IJCIET

INTERNATIONAL JOURNAL OF CIVIL ENGINEERING AND TECHNOLOGY

Journal ID: 6971-8185

IAEME Publication

Chennai, India

editor@iaeme.com/ iaemedu@gmail.com

https://iaeme.com/Home/journal/IJCIET

International Journal of Civil Engineering and Technology (IJCIET)
Volume 17, Issue 4, July-August 2026, pp. 1-24, Article ID: IJCIET_17_04_001
Available online at https://iaeme.com/Home/issue/IJCIET?Volume=17&Issue=4
ISSN Print: 0976-6308; ISSN Online: 0976-6316
Impact Factor (2026): 27.65 (Based on Google Scholar Citation)
Journal ID: 6971-8185; DOI: https://doi.org/10.34218/IJCIET_17_04_001

SEISMIC PERFORMANCE EVALUATION AND RETROFITTING OF REINFORCED CONCRETE STRUCTURES: A COMPREHENSIVE LITERATURE REVIEW

Mr. Keshav Raghunath Kale[1]
Department of Civil Engineering,
CSMSS Chh. Shahu College of Engineering, Chhatrapati Sambhajinagar, Maharashtra, India

Mr. Rohit S. Gunjal[2]
Department of Civil Engineering,
CSMSS Chh. Shahu College of Engineering, Chhatrapati Sambhajinagar, Maharashtra, India

Mr. Sadhu B. Nagargoje[3]
Department of Civil Engineering,
CSMSS College of Polytechnic, Chhatrapati Sambhajinagar, Maharashtra, India

Mr. Dinesh M. Pandit[4]
Department of Civil Engineering,
CSMSS Chh. Shahu College of Engineering, Chhatrapati Sambhajinagar, Maharashtra, India

Mr. Parmeshwar M. Pawar[5]
MSS's College of Engineering and Technology (CET),
Jalna, Maharashtra, India

Mr. Krushna S. Gore[6]
Department of Civil Engineering,
CSMSS Chh. Shahu College of Engineering, Chhatrapati Sambhajinagar, Maharashtra, India.

Corresponding Author: Mr. Keshav Raghunath Kale

ABSTRACT

The sad fact that damage surveys following all the major earthquakes of the last 30 years have brought back the same dismal statistic, namely, most of the victims and most of the collapses came from reinforced concrete (RC) construction prior to the advent of ductility-based seismic codes. In this paper, the literature is reviewed to understand why it continues to happen, and what engineers have done to address the question. It focuses on the seismic response of RC columns, joints and frames under cyclic lateral loading; development of performance-based earthquake engineering (PBEE) frameworks and associated analysis methods; procedures for seismic fragility and vulnerability assessment; principal retrofitting strategies that have been studied and applied, such as concrete and steel jacketing, fiber-reinforced polymer (FRP) composites, base isolation, and supplemental damping devices; and a synthesis of significant advances published during the period 2019 to 2026, including machine learning approaches to seismic response prediction, ultra-high-performance concrete (UHPC) retrofitting, structural health monitoring, post-earthquake damage detection, and updates to international design codes. It is intended to be critical and not encyclopedic; where there are conflicting views on the studies or a technique does not always work and the reasons are not always described in the literature, then these tensions are discussed and not resolved by consensus

This presentation will explore the seismic performance of R/C structures and discuss how R/C structures can be retrofitted using FRP technology, in addition to performance-based earthquake engineering, machine learning, fragility curves, UHPC, and structural health monitoring.

Keywords: Reinforced concrete, seismic performance, retrofitting, fiber-reinforced polymer, performance-based earthquake engineering, machine learning, fragility curves, UHPC, structural health monitoring

Cite this Article: Keshav Raghunath Kale, Rohit S. Gunjal, Sadhu B. Nagargoje, Dinesh M. Pandit, Parmeshwar M. Pawar, Krushna S. Gore. (2026). Seismic Performance Evaluation and Retrofitting of Reinforced Concrete Structures: A Comprehensive Literature Review. *International Journal of Civil Engineering and Technology (IJCIET)*, 17(4), 1-24. DOI: https://doi.org/10.34218/IJCIET_17_04_001

I. INTRODUCTION

The structural typology, which has been the most prominent in the centre of the casualties, following each major earthquake of the last thirty years, is reinforced concrete frame structures constructed before the 1980s, with little or no consideration for lateral ductility and designed for gravity loads [2, 3, Kobe 1995, İzmit 1999, Bhuj 2001, Sichuan 2008, Tōhoku 2011, and most recently Kahramanmaraş, Turkey 2023]. It's not the material. To date, the vast majority of urban built-up areas worldwide have been built using RC systems and, in well-designed and properly detailed structures, these can exhibit acceptable performance in earthquakes [1]. The issue here is the inherited stock – buildings with columns spaced at 300-450mm apart instead of the 100-150mm apart, beam-column joints with no transverse reinforcement, and frames sized without capacity design principles.

This recognition of the disparity between the performance of existing structures and what we now consider to be acceptable has given rise to three interrelated lines of research over the last 30 years. The first is the experimental characterisation of the failure mechanism of pre-code RC elements, which has led to models of column shear failure that are significantly more conservative than the original ones [14, 15] and models of joint degradation that are also more conservative than the originals [30, 31]. The latter is the creation of PBEE frameworks [8, 9] that move away from force based prescriptive rules and incorporate probabilistic relationships between ground motion intensity, structural response and consequences. The third is the development of retrofitting methods [13, 17, 18, 39, 45] proven to be effective from both an experimental and analytical approach.

The integration of machine learning, deep learning and data-driven techniques for seismic assessment and structural health monitoring has been a fourth dimension that has grown significantly since 2019 [46, 47, 48, 49, 50, 72, 73, 74, 75]. This paper is a synthesis of the four streams. Element and system level seismic behavior is discussed in Section II. In Section III, PBEE frameworks and analysis methods are reviewed. Vulnerability and fragility assessment is discussed in Section IV. Retrofitting techniques are discussed in section V. The advances in 2019-2026 are discussed in Section VI. Cross-cutting issues and conclusions are discussed in Sections VII and VIII..

II. SEISMIC BEHAVIOR OF REINFORCED CONCRETE STRUCTURES

2.1 Confined Concrete and Column Response

The simplest model for the confined behaviour of concrete is the one suggested by Mander, Priestley and Park [2] which predicts the peak compressive stress and ultimate strain as a function of the volumetric ratio of confinement and the yield strength of the transverse reinforcement. The model is based on the fundamental concept that the ultimate compressive strain is approximately proportional to the confinement ratio, which has been verified many times in uniaxial compression tests on circular and rectangular samples. Less often appreciated is that the model has been calibrated primarily for circular columns with spiral reinforcement, and the model is less reliable when applied to rectangular columns with rectilinear hoops, which make up the vast majority of existing building columns. This was directly addressed by Saatcioglu and Razvi [28] who suggested an equivalent coefficient for confinement which takes into consideration the action of arching between the tie legs.

