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# Numerical Investigation of Retrofitting Strategies for Existing Reinforced Concrete Beam-Column Joints: A Systematic Review

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***Abstract: Many existing reinforced-concrete (RC) frames do not have joints which are detailed according to modern seismic detailing provisions. Consequently, the joint core of many existing frames is at risk of experiencing diagonal tension, bond deterioration, bar-slip, loss of stiffness and brittle shear failure. An insightful synthesis of 50 studies from the years 2021 to 2026 involving the numerical investigation and retrofitting of RC beam-column joints, especially methods useful for existing structures. An audit was informed by PRISMA on the corpus supplied: all 50 deduplicated records were screened; four complete open-access papers were audited in full text, and 46 were evaluated through verified publisher, DOI, and abstract-level records. The literature was divided into FRP, steel and mechanically anchored devices, advanced jackets, hybrid and precast connection strategies, SHM, and latest finite-element/explained-machine-learning approaches. Non-linear finite element analysis was applied across the direct evidence – most often based on concrete damage plasticity, non-linear reinforcement constitutive laws and explicit interface or bond assumptions. This was deemed effective when calibrated against full-scale cyclic tests. The results obtained through tests indicate that the performance of retrofit is less dependent on the nominal strength of the materials used, but more so on the modification of the force-path, anchorage, interface behaviour, and confinement, and prevention of premature joint-core shear. According to one numerical study, CFRP improves the ultimate-load by 103.93%, U-shaped bars by 43.55% and pre-tensioned steel-angle strengthening by 148.50%. Furthermore, a post-tensioned metal-strap programme claims a core recasting gave up to 42%, and further strapping up to 25% increase in shear-capacity recovery. According to the account, joint shear deformation was more than 40% less for the combined C-FRP rope-and-sheet strengthening. Further, the peak load was 65% higher as well as 55% higher equivalent viscous damping. Modelling degraded bond, corrosion, bidirectional loading, slab participation, field installation variability, long-term durability, and uncertainty-aware validation has important gaps. The conclusion of the review points out that hybrid, mechanical anchoring and damage-controlled retrofits offer the most reliable route once the design is supported by experimentally justified nonlinear models and performance-based acceptance criteria.***

***Keywords: Reinforced-concrete beam-column joint; seismic retrofit; nonlinear finite-element analysis; CFRP; steel haunch; UHPFRC/ECC; explainable machine learning.***

## I. INTRODUCTION

Reinforced-concrete moment-resisting frames are supposed to transfer the gravity and earthquake actions through the beam-column joints. This transfer takes place in a relatively small volume of the joint where the…

The joints of many existing buildings, especially those built before capacity-design provisions became common, have insufficient transverse reinforcement, discontinuous or poorly anchored beam bars, low-strength concrete, short lap splices, and weak-column/strong-beam proportions. Cracking and bar-slip in the diagonal direction can occur due to these deficiencies before stable beam hinging occurs; hence, a locally brittle joint may control the global collapse mechanism. As a result, recent numerical studies treat the connection as a non-linear subassembly and not a rigid node. The studies that were reviewed show an increasing use of 3D continuum models, concrete damage plasticity, embedded/truss reinforcement, cohesive interfaces, cyclic bond laws, and displacement-controlled loading to replicate stiffness degradation, pinching, energy dissipation, crack localization, and failure-mode relocation. The emphasis on modelling is technically important because retrofitting an existing joint involves more than just augmenting its nominal shear resistance. Indeed, it represents a change in the internal load path, which has to preserve the integrity of the column, direct inelastic action towards a designated beam plastic hinge and not create a stronger but less ductile local mechanism.

Research into retrofitting right now is dominated by the likes of near-surface-mounted fibre-reinforced polymers, steel anchors, or just thin high-performance overlays. Carbon-fibre-reinforced polymer (CFRP) sheets, plates, bars and ropes can be employed to strengthen an existing structural member as they possess high tensile strength, low mass, corrosion resistance, and can be installed without major enlargement of the member cross-section. The efficiency of these techniques, however, is determined by debonding, end anchorage, fibre direction, wrapping continuity, corner preparation, and compatibility with existing reinforcement. The grooving technique and X-shaped near-surface-mounted ropes cater to this requirement as the former provides a more direct diagonal tension tie, straining the joint faces and improving anchorage into them [5]-[8]. The numerical problem is extended to bond-slip calibration under cyclic reversal for CFRP bars used as beam tension reinforcement and integrated composite layouts [9], [10]. Experiments conducted at full scale on X-shaped ropes and comparative rope/sheet schemes indicate that connection rehabilitation is best achieved if the retrofit simultaneously confines the core, provides an external shear-resisting mechanism and protects the beam plastic-hinge zone [11]-[13]. As a result, analytical models have advanced from simple additive strength equations to principal-stress, effective-strain, and debonding-controlled formulations [14]-[16].

