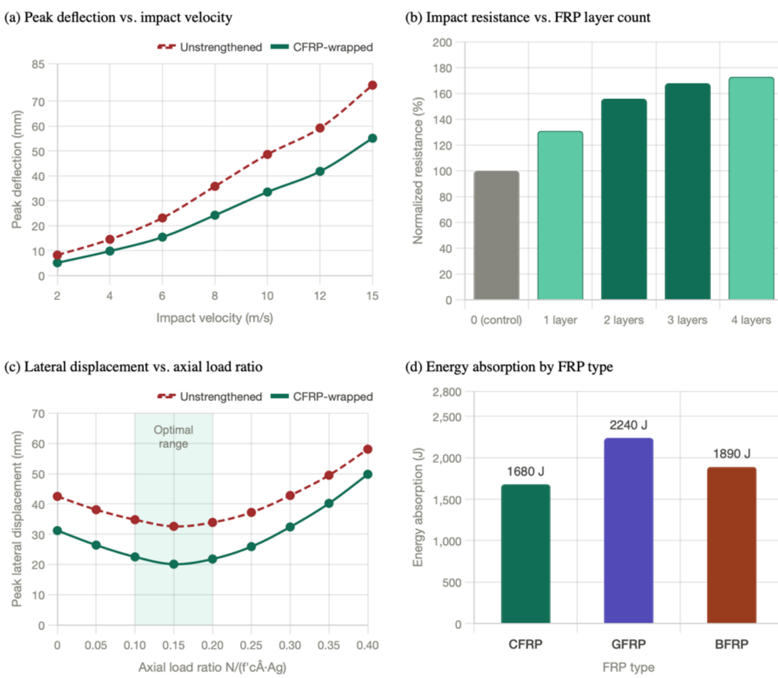

Figure 5 Parametric effect graphs: (a) peak deflection versus impact velocity showing nonlinear increase with velocity-dependent failure mode transition; (b) impact resistance versus FRP layer count showing diminishing returns beyond two to three layers; (c) axial load ratio effects illustrating non-monotonic behavior with optimal range of 0.1 to 0.2; (d) comparison of energy absorption characteristics across CFRP, GFRP, and BFRP systems.

5. Design Considerations and Research Gaps

The parametric trends documented in Section 4 provide a solid technical foundation, but translating these findings into engineering practice requires design frameworks that do not yet exist. This section examines the current state of code provisions, identifies the specific gaps that prevent their development, and outlines practical recommendations that can guide practitioners until formal guidelines emerge.

5.1 Current Code Limitations

ACI PRC-440.2-23, the most widely referenced international guide for externally bonded FRP strengthening, provides detailed provisions for flexural strengthening, shear strengthening, axial load enhancement, and seismic retrofit of RC members (ACI Committee 440, 2023). Its scope addresses static, fatigue, creep, and environmental loading conditions. Impact loading, however, does not appear in any chapter, section heading, or design example within the document. The omission is not an explicit exclusion accompanied by technical justification, but rather a silent absence that leaves the practitioner without guidance for one of the most consequential accidental loading scenarios affecting bridge piers, parking structures, and industrial facilities. The companion European document, fib Bulletin 90, follows a similar pattern: it offers Eurocode-compatible design provisions for static and seismic applications of externally bonded FRP but contains no rate-dependent strength modifiers, dynamic debonding criteria, or impact-specific anchorage requirements (fib, 2019).

This regulatory silence has practical consequences. Engineers tasked with strengthening impact-prone members must either conduct project-specific numerical analyses, which require specialized expertise and computational resources, or apply static design provisions with arbitrary safety factors whose adequacy cannot be verified against any benchmark. Both approach is satisfactory for routine infrastructure projects, and the resulting inconsistency across jurisdictions and project types represents a significant barrier to broader adoption of FRP strengthening for impact-critical applications.

5.2 Research Gaps

Six specific knowledge deficiencies impede the development of impact-oriented design provisions, each requiring targeted research before code committees can formulate reliable recommendations.

The most critical gap concerns repeated low-velocity impact characterization. As documented in Section 3.4, fewer than fifteen experimental programs have examined FRP-strengthened members under successive impact cycles. Structures such as parking garage columns, warehouse frames, and bridge piers along freight corridors experience repeated low-energy collisions over their service lives, and the cumulative damage mechanisms governing progressive stiffness degradation under these conditions remain poorly quantified. The textile-reinforced concrete slab tests by Batarlar et al. (2021) and the corroded slab studies by Daneshvar et al. (2021) represent important initial contributions, but the available data is insufficient to support the development of cumulative damage models applicable across member types and FRP configurations.

Second, the dynamic bond-slip relationship at the FRP-concrete interface lacks reliable experimental characterization at strain rates relevant to impact loading. Static bond-slip models, such as those derived from the anchorage strength framework of Chen and Teng (2001), form the basis of current cohesive zone calibrations used in numerical simulations. Whether these models remain valid at the strain rates encountered during impact, or whether rate-dependent modifications are needed, cannot be resolved without dedicated dynamic single-lap shear testing programs that are currently absent from the literature.