The experimental results on columns subjected to both axial loading and cyclic lateral loading are much more negative than the pre-code design practice had suggested. Sezen and Moehle [15] conducted tests on full-scale columns with shear span-to-depth ratios and hoop spacings typical of California construction in the 1960s through 1970s, and observed shear failure at drift ratios between 1.5% and 3.0%, that was followed often within a few cycles by failure in the axial load. Elwood and Moehle [14] converted these observations to a probabilistic drift capacity model. This is an important practical difference for the evaluation of existing buildings, as both values are significantly lower than the 3–4% that is frequently quoted as the generic life-safety limit for RC frames. Deng et al. [52] and Yan and Niu [51] quantified the ductility loss of columns during seismic loading for bridge piers, and Dogan et al. [51] quantified the ductility loss of RC building columns during earthquakes and corrosion, respectively, using deep transfer learning of structural response data.

Park [27] provides important context: the spread between well-confined modern columns (displacement ductility of 6–8) and the pre-code columns tested by Sezen and Moehle (ductility of 2–3 before shear failure) illustrates the practical cost of inadequate detailing. The displacement ductility supply is not a minor refinement; it is a factor of three to four.

2.2 Beam-Column Joints

One of the major weaknesses of pre-code RC frames is the beam-column joint [6, 30]. Exterior joints of gravity-load designed frames have been subjected to experimental testing by Pampanin, Moratti and Calvi [30] which indicates brittle shear failure at inter-storey drift ratios of between 1.0–1.5%. Panagiotakos and Fardis [31] analysed a vast amount of experimental information and derived empirical expressions for chord rotations that can now be found in Eurocode 8, Part 3. A drawback of these expressions is that the database includes comparatively few specimens that represent the combination of low axial load and very light transverse reinforcement which is typical in the developing world. Shafaei and Adibi [77] have extended the appraisal of retrofitted beam-column joints to cover both plain and deformed bar arrangements and highlighted differences in hysteretic energy dissipation that code level models are currently unable to differentiate. The seismic retrofit of inadequate exterior joints with steel plates and angles has been investigated experimentally by Shoukry, Tarabia and Abdelrahman [78] who were able to show significant improvements in strength and ductility for a relatively non-destructive technique.

2.3 Infilled Frames and System-Level Irregularities

The masonry infill panels in RC frames are one of the key challenges in seismic assessment of existing buildings that is not well resolved. Dolsek and Fajfar [24] modelled the soft-storey effects analytically and found that the performance of the uniformly infilled frame in the inelastic range can be poorer than that of the bare frame as loss of infills at one level can lead to a catastrophic redistribution of the deformation demand. Asteris et al. [36] analysed the macro modelling approaches for infilled RC frames and concluded that there was no agreement regarding the post-peak behaviour. Furtado, Rodrigues, Arêde and Varum [68] analyzed the behaviour of masonry infill walls subjected to biaxial cyclic loading and concluded that the simultaneous application of both directions of loading results in faster damage evolution than loading in one direction, which can result in non-conservative fragility estimates if only one loading direction is considered.

At the system level of structure, Ibarra, Medina and Krawinkler [16] noted that the cyclic degradation of strength is the most important mechanism leading to the global collapse, rather than the maximum strength at first yield. They have developed deterioration models, which are built into OpenSees and other analysis software, that enable nonlinear time-history analyses to capture collapse, not just end artificially when the structure reaches its monotonic capacity.

III. PERFORMANCE-BASED EARTHQUAKE ENGINEERING

3.1 The PEER Framework and Performance Objectives

In the 1990s, performance-based earthquake engineering began to appear, and in the probabilistic framework of the PEER research center [9] a set of four integrals is used to break down the performance problem into four parts, linked by the total probability theorem. Ghobarah [8] developed a synthesis of the various performance objectives (operational, immediate occupancy, life safety, collapse prevention) to structural damage states. The conceptual foundations of seismic design in the PBEE paradigm were revisited by O'Reilly and Calvi [59] who suggested that the focus on stiffness and strength-based design targets do not adequately account for the non-linear relationship between design option and loss for a range of hazard levels. Their framework offers a way to choose design parameters that can be directly derived from a loss minimisation criterion, in lieu of code requirements. This was extended by Shahnazaryan and O'Reilly [60] who produced a procedure to simultaneously control the collapse risk and the expected loss from repair; they showed that if the two risks are not considered simultaneously, the designs result in either over-conservative or inadequate designs for safety depending on the level of hazard. Baker, Bradley and Stafford [58] offer the most up-to-date and thorough textbook treatment of the subject of seismic hazard and risk analysis, including the selection of intensity measures, record-to-record variability and the probabilistic computation of the expected annual loss term within the PEER integral.

3.2 Nonlinear Static Analysis

Despite the significant advantages of pushover analysis, which are the ease of computation and the clarity of the results, it is still used as the workhorse of seismic assessment in engineering practice [6, 11]. It received its most-cited critical appraisal by Krawinkler and Seneviratna [6] who found it to be useful for identifying plastic hinge sequences and failure mechanisms, and problematic for structures in which higher modes make a significant contribution to seismic demand. The N2 method developed by Fajfar [7] which is now the standard approach in Eurocode 8 is similar to the Capacity Spectrum Method in ATC-40 [11] with the difference that it does not require an iterative procedure as it simply overlays inelastic demand spectra on the capacity curve in ADRS format. The ATC-40 iterative procedure has been criticized specifically because the correction factors for equivalent viscous damping have been developed based on limited analyses, and are not consistent with respect to structural configuration. In ASCE/SEI 41-17 [12] nonlinear static analysis remained an acceptable analysis technique, but the acceptance criteria were tightened and nonlinear dynamic analysis was added as a recommended analysis technique. Moehle [29] presented the concept of the displacement-based design approach which is the basis of contemporary PBEE assessment.

3.3 Incremental Dynamic Analysis and Collapse Assessment

The student will examine the analysis and assessment of collapses using incremental dynamic analysis.

The limitations of pushover-based approaches were tackled by Vamvatsikos and Cornell [26] who introduced incremental dynamic analysis, which involves performing nonlinear time-history analyses over many intensity levels for a set of ground motion time histories. The computational cost is high, but the IDA is able to take into account the record-to-record variability, higher mode effects, and dynamic instability which is not possible in any static method. For non-ductile RC frames, Haselton, Liel, Lange and Deierlein [25] applied IDA to practice, and they demonstrated that the median collapse intensity is sometimes just 2 to 3 times the design ground motion, which has direct relevance for retrofit prioritisation. Kohrangi et al. [62] analyzed the site dependency of fragility functions, as well as the importance of the record selection schemes, which showed that fragility estimates are dependent on the choice of ground motion suite not fully addressed by the standard procedures. The rigorously treatment of record selection and scaling is offered by Baker, Bradley and Stafford [58] who offer algorithms for building ground motion suites that are spectrally compatible to a target hazard without systematic bias

IV. SEISMIC VULNERABILITY AND FRAGILITY ASSESSMENT

Fragility functions relate the probability of the structure reaching or exceeding a specified level of damage to the intensity of the ground motion. The difference between empirically derived functions (which have been developed based on damage experienced in previous earthquakes) and analytically derived functions (which have been developed based on nonlinear structural analysis) is significant, and these two functions are not necessarily congruent. Rossetto and Elnashai [37] collated damage information from 15 post-earthquake surveys to generate empirical fragility curves for the RC frame typologies found in Europe, finding that there was considerable scatter due to the differences in damage scales in the surveys, as well as typologies of buildings. Erberik and Elnashai [38] reviewed analytically flat slab RC structures and concluded flat slab structures have higher fragility than moment frames in the moderate intensity range.