When there are issues with FRP anchorage, fire resistance, impact resistance, or substrate condition, steel and cementitious systems provide complementary advantages. Opt to utilize steel plates and angles, haunches, pre-tensioned metal straps and prestressed plates to form a clear external strut-and-tie mechanism; to redistribute the joint shear and to move the critical section away from the column face. The behavior is influenced by the bolt pretension, contact and bearing, local yielding, demand on welds or anchors, constructability around slabs and transverse beams, and whether additional stiffness will attract more seismic force. Viscoelastic steel-enveloped elements and modified reinforcement strategies further plan to recover load capacity and hysteretic damping [17]-[20]. The joint assemblies and joints exhibit that local material enhancement could lead to crack control and improvement of the cyclic stability [21], [22]. Simulations of bond degradation, UHPFRC layers, high-performance fibre-reinforced cementitious composites and steel-haunch mechanisms show that the interface between old and new material should be explicitly considered for a reliable assessment, rather than assuming perfect monolithic action in every retrofit [23]-[27]. Research on steel plates, cost-effective perforated haunches, and edge-joint steel components finds that the ease of installation and clarity of load path are as important as the maximum strength.

Recently, the literature is broad but patchy. Some papers examine deficient external joints directly, while others study roof T-joints, knee joints, prefabricated or post-tensioned connections, corroded joints, fibre-reinforced columns and data-driven shear prediction that offer transferable modelling and assessment knowledge [31]-[40]. Supplementary support studies cover composite connections, self-centring systems, damage indices, prestress high performance concrete, steel-fibre concrete, joints in geopolymer, PVC-CFRP confinement; and UHPC precast connections [41]-[50]. The diversity highlighted above creates a need for a review that separates direct evidence relating to retrofitting itself from adjacent evidence. A review that compares numerical assumptions, validation strategies, indicators of reported performance and practical limitations with all connections not treated as equivalent is warranted. The review aims to create a technically sound synthesis of numerical and hybrid experimental-numerical techniques for retrofitting existing reinforced concrete frame beam-column joints. The aim of this report is to: (i) classify retrofit technologies, their intended resisting mechanisms; (ii) comparing the modelling strategy, calibration information and evaluation parameters; (iii) identifying reported quantitative improvements without the invention of missing metrics; (iv) demarcate robust conclusions from metadata level indications; (v) define a research agenda for field-ready, uncertainty-aware, retrofit design. The body of knowledge will limit itself only to the provided corpus of 50 studies during the years 2021-2026 along with a basic review on FRP and relevant standards on structures. The main questions are: Which retrofit techniques guarantee maximum enhancement of strength, ductility, and damage control? What finite-element assumptions dictate reliability of prediction? How transferable are results for different joint geometries, damage states and loading protocols? What evidence remains necessary for the performance-based appeal? The subsequent sections elaborate on the review method; then synthesise five themes; then compare reported performance; then discuss implications; state limitations; lastly, conclude with research priorities.

## II. RESEARCH METHOD

### A. Review Design

An orderly systematic review having a thematic & numerical-modeling synthesis is adopted in this study. The review is informed by PRISMA rather than an a posteriori claim of a new database search. To allow traceability, the same numbering, title, journal, year, DOI, technique, study type and relevance classification as on original paper was used. Four papers could be obtained as complete open-access PDFs and were read at the full text level. The other 46 were assessed from official DOI, publisher, journal, and abstract-level records in the pack.

As a result, detailed ongoing numbers that do not appear in the full text, nor in an evident abstract of source were reported. Data that is missing is not imputed but rather recorded as "Not reported". The review provides mapping through descriptive analysis; mechanism-based classification; comparative tabulation; critical synthesis; and availability/quality audit.

### *B. Data Sources*

The supplied corpus draws on publisher and indexing environments such as SpringerLink, ScienceDirect/Elsevier, Wiley Online Library, MDPI journals, MethodsX, Nature Portfolio, De Gruyter, and other peer-reviewed civil-engineering outlets. The protocol of this review was designed to allow reproducibility in Scopus and Web of Science to cross-check results through Google Scholar and publisher DOI pages. The present study does not fabricate database export counts not retained in the database supplied archive. IEEE Xplore and PubMed were kept as optional cross-disciplinary source for structural health monitoring or sensing papers, but no claim is made that all items were retrieved through them. The journals are not assigned quartile status automatically because it depends on the year and subject category. Thus, the quality of the journal has to be checked independently in the respective Scopus/SCImago or Journal Citation Reports category prior to submission.