Third, scale effects limit the transferability of laboratory findings. The majority of experimental programs reviewed in Section 3 employ reduced-scale specimens with cross-sectional dimensions between 150 and 300 mm, tested under controlled drop-weight conditions. Full-scale validation under realistic vehicle collision scenarios, with the associated complexities of multi-directional loading, irregular impactor geometry, and boundary condition variability, remains essential before laboratory-derived strengthening recommendations can be applied to field structures with confidence.

Fourth, the interaction between environmental degradation and impact resistance is virtually unexplored. FRP systems in service are exposed to moisture, temperature cycling, ultraviolet radiation, and chemical attack, all of which degrade the polymer matrix and the FRP-concrete bond over time (Siddika et al., 2020). Whether an FRP system that has undergone ten years of environmental exposure retains its impact enhancement capacity is a question that cannot currently be answered.

Fifth, column behavior under combined axial compression and lateral impact has only entered systematic investigation since 2020, as discussed in Section 3.3. The parametric space defined by axial load ratio, impact velocity, impact location along the column height, and FRP wrapping configuration is vast, and the available experimental database covers only a fraction of the combinations encountered in practice.

Sixth, validated analytical models that can predict impact capacity without requiring full finite element analysis are needed for routine design application. Energy-based approaches that balance input kinetic energy against structural absorption capacity have been proposed, but their accuracy outside the calibration database is limited, with typical prediction errors of 15 to 30 percent reported across member types (Pham and Hao, 2016).

5.3 Interim Design Recommendations

Until formal code provisions are developed, the evidence synthesized in this review supports several interim recommendations for practitioners. Full wrapping should be preferred over partial configurations for any member where impact loading is anticipated, since the confinement provided by full wraps both enhances shear resistance and prevents the concrete spalling that accelerates collapse under repeated loading. Mechanical anchorage should accompany externally bonded FRP in all impact applications, given the consistent experimental observation that adhesive bonds alone are insufficient to sustain load transfer during the rapid stress redistributions characteristic of impact events. Conservative safety factors exceeding those prescribed for static conditions should be applied, reflecting the limited calibration data available for dynamic applications. Finally, the axial load ratio in FRP-strengthened columns should be maintained below 0.2 where possible, as multiple studies confirm that higher ratios compromise the confinement mechanism upon which the strengthening strategy depends.

6. Conclusions

This review has synthesized experimental, numerical, and analytical developments in the impact behavior of FRP-strengthened RC members published between 2016 and 2025, updating and extending the foundational synthesis established by Pham and Hao (2016). The following conclusions emerge from the evidence.

FRP strengthening consistently improves the impact resistance of RC beams, columns, and slabs, with reported capacity increases of 20 to 60 percent and displacement reductions of 25 to 40 percent depending on the strengthening configuration and loading severity. Full wrapping outperforms partial schemes across all member types, and CFRP provides superior stiffness enhancement while GFRP and BFRP offer greater deformation capacity and energy absorption, respectively. These performance differences are governed not by the tensile strength of the FRP alone, but by the interplay between fiber stiffness, matrix integrity, and the FRP-concrete interface under dynamic conditions.

The most significant mechanistic finding is that FRP strengthening shifts the failure hierarchy from brittle shear-dominated collapse toward more ductile flexural responses, a transition that fundamentally alters the safety margin of strengthened structures under impact. However, this benefit is contingent on effective anchorage. Debonding at the FRP-concrete interface remains the dominant collapse trigger, and the experimental record consistently demonstrates that unanchored externally bonded systems cannot sustain load transfer through the rapid stress redistributions that characterize impact events.

Numerical simulations using ABAQUS/Explicit and LS-DYNA, when calibrated with appropriate constitutive models for concrete, FRP, and the bond interface, reproduce experimental trends with sufficient accuracy to support parametric exploration. The sensitivity of predictions to DIF model selection, mesh refinement, and interface calibration, however, means that numerical results should be interpreted as indicative rather than definitive in the absence of case-specific experimental validation.

The parametric synthesis identifies two to three FRP layers and axial load ratios of 0.1 to 0.2 as the ranges that optimize impact performance. Beyond these thresholds, diminishing returns in FRP efficiency and increasing risk of compression-dominated failure, respectively, limit the effectiveness of additional strengthening.

The absence of impact provisions in ACI PRC-440.2-23 and fib Bulletin 90 constitutes the most consequential gap between the accumulated research knowledge and current engineering practice. Closing this gap requires coordinated progress on repeated impact characterization, dynamic bond-slip quantification, full-scale validation, and reliability-based calibration of safety factors specific to impact loading. The accumulated experimental and numerical database reviewed here provides a credible foundation for initiating this code development process. What remains is the institutional commitment to translate research evidence into the validated design frameworks that infrastructure protection demands.

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