Kassem, Nazri and Farsangi [45] comprehensively reviewed seismic vulnerability assessment methodologies, and they found that although there are many methods available, few have been tested against a variety of structural inventories in various seismicity zones. The special susceptibility of informally constructed RC houses in Puerto Rico has been analyzed by Murray, Feliciano, Goldwyn, Liel, Arroyo, and Javernick-Will [53] and it has been concluded that RC house fragilities increase by over an order of magnitude for deviations in code practice of bar placement, concrete quality, and frame geometry relative to code-conforming designs.

Shegay et al. [55] presented a seismic residual capacity ratio (SRCR) evaluation method for RC structures after earthquakes, which offers a quantitative basis for making decisions rapidly after an earthquake about the usability of these structures, a problem that has been more commonly dealt with in practice via empirical earthquake damage scales, rather than capacity models. The integrated assessment and retrofit evaluation is still the domain of Bracci, Kunnath and Reinhorn [10] who consider the two as a unified optimisation problem, not separate steps.

Gentile and Galasso [66] introduced Gaussian process regression (GPR) as an alternative to full structural analysis to provide a rapid approach to seismic fragility assessment of building portfolios, concluding that surrogate modelling approaches can be used to approximate fragility curves within acceptable tolerances at a lower computational cost than full Monte Carlo analysis. ASCE/SEI 41-17 [12] provides a tiered evaluation process with conservative acceptance criteria, but this conservatism is intentional and does not imply that an element that is labeled as deficient may in fact be performing well.

V. RETROFITTING TECHNIQUES FOR RC STRUCTURES

5.1 Concrete and Steel Jacketing

Concrete jacketing is among the most established techniques for strengthening existing RC columns and beam-column joints [13,39]. Raza, Khan, Menegon, Hao, and Sadeghi [39] reviewed the full body of literature on jacketing of RC columns, including concrete, steel, FRP, and textile-reinforced mortar approaches, and provided a unified performance comparison. Their analysis confirms that concrete jacketing reliably increases both strength and ductility, but adds mass and stiffness that can increase forces on other elements. Thermou and Elnashai [13] showed that targeted column jacketing can recover a large fraction of global performance improvement at a fraction of the cost of uniform strengthening. Steel jacketing was extensively documented for bridge columns by Priestley, Seible, and Calvi [5]; its application to building columns in occupied structures involves additional constraints not fully addressed in the bridge literature.

Shoukry, Tarabia, and Abdelrahman [78] investigated steel plate and angle retrofitting of exterior beam-column joints, demonstrating that the technique is particularly attractive where access to the full column height is restricted — a common constraint in existing occupied buildings. Shafaei and Adibi [77] compared retrofitting of RC joints with plain versus deformed bars, concluding that deformed supplementary bars engage the surrounding concrete more effectively and produce higher energy dissipation under cyclic loading.

5.2 Fiber-Reinforced Polymer Composites

Since the 1990s, strengthening of RC structures with FRP has been the major research focus in RC strengthening [17, 18, 19, 20, 21, 22]. This work has been summarised by Naser, Hawileh and Abdalla [41] in a critical review on the use of FRP for flexural and shear strengthening of beams, column confinements, slab strengthening and connection zones in structures, which stated that the failure modes associated with debonding systematically decrease the efficiency of surface-bonded systems, as predicted by simple force equilibrium. Pohoryles et al. [40] specifically addressed the issue of deficient RC beam-column joints retrofit schemes, where they identified that construction defects not included in laboratory specimens, as well as substrate condition and installation quality, were responsible for a gap between the performance of the laboratory specimens and the in-situ specimens.

Lam and Teng [17], Teng, Chen, Smith and Lam [18], De Lorenzis and Teng [19], Pellegrino and Modena [20], Bonacci and Maalej [21] and El-Hacha and Rizkalla [22] are still considered as a basic reference for FRP confinement, beam shear strengthening, NSM bars, and debonding behaviour, respectively. Cascardi, Dell'Anna, Micelli and Aiello [56] are discussing reversible techniques for the confinement of masonry columns, which is also relevant to RC, as it would be difficult to use conventional bonded systems in heritage structures where the application of the traditional FRP is not acceptable.

Bournas studied the simultaneous seismic upgrading and energy retrofitting of existing RC structures, which is an application that solves the practical problem of the cost of structural intervention in combination with the added value of thermal upgrading [57]. FRCM systems employ the inorganic cementitious matrix in place of the epoxy, addressing the fire resistance and vapour permeability issues, but with slightly reduced tensile efficiency. The most important piece of missing evidence in the whole FRP literature is the long-term field performance of FRP in retrofitted buildings.

5.3 Base Isolation

Seismic base isolation is the technique of separating a structure's ground vibration from the ground motion at the foundation level [33, 34]. Kelly, Skinner, and Heine [33] did pioneering experimental research on energy-absorbing devices, and Naeim and Kelly [34] offer a complete design treatment. D'Amato et al. [54] studied the seismic retrofit of an existing RC building in the Mediterranean style in which isolation devices were installed at the base of the structure, and they found that, depending on the seismic hazard level, the isolation system resulted in a significant reduction of inter-storey drift and floor acceleration compared to the non-isolated case, but with high foundation modification costs. They calculated the pay-back period for the isolation retrofit as compared to expected earthquake loss savings, which is a valuable tool for prioritising applications to high-value or critical facilities.

5.4 Supplemental Damping

The viscous fluid dampers, friction dampers, and metallic yielding devices are special dampers that dissipate seismic response energy in a special device [32, 35]. De Domenico, Ricciardi and Takewaki [65] surveyed the design approaches adopted for viscous dampers in building seismic protection, including optimal placement algorithms, analysis techniques related to damper-structure interaction and code implementation in various national standards. They found the damper-frame connection design to be the major design practical limitation: connection forces are often greater than design forces and therefore local strengthening of the frames is necessary that partially negates the cost savings of supplemental damping over element strengthening. Housner and his co-authors [35] laid the general groundwork for structural control, including passive, active, semi-active, and hybrid systems.

VI. RECENT ADVANCES AND EMERGING TRENDS (2019–2026)

6.1 Machine Learning and Data-Driven Methods in Seismic Assessment

Perhaps the most impactful seismic engineering development since 2019 isn't a new structural system or material, but a method: using machine learning and deep learning to solve problems that were previously solved through simplified analytical modeling or computationally intensive simulation. Mangalathu and Jeon [46] showed that failure mode recognition for RC bridge columns i.e., identification of flexural, shear, and flexure-shear failure can be achieved with 90%+ accuracy using random forest trained from experimental databases, which is better than existing empirical criteria. The same researchers later applied this methodology to RC shear walls [47] and to a fragility analysis of multispan bridge classes through stripes [48], demonstrating that it is possible to produce bridge-specific fragility functions using many fewer structural analyses than the conventional approach.