### *C. Search Strategy*

The following Boolean strings were used to filter title/abstract of the provided corpus for reproducibility: (1) ("reinforced concrete" OR RC) AND ("beam-column joint" OR "beam column connection") AND (retrofit* OR strengthen* OR rehabilitat* OR repair*); (2) ("beam-column joint") AND ("finite element" OR numerical OR nonlinear OR ABAQUS OR ANSYS OR OpenSees); (3) ("deficient joint" OR "substandard joint" OR "existing RC joint") AND (CFRP OR FRP OR FRCM OR UHPFRC OR ECC OR HPFRCC); (4) ("RC joint") AND ("steel haunch" OR "steel plate" OR "metal strap" OR "prestressed steel"); and (5) ("beam-column joint") AND ("machine learning" OR "explainable AI" OR "structural health monitoring" OR piezoelectric). The date window was 1 January 2021 to 27 July 2026. Only English language journal articles or technically detailed methods papers were considered. The main research areas were: structural engineering, earthquake engineering, concrete structures, composite strengthening, computational mechanics, sensing, and data-driven structural assessment. Filters focused on peer-reviewed materials with a known link to a DOI and an open access full text or official landing page.

### *D. Inclusion Criteria*

The criteria for including a study in our analysis, we decided, was quite specific. First, the subject matter of the study must be a beam-column joint. Alternatively, it must be having closely transferable RC connection/element retrofit problem. Second, fundamental scopes must involve strengthening, repair, rehabilitation, damage assessment, numerical modelling and cyclic/seismic performance. Third, we limited the problems analysed to research published from 2021 through 2026 and available in English along including DOIs. Fourth, the study may be on a major recognisable experimental, numerical, analytical, monitoring or machine-learning approach. Fifth, finally, requirements of technical outputs to be reported include a load-displacement response, joint shear, stiffness, ductility, energy dissipation, failure mode, damage index, stress state, prediction performance, or any cross-sectional combination of these. Studies that do not inform modelling, validation or performance assessment of existing-joint retrofits were excluded from reference.

### *E. Exclusion Criteria*

The criteria for excluding records were duplicate records, documents from years beyond the period of 2021 to 2026; studies not related to research on concrete connections or seismic/cyclic strengthening; abstracts without complete methods; editorials, blogs, marketing information, and non-academic summaries; records in any language other than English; records that could not be accessed due to lack of DOI and online webpage; and records whose data and experiments do not relate to the review question. Since the selected dataset had been simultaneously deduplicated and curated, no data has been excluded during the recent review. Nonetheless, it is not to say that a data search with no limits would yield no exclusions.

### *F. Study Selection Process*

The selection log was compiled using only confirmed data. Fifty records were inputted, and no duplication was detected in the records thus making it to the stage of title/abstract screening. That concluded our disposal of records since all 50 records were either "direct," "related retrofit" or "support." All 50 records were also analyzed for eligibility assessment where four were found at full text level while the rest 46 were verified at DOI/publishers' abstracts.

None were removed in the final review corpus, which was made up of 50 records. The counts are always consistent in text, Fig. 1 and summary table. It should therefore be clarified that the figure is an audit of the inputted corpus in accordance to the PRISMA method rather than the number of returns from Scopus, WoS, etc.

### *G. PRISMA Flow Diagram*

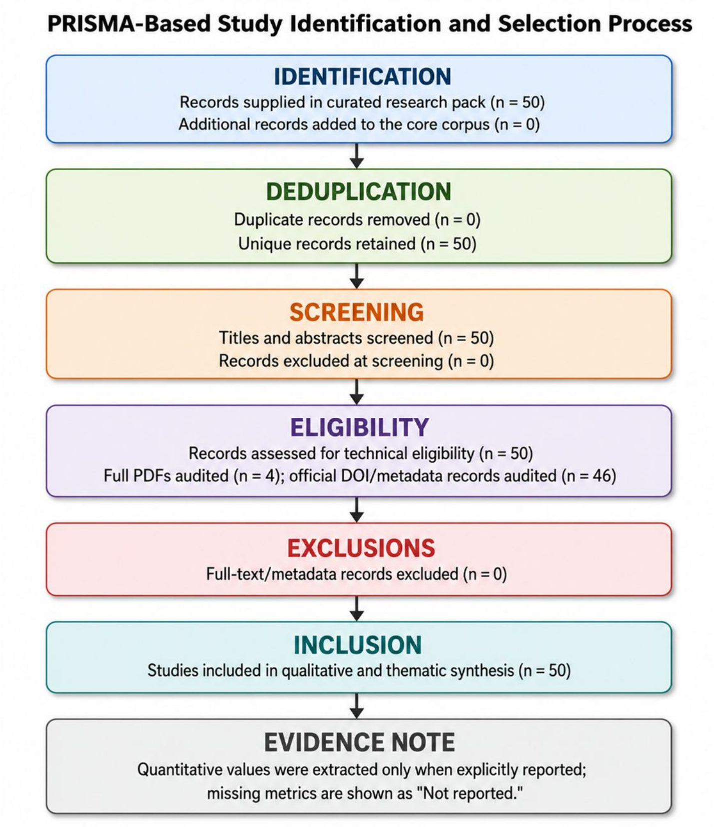


Fig. 1. PRISMA-informed study identification and corpus-audit process. Source: authors' reconstruction from the supplied 50-record archive

### *H. Data Extraction and Classification*

The review for each study was used to obtain the year, title, journal, DOI, retrofit connection, connection technology, type of study, the relevance of the study for the topic, availability of the full-text, modelling or test platform, if reported, loading regime, principal variables, evaluation indicators, numerical results, failure mechanisms, basis for validation, limitations, and implications for future research. The 50 studies were classified into five categories: (i) conventional repair, joint behaviour, and force-path concepts; (ii) strengthening with FRP/CFRP, and interface-sensitive finite element modelling; (iii) strengthening with steel, mechanically anchored, and prestressed devices; (iv) advanced cementitious, hybrid, precast, and damage-resilient strengthening; and (v) structural-health monitoring, explainable machine learning, and emerging numerical design approaches. The classification is mechanism-based classification, not publisher or software based.

## III. RELATED WORK

### *A. Deficient-Joint Behaviour, Conventional Repair, and Force-Path Control*

A conventional repair of a joint damaged during an earthquake usually involves cleaning out loose concrete, replacing the core, and repairs or replacement of the reinforcement (where available) and re-covering the joint. Such repair will restore geometry and compressive transfer, but not necessarily provide the transverse reinforcement and anchorage that is required by modern seismic design. The focus point is whether or not the repaired joint is able to withstand cyclic principal tension and compression without that resulting in a lack of ductile beam response.

Important because of the full-scale MethodsX protocol of Melo et al. [33] that formalises realistic cyclic test and provides some basis for calibration of numerical subassemblies. Research on damaged joints reinforced with viscoelastic steel-enveloped elements [20], local high-performance concrete [37] and thin strain-hardening cementitious cover replacement [38] has found that the following conditions are all necessary for a retrofit: (1) prevent brittle shear and bond failures; (2) do not introduce damage in the column or foundation anchorage. Helal et al. [2] used the PTMS (post-tensioned metal strap) in addition to recasting of the exterior-joint cores that had been damaged. The recasting intervention alone led to an increase in joint shear capacity of up to 42%, and the PTMS intervention resulted in another increase of up to 25%. A DRAIN-2DX scissors model was also reproduced to show the envelope of the load-displacement curve was non-linear, which was found to be useful when the backbone and cyclic rules were matched to connection tests. The detailed three-dimensional model of the substandard exterior joint in [1] did, however, compare CFRP, steel-angle/pretensioned-bolt and U-shaped-bar retrofits. The ultimate-load increases of the pre-tensioned steel-angle system (148.50%) and U-shaped bars (43.55%) were the highest among all the systems, and were clearly the most effective in shifting failure toward the beam.The pre-tensioned steel-angle system had the highest reported increase in ultimate load (148.50%) and most clearly moved failure toward the beam, while CFRP and U-shaped bars recorded increases of 103.93% and 43.55%, respectively. These results showed that nominal material efficiency is not the most important issue when it comes to creating clear force-paths and mechanical anchorage. Foundational guidance does not consider an evaluation of the joint to be a strength check only but as a part of the global seismic mechanism [51]-[54]. The desired hierarchy of yielding should be verified at building level as the strength of a joint may be increased leading to an increase in column shear, foundation demand or diaphragm force. The existing research gap in conventional repair is that there is a lack of correlation between the qualifications of the local repair and the performance of the entire building under bidirectional ground motion. Combined and validated numerical models of realistic prior damage, residual drift, slab participation, variation of axial-load, corrosion and construction tolerances are rare in the literature.