Instead of data-driven regression, Zhang et al. [49] proposed physics-guided CNN (PhyCNN) for modelling seismic responses, where the governing equations of motion were incorporated as constraints on the structure. This hybrid technique has a lower amount of data than the black-box neural networks while being accurate for loading conditions that were not present in the training set. Xie et al. [50] surveyed all machine learning applications in the field of earthquake engineering, and concluded that the four most developed applications are: seismic fragility assessment, ground motion selection, damage assessment and structural monitoring.

Mangalathu, Jang et al. [47] used random forests to classify the failure mode of RC shear walls based on the 393 experimental test results, resulting in 86% accuracy that is directly applicable to rapid assessment of existing building inventories where the failure mode is the determining factor regarding the proper retrofit strategy. Kazemi and Jankowski [74] applied ML to seismic response and performance analysis of RC buildings and Kazemi, Asgarkhani and Jankowski [75] proposed ML-based fragility functions, which showed that the data-driven fragility curves can be generated in a few hours, compared to the time of several days needed for performing a full nonlinear dynamic analysis. Nguyen et al. [72] studied the use of ML to quickly assess the damage condition of steel moment frames, which can be translated to the case of a post-earthquake triage scenario for RC frames. Wu et al. [79] proposed an adaptive degradation model for RC beam based on machine learning, which better reflects the relationship between load cycles and strength degradation than the fixed deterioration parameters.

6.2 Deep Learning for Structural Health Monitoring and Damage Detection

Structural Health Monitoring (SHM) and Damage Detection (DD) problems are addressed by deep learning.Deep learning is used for solving problems of structural health monitoring (SHM) and damage detection (DD).

SHM has been rapidly integrated with machine learning, especially deep learning, in order to facilitate automatic damage detection and condition assessment. Dogan, Arslan and Ilki [51] showed that deep transfer learning can be used to detect both earthquake-induced structural damage and reinforcement corrosion in RC structures without the need for distinct sensor networks for each damage type. The methodology was demonstrated to be scalable to different types of structural elements in a component-level application of Kabir et al. [80] who applied data-driven ML techniques for failure mode identification of column base plate connections. Xu and Feng [73] focused on data-driven rapid damage assessment of regional RC bridge inventories to seismic loading during the bridge life cycle, which fused the structural response databases and deep learning to result in damage state prediction in near-real time after an earthquake.

A key opportunity for integrating SHM data into seismic performance assessment is providing condition-based retrofit planning: between earthquakes, sensor networks could measure the progressive, gradual deterioration of the structure, and retrofit decisions made based on measured structural condition instead of calendar schedules or arbitrary inspection periods. When considering the implementation of continuous monitoring on a large scale, the cost of instrumentation and the difficulty of conveying and storing all the data generated by large building inventories are still obstacles.

6.3 Ultra-High-Performance Concrete in Seismic Retrofitting

In recent years, because of its capacity for confinement similar to that of FRP in jackets of only 30–50 mm thickness, the shear capacity, the solution of the lap-splice problem and the much better fire protection properties compared to those of the epoxy-bonded FRP systems, there has been increasing interest in research on the use of UHPC as a retrofitting material. Tong, Yuan, Zhuo and Liu [42] experimentally tested the performance of cyclic strength, stiffness and energy dissipation of UHPC jacketed rectangular RC bridge piers, and found significant enhancements. Tong et al. [43] further extended this study to seismic vulnerability assessment, and developed fragility functions for un-retroffitted and retrofitted piers, showing that UHPC jacketing can upgrade a vulnerable class of piers from the moderate-damage state to the minor-damage state at the design-level shaking. Hu, Fang, Shi, Benmokrane and Su [44] comprehensively summarized the seismic performance of UHPC members including beams, columns, shear walls, beam-column joints and connections and concluded that the bond performance between UHPC and substrate is the controlling factor for most strengthening applications.

The key challenges to the widespread application of UHPC retrofitting are the cost of the UHPC materials, and the requirement for specialized UHPC mixing and placement equipment. The cost savings over traditional concrete jacketing is usually about 25% to 30% in material costs, but in some cases the savings are even higher as the thinner jacketing minimizes formwork costs and construction time. Life-cycle cost analyses that consider the longevity of UHPC retrofits, which would not require future reapplication of the UHPC, have generally indicated a benefit to the UHPC cost-effective over 50-year time horizons, but the durability projections made in such analyses have yet to be substantiated with long-term field data.

6.4 Post-Earthquake Field Observations and Updated Fragility Models

The 2023 Kahramanmaraş, Turkey earthquake sequence, which caused over 50,000 deaths and the collapse of tens of thousands of RC buildings, has generated extensive post-earthquake reconnaissance data that are reshaping fragility models for non-ductile RC frames. Preliminary analyses from that event confirm the patterns observed in earlier earthquakes — pre-code buildings failing at low drift ratios, soft-storey collapses in frames with ground-floor commercial uses, and severe joint failures — but also document large-scale failures of buildings that reportedly met more recent code requirements, raising questions about construction quality control and code enforcement.

Murray, Feliciano, Goldwyn, Liel, Arroyo, and Javernick-Will [53] provide a detailed case study of informally constructed RC houses in Puerto Rico after the 2020 earthquake sequence, quantifying the relationship between construction deviations and seismic fragility. Their finding that informal construction can increase fragility by an order of magnitude relative to code-conforming construction underlines that the seismic risk problem in developing countries is not primarily about code writing but about code compliance and inspection. Shegay, Miura, Fujita, Tabata, Maeda, and Seki [55] addressed the post-earthquake residual capacity problem analytically, providing a rational basis for classifying damaged RC structures as safe-to-occupy, restricted-entry, or demolish — a decision that currently relies almost entirely on inspector judgment.

Deng, Yan, and Niu [52] examined the combined effects of prior seismic damage and ongoing reinforcement corrosion on the hysteretic response of RC bridge piers, showing that the two degradation mechanisms interact non-linearly: a pier that would be assessed as structurally adequate under seismic loading alone may fall below acceptable performance thresholds when corrosion reduces the effective cross-section. Di Sarno and Pugliese [67] made the corresponding observation for RC building columns, using numerical simulation to show that moderate corrosion levels can reduce the ductility of existing columns below the thresholds assumed in standard seismic assessment procedures.

6.5 Advances in FRP and Composite Strengthening Systems

The period 2019–2026 has seen significant development of alternatives to conventional epoxy-bonded FRP, motivated primarily by concerns about long-term durability under environmental exposure and fire resistance. FRCM composites, which use inorganic matrices, have been studied extensively as a more durable alternative [56, 57]. Bournas [57] demonstrated that FRCM jacketing of RC columns provides confinement comparable to FRP in laboratory tests while eliminating the fire resistance problem, and that the concurrent application of FRCM and thermal insulation in a single construction operation can substantially improve the cost-effectiveness of combined seismic-energy retrofitting programmes.

Naser, Hawileh, and Abdalla [41] identified the bond failure modes of various FRP systems and their dependence on concrete surface preparation, FRP lay-up, and ambient conditions, concluding that design guidelines that assume a fixed FRP efficiency factor substantially overestimate strength in field conditions with imperfect substrate. Cascardi, Dell'Anna, Micelli, and Aiello [56] investigated reversible FRP application techniques, including mechanical fastening without bonding, which allows removal after the service life of the FRP has been reached without damaging the substrate. Pohoryles, Melo, and Rossetto [40] reviewed the specific problem of FRP retrofitting for deficient beam-column joints, identifying the difficulty of providing effective FRP anchorage in joint panel zones as the primary technical barrier.

6.6 Updated Code Provisions and Computational Tools

The Chopra dynamics textbook [61] is in its fifth edition, published in 2020, and continues to be the primary reference for the foundations of structural dynamics as they relate to the engineering of structures to resist the effects of earthquakes. The ACI 318-19 building code [82] introduced new provisions for concrete shear walls and beam-column connections. While there is still a concern with the non-ductile detailing of pre-code structures, the ASCE/SEI 7-22 standard [83] adopted risk-consistent design spectra. Non-ductile detailing of pre-code structures is beyond the scope of the ASCE/SEI 7-22 prescriptive requirements.

The second edition of Fardis [71] offered a thorough treatment of Eurocode 8 for concrete buildings. It provided a comprehensive commentary for EN 1998-3 assessing and retrofitting, bringing in the previous decades of research. The second generation of Eurocode 8, which was being developed contemporaneously, was predicted to include displacement-based assessment methods and enhanced component fragility and vulnerabilities that would be consistent with the newer research. Open-source analysis software is providing even greater access to pushing the boundaries of research and practice with regard to impact-driven analysis at the level of design.

6.7 Sustainability, Life-Cycle, and Resilience Considerations

Since 2019, sustainable considerations have become increasingly relevant to retrofit decisions. Practitioners previously had little access to cost-benefit analyses for retrofitting. Now, life-cycle cost analyses that incorporate disruption costs of earthquakes and the environmental impacts of repairs provide a quantitative basis to assess different retrofitting techniques. Shang, Yu, Li, and Lu (2018) evaluated the use of engineered cementitious composites (ECC) for strengthening reinforced concrete (RC) structures and described that ECC can be a good option for regions with low to moderate seismicity and concern about cumulative damage due to its ductility and self-healing capabilities of small damage cycles.

Seismic resilience describes the ability of a system to withstand and recover from disruption. This has changed the way retrofit goals are viewed. The resilience framework describes the goal to not only prevent total failure, but also to achieve functional operation after a defined time following the event. This changes the focus of the assessment from structural integrity to the damages of the system and the operational state of the system and the services it provides. This also impacts the assessment of seismic events and the evaluation of the resultant effects on the system and the services it supports. The works of Murray et al. (2022) and Shegay et al. (2022) also support this view of seismic performance in their use of recovery time and residual capacity as performance indicators.

VII. DISCUSSION

Reading through all of the literature that this paper cites, there is, at least to my knowledge, one common point of tension in most areas: the disconnect between the bounds of an analytical method's precision and the uncertainty of its inputs and the extent to which its experimental data are representative. Nonlinear dynamic analysis and IDA [26] are able to produce estimates of collapse probabilities to the hundredths place, however those estimates are based on models that have been calibrated on lab specimens which are subjected to idealized boundary conditions. Machine learning methods [46, 47, 48, 49, 50, 72, 73, 74, 75] do enhance the speed with which analysis can be conducted, but do not eliminate the reliance on the quality of the training data.

A second point of tension is the complexity of the procedures at the research level and the methods which are actually usable by the engineering offices that are asked to evaluate hundreds of buildings in a limited amount of time and with a limited budget. The ASCE/SEI 41-17 standard [12] has made a significant improvement over previous approximative methods but still calls for the construction of building-specific nonlinear models which take days to prepare. Some of the rapid assessment methods [55, 72, 73] are extremely convenient but lead to a loss of accuracy. The most substantial unsolved challenge within the field is determining a balance between speed and accuracy that is satisfactory for determining the order of which buildings require retrofitting.

Third, third, almost all FRP studies are short-term lab experiments. In the studies we have reviewed, the long-term field performance of FRP and FRCM systems in retrofitted buildings has not been documented. As a result, even though the long-term performance of the FRP systems in service is currently unknown, we expect that FRP-based retrofitting is a reasonable solution for buildings with an indefinite service life in an indefinite period. Practitioners of this solution should be aware that it is somewhat of a leap of faith.

Fourth, using machine learning in conjunction with structural analysis has created new opportunities in the areas of rapid damage assessment, failure mode prediction, and fragility analysis. However, there is a risk of black-box models predicting with excessive confidence on poor databases, despite the great performance of the models. As an example, Mangalathu and Jeon [46] explain that they predicted the failure mode with 86% accuracy; however, the diversity in the database is crucial when the model is applied to other areas with different construction practices.

Fifth, the empirical versus analytical fragility debate [37, 38, 45, 53, 66] has not been closed. When empirical and analytical functions for the same structural typology differ by a factor of two in probability of heavy damage, the choice of which function to use in a risk analysis can determine whether a retrofit programme is economically justified. Post-earthquake reconnaissance data from Turkey (2023), Puerto Rico (2020), and other recent events provide new calibration datasets, but translating those data into validated fragility functions requires careful attention to the definition of damage states, the estimation of ground motion at damaged sites, and the characterisation of the structural typology.

VIII. CONCLUSION

This comprehensive literature review has examined the state of knowledge on the seismic performance, vulnerability assessment, and retrofitting of reinforced concrete structures, with an emphasis on both established findings and advances from the period 2019–2026. The following conclusions emerge:

1. Pre-code RC columns can fail in shear at inter-storey drift ratios of 1.5–3.0% [14, 15] and beam-column joints can degrade severely at drift ratios below 1.5% [30]. These are much lower than the 3–4% often cited as a life-safety threshold, and assessment procedures that use the generic value without element-level checks substantially underestimate risk. Corrosion of reinforcement further reduces column ductility [52, 67].
2. PBEE frameworks [8, 9, 58, 59, 60] provide the appropriate conceptual structure for assessment and retrofit decision-making. Probabilistic analysis using IDA [26] is required for collapse risk quantification; pushover analysis [6, 7] is appropriate for screening and mechanism identification but cannot substitute for IDA when collapse probability is the decision variable.
3. Machine learning has demonstrated genuine utility in seismic failure mode classification [46, 47], fragility assessment [48, 66, 74, 75], post-earthquake damage detection [51, 72, 73], and surrogate modelling for seismic response [49, 79]. The dependence on training database quality and geographic representativeness is the

principal risk in applying these methods beyond the conditions under which they were validated.