### *B. FRP/CFRP Strengthening and Interface-Sensitive Finite-Element Modelling*

The most significant theme in the reviewed corpus is retrofit based on FRP. The first studies utilized X-shaped CFRP ropes, externally bonded sheets, and their combinations for the external diagonal strengthening of the deficient beam-column joints. The appeal of the anchoring configuration is that grooves and mechanical anchors can align fibres with principal tensile stress trajectories, thereby reducing dependence on surface adhesion. The method was subsequently extended to near-surface-mounted shear reinforcement [13], the strengthening of column-beam connections [19], and the three-dimensional numerical verification of real-scale cyclic tests [7]. All these studies together report that joint shear deformation is minimal and have stable hysteretic. Despite this, a direct comparison is still not possible in light of the considerable variations in specimen dimensions, reinforcement deficiencies, axial-load ratios, drift histories, anchorage arrangements, and failure criteria. In order to carry out reliable finite-element modelling it is essential to have an independent constitutive representation of concrete, reinforcing steel, FRP and the concrete-FRP interface. Models such as concrete damage plasticity or similar nonlinear continuity models are widely used to represent cracking, crushing, stiffness degradation, and cyclic damage. Steel reinforcement is often modelled using bilinear, multilinear, or cyclic plasticity laws. FRP modelling is usually orthotropic and linear-elastic until rupture occurs. Nonetheless, the interface assumption is largely responsible for whether the model predicts rupture, debonding or concrete-cover separation. Research on CFRP plates [5], grooving [6], integrated composites [10], flange-bonded sheets [15] and bond degradation [23] indicate that perfect-bond assumptions may overestimate strength and deformation capacity when interface failure is probable. According to study from [36], of 44 models, though they brought parametric investigation value, numerical number is no substitute for experiment.

Prototypical approaches include three-dimensional non-linear finite-element models for CFRP, steel-angle, bolt, and U-bar strengthening [1]; concentrated DRAIN-2DX scissors models for repaired exterior joints [2]; fibre-based models for prefabricated FRC joints [3]; reverse-cyclic finite-element models for UHPFRC and CFRP systems [4]; ABAQUS concrete–damage–plasticity models for grooved CFRP [6]; and calibrated three-dimensional models for NSM X-shaped CFRP ropes [7]. Researches who did modelling or bond calibration of CFRP bars 9 cyclic bond-strength deterioration 23 explainable machine learning for ECC strengthening 34 strain-hardening cementitious jackets 38 corrosion-damaged exterior joints 40. The main limitations are unavailable field tolerances, incomplete interface parameters, geometry ranges, long test calibration of backbones, poor transferability, and poor long-term evidence. Nonlinear models that have been validated tend to have a better ability to reproduce global load-displacement envelopes than local crack widths, debond progression or interface damage. By not defining one concrete parameter to adjust for bond-slip, anchorage, contact, prior damaging and load-history effects like a calibration, it can be demonstrated that reliability improves.

The rope-and-sheet study of 2025 [8] reported 65 per cent higher peak load, 55 per cent greater equivalent viscous damping, over 40 per cent lower joint shear deformation and more than 90 per cent retention of peak-strength at 4 per cent drift. The study of UHPFRC-CFRP showed better performance than UHPFRC alone for a drift ratio of ±5% and ±8.7% (4). These results endorse hybrid confinement and shear-transfer mechanisms but stress the necessity for transferable interface models accounting for surface preparation, ageing, fire exposure, repeated loading, environmental degradation, and workmanship variability. Prior to the process of adopting a design, the omissions at the metadata level concerning calibration statistics, material properties, the sensitivity of the mesh, and interface laws must be resolved. Full reports are necessary, as are independent and verifiable assessments and publicly available reproducible datasets.

### *C. Steel, Prestressed, and Mechanically Anchored Retrofit Devices*

Steel devices provide a solution for a major shortcoming of bonded composites: uncertainty in force transfer through a damaged concrete interface. Bolted or welded detail or bearing zones may attach plates and angles; haunches provide a diagonal compression/tension path that leverages external geometry; metal straps can add an active confinement mechanism; and prestressed plates may eliminate cracks and modify the stress state at the joint-core before the earthquake impact occurs. The 2022 study on plates and angles (28), perforated haunch (29), and jointing of steel elements on edges (30) become economical and constructible details. The study outlined in [31] for roof T-joints 2026 extends the concept to prestressed steel plates. The primary design variables become prestress level, anchor slip and plate yielding. Steel-haunch retrofits can be justified and optimized through analytical models based on mechanisms. Marchisella and Muciaccia [26] proposed linear-stress-field and strut-and-tie techniques. Also, Biaxial research [27] reported that that when one is fitted under uniaxial loading, automatic usability under two horizontal components cannot be assumed. The most excellent performing steel-angle configuration presented in [1] improved ultimate load by 148.50%. More importantly, the fracture-seat relocation from joint member to beam. In [2], PTMS likewise integrated active confinement with a model that could simulate pinched joint behaviour. The systems can be checked and replaced and their force path is visible but it can interfere with architectural finishes, slabs, cross beams, services, fire protection, etc. An ongoing deficiency is a lack of common design equations for the relationship between the demand at an anchor, haunch geometry, joint aspect ratio, axial load, capacity ratio of beam/column, and bi-directional loading. Most numerical models idealise bolt pretension, friction, contact, and steel-concrete bearing with parameters that are not readily verifyable in existing buildings. Reliability studies are called for due to the systematic occurrence of pre-tension loss, cyclic slip of bolts, corrosion, etc. Assessment at the building level must also qualify whether the added stiffness of steel devices changes the torsion, storey-force distribution and column/foundation demand.