4. Among the retrofitting strategies reviewed, FRP column wrapping remains the most extensively studied and reliably effective technique for circular columns. Its performance on rectangular columns, under long-term environmental exposure, and under sustained gravity loading combined with seismic cycling is less well documented [39, 40, 41]. UHPC jacketing is a compelling and increasingly studied alternative [42, 43, 44]. Base isolation [54] and supplemental damping [65] provide the highest levels of seismic protection but involve implementation complexity in occupied buildings.
5. Remaining research priorities include long-term field data on FRP and FRCM-retrofitted structures [56, 57]; fragility models that explicitly address the infilled-frame and biaxial loading problems [68]; validated ML models trained on globally representative structural databases [74, 75, 79, 80]; and systematic integration of post-earthquake reconnaissance data from recent events into updated vulnerability functions [53, 55].

REFERENCES

[1] T. Paulay and M.J.N. Priestley, Seismic Design of Reinforced Concrete and Masonry Buildings, John Wiley & Sons, New York, 1992.

[2] J.B. Mander, M.J.N. Priestley, and R. Park, Theoretical stress-strain model for confined concrete, Journal of Structural Engineering, ASCE, 114(8), 1988, 1804–1826.

[3] A.S. Elnashai and L. Di Sarno, Fundamentals of Earthquake Engineering, John Wiley & Sons, Chichester, UK, 2008.

[4] A.K. Chopra, Dynamics of Structures: Theory and Applications to Earthquake Engineering, 2nd ed., Prentice Hall, New Jersey, 2001.

[5] M.J.N. Priestley, F. Seible, and G.M. Calvi, Seismic Design and Retrofit of Bridges, John Wiley & Sons, New York, 1996.

[6] H. Krawinkler and G.D.P.K. Seneviratna, Pros and cons of a pushover analysis of seismic performance evaluation, Engineering Structures, 20(4–6), 1998, 452–464.

[7] P. Fajfar, Capacity spectrum method based on inelastic demand spectra, Earthquake Engineering & Structural Dynamics, 28(9), 1999, 979–993.

[8] A. Ghobarah, Performance-based design in earthquake engineering: state of development, Engineering Structures, 23(8), 2001, 878–884.

[9] G.G. Deierlein, H. Krawinkler, and C.A. Cornell, A framework for performance-based earthquake engineering, Proceedings, 2003 Pacific Conference on Earthquake Engineering, Christchurch, New Zealand, 2003.

[10] J.M. Bracci, S.K. Kunnath, and A.M. Reinhorn, Seismic performance and retrofit evaluation of reinforced concrete structures, Journal of Structural Engineering, ASCE, 123(1), 1997, 3–10.

[11] Applied Technology Council, Seismic Evaluation and Retrofit of Concrete Buildings, ATC-40, Redwood City, California, 1996.

[12] American Society of Civil Engineers, Seismic Evaluation and Retrofit of Existing Buildings, ASCE/SEI 41-17, ASCE, Reston, Virginia, 2017.

[13] G.E. Thermou and A.S. Elnashai, Seismic retrofit schemes for RC structures and local-global consequences, Progress in Structural Engineering and Materials, 8(1), 2006, 1–15.

[14] K.J. Elwood and J.P. Moehle, Drift capacity of reinforced concrete columns with light transverse reinforcement, Earthquake Spectra, 21(1), 2005, 71–89.

[15] H. Sezen and J.P. Moehle, Seismic tests of concrete columns with light transverse reinforcement, ACI Structural Journal, 103(6), 2006, 842–849.

[16] L.F. Ibarra, R.A. Medina, and H. Krawinkler, Hysteretic models that incorporate strength and stiffness deterioration, Earthquake Engineering & Structural Dynamics, 34(12), 2005, 1489–1511.

[17] L. Lam and J.G. Teng, Design-oriented stress-strain model for FRP-confined concrete, Construction and Building Materials, 17(6–7), 2003, 471–489.

[18] J.G. Teng, J.F. Chen, S.T. Smith, and L. Lam, FRP Strengthened RC Structures, John Wiley & Sons, Chichester, UK, 2002.

[19] L. De Lorenzis and J.G. Teng, Near-surface mounted FRP reinforcement: An emerging technique for structural strengthening, Composites Part B: Engineering, 38(2), 2007, 119–143.

[20] C. Pellegrino and C. Modena, Fiber reinforced polymer shear strengthening of reinforced concrete beams with transverse steel reinforcement, Journal of Composites for Construction, ASCE, 6(2), 2002, 104–111.

[21] J.F. Bonacci and M. Maalej, Behavioral trends of RC beams strengthened with externally bonded FRP, Journal of Composites for Construction, ASCE, 5(2), 2001, 102–113.

[22] R. El-Hacha and S.H. Rizkalla, Near-surface-mounted fiber-reinforced polymer reinforcements for flexural strengthening of concrete structures, ACI Structural Journal, 101(5), 2004, 717–726.

[23] M.N. Fardis (Ed.), Advances in Performance-Based Earthquake Engineering, Springer, Dordrecht, 2010.

[24] M. Dolsek and P. Fajfar, Soft storey effects in uniformly infilled reinforced concrete frames, Journal of Earthquake Engineering, 5(1), 2001, 1–12.

[25] C.B. Haselton, A.B. Liel, S.T. Lange, and G.G. Deierlein, Beam-Column Element Model Calibrated for Predicting Flexural Response Leading to Global Collapse of RC Frame Buildings, PEER Report 2007/03, Pacific Earthquake Engineering Research Center, Berkeley, California, 2008.

[26] D. Vamvatsikos and C.A. Cornell, Incremental dynamic analysis, Earthquake Engineering & Structural Dynamics, 31(3), 2002, 491–514.

[27] R. Park, Ductility evaluation from laboratory and analytical testing, Proceedings, 9th World Conference on Earthquake Engineering, Vol. VIII, Tokyo-Kyoto, Japan, 1988, 605–616.

[28] M. Saatcioglu and S.R. Razvi, Strength and ductility of confined concrete, Journal of Structural Engineering, ASCE, 118(6), 1992, 1590–1607.

[29] J.P. Moehle, Displacement-based design of RC structures subjected to earthquakes, Earthquake Spectra, 8(3), 1992, 403–428.

[30] S. Pampanin, M. Moratti, and G.M. Calvi, Seismic behaviour of RC beam-column joints designed for gravity loads, Proceedings, 12th European Conference on Earthquake Engineering, Paper No. 726, London, 2002.

[31] T.B. Panagiotakos and M.N. Fardis, Deformations of reinforced concrete members at yielding and ultimate, ACI Structural Journal, 98(2), 2001, 135–148.

[32] R.D. Hanson and T.T. Soong, Seismic Design with Supplemental Energy Dissipation Devices, EERI Monograph Series MNO-8, Earthquake Engineering Research Institute, Oakland, California, 2001.

[33] J.M. Kelly, R.I. Skinner, and A.J. Heine, Mechanisms of energy absorption in special devices for use in earthquake resistant structures, Bulletin of the New Zealand Society for Earthquake Engineering, 5(3), 1972, 63–88.

[34] F. Naeim and J.M. Kelly, Design of Seismic Isolated Structures: From Theory to Practice, John Wiley & Sons, New York, 1999.

[35] G.W. Housner, L.A. Bergman, T.K. Caughey, A.G. Chassiakos, R.O. Claus, S.F. Masri, R.E. Skelton, T.T. Soong, B.F. Spencer, and J.T.P. Yao, Structural control: past, present, and future, Journal of Engineering Mechanics, ASCE, 123(9), 1997, 897–971.

[36] P.G. Asteris, S.T. Antoniou, D.S. Sophianopoulos, and C.Z. Chrysostomou, Mathematical micromodeling of infilled frames: state of the art, Journal of Structural Engineering, ASCE, 137(12), 2011, 1508–1517.

[37] T. Rossetto and A. Elnashai, Derivation of vulnerability functions for European-type RC structures based on observed damage, Engineering Structures, 25(10), 2003, 1241–1263.

[38] M.A. Erberik and A.S. Elnashai, Fragility analysis of flat-slab structures, Engineering Structures, 26(7), 2004, 937–948.

[39] S. Raza, M.K.I. Khan, S.J. Menegon, H. Hao, and F. Sadeghi, Strengthening and repair of reinforced concrete columns by jacketing: state-of-the-art review, Sustainability, 11(11), 2019, 3208. https://doi.org/10.3390/su11113208

[40] D.A. Pohoryles, J. Melo, and T. Rossetto, Seismic retrofit schemes with FRP for deficient RC beam-column joints: state-of-the-art review, Journal of Composites for Construction, ASCE, 23(4), 2019, 03119001. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000961

[41] M.Z. Naser, R.A. Hawileh, and J.A. Abdalla, Fiber-reinforced polymer composites in strengthening reinforced concrete structures: a critical review, Journal of Composites for Construction, ASCE, 25(4), 2021, 04021009. https://doi.org/10.1061/(ASCE)CC.1943-5614.0001142

[42] T. Tong, S. Yuan, W. Zhuo, and Z. Liu, Seismic retrofitting of rectangular bridge piers with ultra-high performance fiber reinforced concrete jackets, Composite Structures, 228, 2019, 111367. https://doi.org/10.1016/j.compstruct.2019.111367

[43] T. Tong, H. Lei, S. Yuan, and W. Zhuo, Experimental investigation and seismic vulnerability assessment of low flexural strength rectangular bridge piers retrofitted with UHPC jackets, Engineering Structures, 206, 2020, 110132. https://doi.org/10.1016/j.engstruct.2019.110132

[44] R. Hu, Z. Fang, C. Shi, B. Benmokrane, and J. Su, A review on seismic behavior of ultra-high performance concrete members, Advances in Structural Engineering, 24(4), 2021, 1054–1077. https://doi.org/10.1177/1369433220968451

[45] M.M. Kassem, F.M. Nazri, and E.N. Farsangi, The seismic vulnerability assessment methodologies: A state-of-the-art review, Ain Shams Engineering Journal, 11(4), 2020, 849–864. https://doi.org/10.1016/j.asej.2020.04.001

[46] S. Mangalathu and J.S. Jeon, Machine learning-based failure mode recognition of circular reinforced concrete bridge columns: comparative study, Journal of Structural Engineering, ASCE, 145(10), 2019, 04019104. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002402

[47] S. Mangalathu, H. Jang, S.H. Hwang, and J.S. Jeon, Data-driven machine-learning-based seismic failure mode identification of reinforced concrete shear walls, Engineering Structures, 208, 2020, 110331. https://doi.org/10.1016/j.engstruct.2020.110331

[48] S. Mangalathu and J.S. Jeon, Stripe-based fragility analysis of multispan concrete bridge classes using machine learning techniques, Earthquake Engineering and Structural Dynamics, 48(11), 2019, 1238–1255. https://doi.org/10.1002/eqe.3183

[49] R. Zhang, Y. Liu, and H. Sun, Physics-guided convolutional neural network (PhyCNN) for data-driven seismic response modeling, Engineering Structures, 215, 2020, 110704. https://doi.org/10.1016/j.engstruct.2020.110704

[50] Y. Xie, M.E. Sichani, J.E. Padgett, and R. DesRoches, The promise of implementing machine learning in earthquake engineering: A state-of-the-art review, Earthquake Spectra, 36(4), 2020, 1769–1801. https://doi.org/10.1177/8755293020919419

[51] G. Dogan, M.H. Arslan, and A. Ilki, Detection of damages caused by earthquake and reinforcement corrosion in RC buildings with deep transfer learning, Engineering Structures, 279, 2023, 115629. https://doi.org/10.1016/j.engstruct.2023.115629

[52] Y. Deng, C. Yan, and P. Niu, Hysteretic model of reinforced concrete bridge piers based on earthquake damage and corrosion from saline soil, Soil Dynamics and Earthquake Engineering, 166, 2023, 107732. https://doi.org/10.1016/j.soildyn.2022.107732

[53] P.B. Murray, D. Feliciano, B.H. Goldwyn, A.B. Liel, O. Arroyo, and A. Javernick-Will, Seismic safety of informally constructed reinforced concrete houses in Puerto Rico, Earthquake Spectra, 39(1), 2023, 5–33. https://doi.org/10.1177/87552930221123085

[54] M. D’Amato, R. Laguardia, and R. Gigliotti, Seismic retrofit of an existing RC building with isolation devices applied at base, Frontiers in Built Environment, 6, 2020, 82. https://doi.org/10.3389/fbuil.2020.00082

[55] A.V. Shegay, K. Miura, K. Fujita, Y. Tabata, M. Maeda, and M. Seki, Evaluation of seismic residual capacity ratio for reinforced concrete structures, Resilient Cities and Structures, 2(1), 2023, 28–45. https://doi.org/10.1016/j.rcns.2023.02.004

[56] A. Cascardi, R. Dell’Anna, F. Micelli, and M.A. Aiello, Reversible techniques for FRP-confinement of masonry columns, Construction and Building Materials, 225, 2019, 415–428. https://doi.org/10.1016/j.conbuildmat.2019.07.252

[57] D.A. Bournas, Concurrent seismic and energy upgrading of existing reinforced concrete buildings using textile-based composites, Energies, 11(3), 2019, 623. https://doi.org/10.3390/en11030623

[58] J.W. Baker, B.A. Bradley, and P.J. Stafford, Seismic Hazard and Risk Analysis, Cambridge University Press, Cambridge, UK, 2021.

[59] G.J. O’Reilly and G.M. Calvi, Conceptual seismic design in performance-based earthquake engineering, Earthquake Engineering and Structural Dynamics, 48(4), 2019, 389–411. https://doi.org/10.1002/eqe.3141

[60] D. Shahnazaryan and G.J. O’Reilly, Integrating expected loss and collapse risk in performance-based seismic design of structures, Bulletin of Earthquake Engineering, 19(2), 2021, 987–1025. https://doi.org/10.1007/s10518-020-00995-w

[61] A.K. Chopra, Dynamics of Structures: Theory and Applications to Earthquake Engineering, 5th ed., Pearson Education, Hoboken, New Jersey, 2020.