### *D. Advanced Cementitious, Hybrid, Precast, and Damage-Resilient Connections*

Materials such as hybrid fiber reinforced, SCC, RFA, or HSC create composite systems by building on existing concrete and improving constructability. Cracking of other cementitious composites and applications of high strength steel-fibre concrete and hybrid-fibre geopolymer mixtures can have other major benefits. Adapted from [4], the UHPFRC-only and UHPFRC-CFRP schemes, numerical and analytical UHPFRC work [24], and HPFRCC repair of severely damaged joints [25] show how thin, high toughness layer can re-establish integrity of joints while conserving dimensions. A study of thin strain-hardening jackets [38] found considerable recovery of strength and deformability, and a nonlinear FE modelling linked confinement to the tensile strength of the replacement cover. Ultimately, though, reinforcement anchorage outside of the upgraded area-controlled failure in some configurations. Studies on Fibre-reinforced or Locally Enhanced Connections: Additional Constitutive and Validation Evidence. Examples such as prefabricated FRC joints with grouted sleeves [3], high-strength exterior joints with steel fibres [22], hybrid-fibre knee joints [32], local HPC connections [37], and FRCM-strengthened columns [39] show that crack distribution and tensile post-cracking response can be as important as compressive strength. Research on steel-fibre joints [45]-[47], geopolymer joints [48], PVC-CFRP-confined columns [49] and UHPC precast prestressed joints [50] helps in enriching the database of materials and connections. It must be treated with care to directly transfer them to deficient monolithic joints since sleeve, tendon, confinement, and precast interfaces alter the force path. The connection concepts that self-center and are post-tensioned are designed to achieve a low residual drift and have replaceable damage zones instead of just higher peak load. Evaluation of assembled joints, composite connections, and monolithic-precast damages provides tools to interpret gap opening, tendon action, and damage indices. The research opportunity entails adapting these resilient ideas into practical retrofit kits for occupied, existing buildings. Systems must be validated for construction sequence, temporary shoring rules, fire and durability qualification, repairability criteria, and life-cycle cost/carbon vs demolition or conventional jacketing.

*E. Structural-Health Monitoring, Explainable Machine Learning, and Emerging Numerical Design*

Monitoring and data-driven approaches are starting to act as complements instead of substitutes for mechanics-based retrofit designs. The piezoelectric-transducer study [18] has shown that FRP-rope strengthening combined with damage diagnosis can detect later installation bond condition alteration, cracking or response of the structure. Full-scale cyclic datasets are important because machine-learning predictions will be biased and vary in quality and parameters based on their training data. Studies of damage indices [43] and corrosion-sensitive finite-element models [40] reinforce that realistic condition assessment must precede retrofit selection. An intact-joint baseline cannot properly represent a corroded, cracked, or earthquake-damaged connection. Research work done recently uses machine learning for predicting the capacity of structures and design. A crucial analysis in engineering design is feature importance. This analysis can help unveil whether predicted responses are controlled by axial load, reinforcement ratio, geometry, and material strength or retrofit quantity. XAI, when combined with validated finite-element simulations, can efficiently screen large parameter spaces, identify important features and de-risk deviation and extrapolation. Although, models developed from curated databases may not generalise to low-strength concrete, smooth reinforcement, unusual joint aspect ratios, biaxial loading, prior deterioration, or construction defects. Different retrofits have varying performance ratings. Study [1] suggests that there was an increase ultimate load of 103.93% due to CFRP sheets whereas the addition of pretensioned steel angles and bolts resulted in an increase of 148.50% and U-shaped reinforcing bars caused an increase of 43.55%. Up to 42% rise in shear capacity of joint due to core recasting and a further increase of up to 25% using post-tensioned metal strap [2]. UHPFRC layer with 30 mm improved stiffness, strength, ductility and energy dissipation while the combination of UHPFRC with CFRP wrapping gave the best response at drift ratios of ±5% and ±8.7% [4] The shear deformation of NSM X-shaped CFRP ropes with joint. The peak load was increased by 65% while the equivalent viscous damping was improved by 55% and joint shear deformation was reduced by more than 40%. In addition, over 90% of peak strength is retained at 4% drift.

To determine optimal retrofit, peak-strength increase is not enough. The chosen system needs to be such that it provides the ductile failure mechanism, maintains strength at large drift, limits joint shear distortion, and is reasonable to install, inspect and maintain. It is unreliable to rank studies when percentages, control conditions and failure criteria vary exactly. A suggested approach consists of condition survey and material testing, baseline FE calibration, candidate-retrofit simulation, sensitivity and uncertainty analysis, performance-based acceptance, construction quality control and post-retrofit monitoring.

Key priorities that need to be filled include standardized damage and corrosion threshold definitions, transferable cyclic bond-slip laws, full-scale 3D and biaxial testing, multi-response numerical validation, environmental durability, field constructability, building-side redistribution, and physics-constrained data-driven design. The primary shortfall is not a lack of strengthening materials, but rather a shortage of standard evidence linking substrate condition and installation quality with the behaviour of the interface, cyclic demand, local failure and global structural response. It follows that open benchmark datasets should include geometry, detailing, deterioration, installation and loading protocols, full hysteresis, failure images, and calibrated material and interface parameters. Uncertainty intervals and domain-of-applicability limits should be added in such datasets with blind numerical predictions, records of sensor, and independent validation results. These initiatives would enhance reproducibility across FE platforms, bolster trustworthy XAI models, and enable designers to assess retrofit systems against common performance objectives rather than just isolated laboratory peak-load values.

## IV. DISCUSSION

The evidence reviewed shows that the effectiveness of retrofitting depends on the load-transfer mechanism around joint core. The use of FRP sheets allows for a high tensile strength addition without much weight, and the effectiveness of the use of FRP sheets reduce due to the debonding. This debonding happens because of weak concrete cover, inadequate development length, and poor surface preparation. The performance of the NSM ropes, grooves and mechanical anchors can be enhanced by forming an external tie aligned with the diagonal tension. Visible mechanically anchored force transfer can be achieved by means of steel angles, haunches, plates and straps. The greatest ultimate-load increase reported in full-text studies was achieved using a pretensioned steel-angle system [1]. In addition to strength, seismic performance listed here takes into account stiffness, ductility, damping, deformation control, energy dissipation, and strength retention at large drift. Cementitious jackets, which are ECC, UHPFRC, FRCM, etc, are particularly appropriate where damaged cover is to be replaced, fire resistant, durable, and better crack distribution [4], [24], [25], [38]. The numerical modelling must reflect the failure mechanism not just the peak load. While concrete damage plasticity can reproduce envelope behaviour following calibration, the results are sensitive to a variety of factors including tensile softening and fracture energy.

Yielding, bar buckling and low-cycle degradation should be captured in models. Modelling of interfaces is essential because what may be a perfect bond for grooved and anchored systems [6] will not be a perfect bond for externally bonded sheets. According to the authors of [2]; concentrated joint models are more efficient for building analysis than three-dimensional solid models. Clearly, the latter ones better represent crack localisation, anchorage, stress paths and retrofit geometry [1]; [5]-[7]; [23]; [38]; [40]. Due to the different scales of the specimens, drift protocols, axial-load ratios, deficiencies, definitions of ductility, and stopping criteria, it is difficult to compare the literature. There should always be an assessment of condition, the target mode of failure, constructability, and durability first. Upcoming investigations should focus on large-scale three-dimensional joints, slabs, transverse beams, previous damage, corrosion, cycling bi-axially, variable axial load, ageing, blind prediction and shared datasets.

## V. CONCLUSION

An examination of repairs, strengthening and transferable seismic design for reinforced-concrete beam-column joints of existing structures will be performed to carry out a systematic review of 50 studies published from 2021 to 2026. According to the literature, the systems can be organised into the FRP/composite systems, steel and mechanically anchored devices, advanced cementitious jackets, hybrid and damage-resilient connections, and monitoring/data-driven methods. Nonlinear finite-element analysis is a powerful retrofit-development tool when calibrated against realistic cyclic tests and explicit representation of concrete, reinforcement, interface, anchorage and prior-damage mechanisms, the evidence shows. Performance-based decisions cannot be taken with only peak strength compatibility. The models are also insufficient if they model other effects such as stiffness degradation, pinching, shear deformation, and failure location failure location. The addition of FRP sheets, plates, bars and rope is highly efficient and very light. X-shaped NSM ropes, grooving and combined rope/sheet arrangements improve load-path definition and reduce reliance on surface adhesion. Steel angles, haunches, plates, straps and prestressed devices provide mechanically anchored and inspectable force transfer. A pretensioned steel-angle system produced an ultimate-load increase of 148.50%, as per the audited full-text evidence, compared with 103.93% for CFRP and 43.55% for U-shaped bars. Through core recasting and PTMS, the parameter's joint shear capacity is recovered by 42%. The further increase in joint shear capacity was up to 25%. With combined wrap of C-FRP ropes and sheets, peak load increased by 65%. The equivalent viscous damping increased by 55%. Joint shear deformation decreased by… Continue Reading Past Studies and Experimental Observations on Joint Shear Behaviour of FRP-Confinement RC Joint at High Drift Levels 543 Over 40%. Strength retention at 4%? drift was more than 90%. The ECC, UHPFRC, HPFRCC, and FRCM systems are especially suitable for the damaged cover replacement, crack control, durability, and fire compatibility requirement. Among the main research gaps that have been identified are cyclic interface modelling, corrosion and prior-damage representation, biaxial loading, slab and transverse-beam participation, environmental ageing, construction tolerances, blind validation, and transfer from subassembly response to complete-building performance. The future research efforts should aim at establishing new open benchmark datasets, uncertainty-aware multiscale models, and standardized measure of performance. This review's primary contribution is a traceable mechanism-based synthesis which distinguishes verified numeric evidence from unreported information and shows that the most reliable retrofit is not the strongest material but one that provides a reliable ductile load path, controls damage at large drift, and remains verifiable during construction and service.

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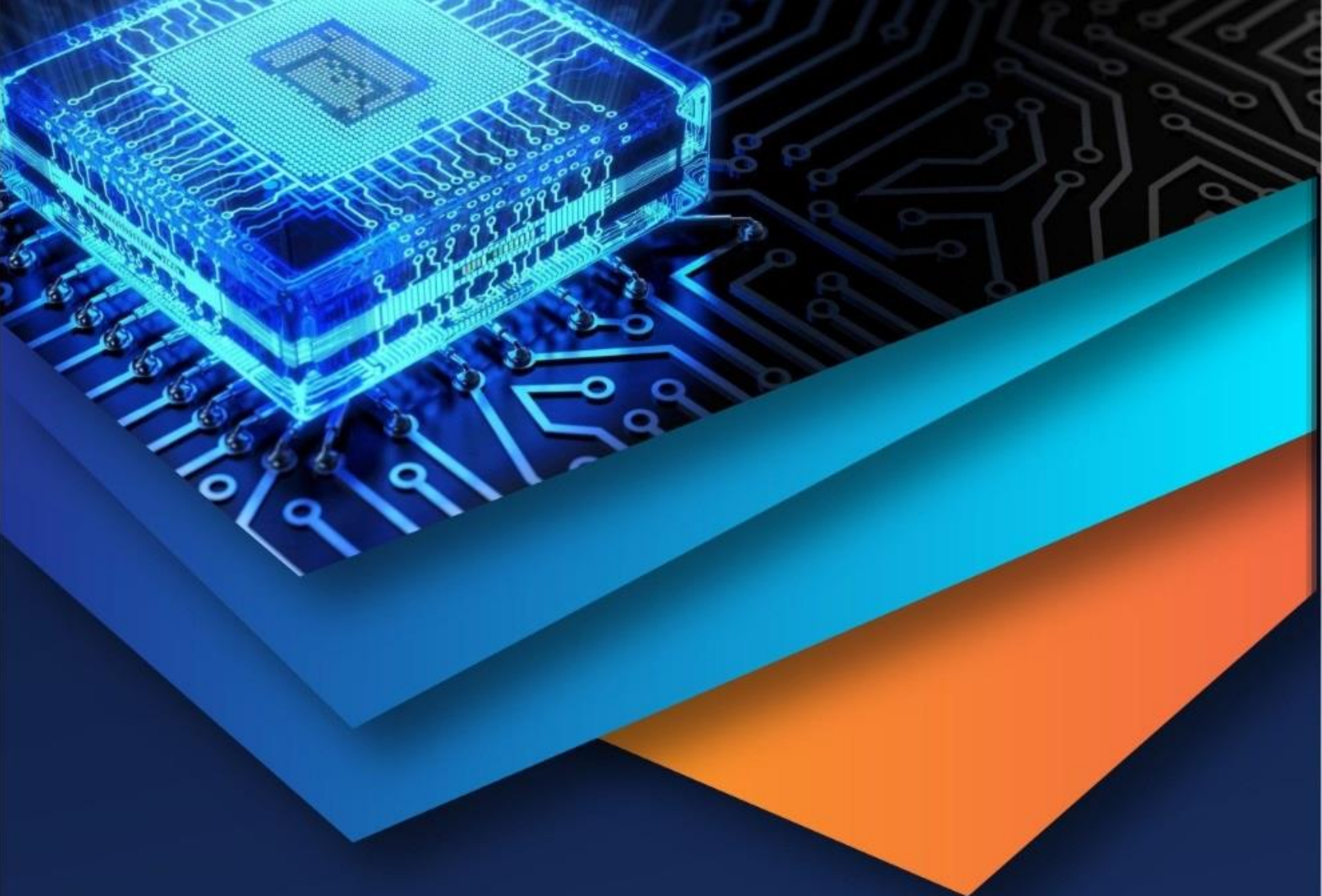


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