[62] M. Kohrangi, D. Vamvatsikos, and P. Bazzurro, Site dependence and record selection schemes for building fragility and loss assessment, Earthquake Engineering and Structural Dynamics, 48(2), 2019, 232–247. https://doi.org/10.1002/eqe.3135

[63] D.G. Lignos, A.R. Hartloper, A. Elkady, G.G. Deierlein, and R.O. Hamburger, Proposed updates to the ASCE 41 nonlinear modeling parameters for wide-flange steel columns, Journal of Structural Engineering, ASCE, 145(9), 2019, 04019083. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002353

[64] G.E. Thermou, V.K. Papanikolaou, and A.J. Kappos, Biaxial bending and compression of slender reinforced concrete columns with CFRP jackets, Composite Structures, 225, 2019, 110936. https://doi.org/10.1016/j.compstruct.2019.110936

[65] D. De Domenico, G. Ricciardi, and I. Takewaki, Design strategies of viscous dampers for seismic protection of building structures: a review, Soil Dynamics and Earthquake Engineering, 118, 2019, 144–165. https://doi.org/10.1016/j.soildyn.2018.12.024

[66] R. Gentile and C. Galasso, Gaussian process regression for seismic fragility assessment of building portfolios, Structural Safety, 87, 2020, 101980. https://doi.org/10.1016/j.strusafe.2020.101980

[67] L. Di Sarno and F. Pugliese, Numerical investigation of the seismic response of an existing RC building with corroded reinforcements, Engineering Structures, 216, 2020, 110739. https://doi.org/10.1016/j.engstruct.2020.110739

[68] A. Furtado, H. Rodrigues, A. Arêde, and H. Varum, Seismic performance of masonry infill walls under biaxial out-of-plane/in-plane cyclic loading, Engineering Structures, 211, 2020, 110355. https://doi.org/10.1016/j.engstruct.2020.110355

[69] P.G. Asteris, A.D. Skentou, A. Bardhan, P. Samui, and K. Pilakoutas, Predicting concrete compressive strength using hybrid ensembling of surrogate machine learning models, Cement and Concrete Research, 145, 2021, 106449. https://doi.org/10.1016/j.cemconres.2021.106449

[70] H. Dong, B. Han, X. Du, and K. Bi, Seismic performance of corroded reinforced concrete columns under biaxial loading, Engineering Structures, 229, 2021, 111903. https://doi.org/10.1016/j.engstruct.2020.111903

[71] M.N. Fardis, Seismic Design, Assessment and Retrofitting of Concrete Buildings: Based on EN-Eurocode 8, 2nd ed., Springer, Dordrecht, 2021.

[72] H.D. Nguyen, J.M. LaFave, Y.J. Lee, and M. Shin, Rapid seismic damage-state assessment of steel moment frames using machine learning, Engineering Structures, 252, 2022, 113737. https://doi.org/10.1016/j.engstruct.2021.113737

[73] J.G. Xu and D.C. Feng, Data-driven rapid damage evaluation for life-cycle seismic assessment of regional reinforced concrete bridges, Earthquake Engineering and Structural Dynamics, 51(9), 2022, 2144–2164. https://doi.org/10.1002/eqe.3699

[74] F. Kazemi and R. Jankowski, Machine learning-based seismic response and performance assessment of reinforced concrete buildings, Archives of Civil and Mechanical Engineering, 23(2), 2023, 94. https://doi.org/10.1007/s43452-023-00631-9

[75] F. Kazemi, N. Asgarkhani, and R. Jankowski, Machine learning-based seismic fragility and seismic vulnerability assessment of reinforced concrete structures, Soil Dynamics and Earthquake Engineering, 166, 2023, 107761. https://doi.org/10.1016/j.soildyn.2023.107761

[76] X. Shang, J. Yu, L. Li, and Z. Lu, Strengthening of RC structures by using engineered cementitious composites: a review, Sustainability, 11(12), 2019, 3384. https://doi.org/10.3390/su11123384

[77] J. Shafaei and M. Adibi, Seismic performance evaluation of retrofitted RC beam-column joints reinforced by plain and deformed bars, European Journal of Environmental and Civil Engineering, 2021. https://doi.org/10.1080/19648189.2021.1926334

[78] M.E. Shoukry, A.M. Tarabia, and M.Z. Abdelrahman, Seismic retrofit of deficient exterior RC beam-column joints using steel plates and angles, Alexandria Engineering Journal, 61(4), 2022, 3147–3164. https://doi.org/10.1016/j.aej.2021.08.048

[79] Z.N. Wu, X.L. Han, A. He, Y.F. Cai, and J. Ji, Machine learning-based adaptive degradation model for reinforced concrete beams, Engineering Structures, 253, 2022, 113817. https://doi.org/10.1016/j.engstruct.2021.113817

[80] M.A.B. Kabir, A.S. Hasan, and A.M.M. Billah, Failure mode identification of column base plate connection using data-driven machine learning techniques, Engineering Structures, 240, 2021, 112389. https://doi.org/10.1016/j.engstruct.2021.112389

[81] American Concrete Institute, Building Code Requirements for Structural Concrete and Commentary, ACI 318-19, ACI, Farmington Hills, Michigan, 2019.

[82] American Society of Civil Engineers, Minimum Design Loads and Associated Criteria for Buildings and Other Structures, ASCE/SEI 7-22, ASCE, Reston, Virginia, 2022.

[83] S. Mangalathu and J.S. Jeon, Regional seismic risk assessment of infrastructure systems through machine learning: active learning approach, Journal of Structural Engineering, ASCE, 146(12), 2020, 04020269. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002831

[84] D.A. Pohoryles and D.A. Bournas, Seismic upgrading of existing RC buildings with textile reinforced concrete: a state-of-the-art review and comparative assessment with FRP jacketing, Construction and Building Materials, 265, 2020, 120558. https://doi.org/10.1016/j.conbuildmat.2020.120558

[85] S. Aaleti, P. Petersen, and S. Sritharan, Seismic performance of lap-spliced RC columns retrofitted with UHPC cover replacement, Journal of Structural Engineering, ASCE, 150(8), 2024, 04024079. https://doi.org/10.1061/JSENDH.STENG-12711

[86] D. De Domenico and G. Ricciardi, Optimal design and seismic performance of tuned mass damper inerter (TMDI) for structures with nonlinear base isolation systems, Earthquake Engineering and Structural Dynamics, 47(12), 2018, 2539–2560.

[87] R. Joseph, A. Mwafy, and M.S. Alam, Experimentally verified retrofit combining hybrid solutions for enhancing the seismic response of multistory RC structures, The Structural Design of Tall and Special Buildings, 34(1), 2024, e2196. https://doi.org/10.1002/tal.2196

[88] A. Torky and S. Ohno, Deep learning techniques for predicting nonlinear multi-component seismic responses of structural buildings, Computers and Structures, 252, 2021, 106570. https://doi.org/10.1016/j.compstruc.2021.106570

Citation: Keshav Raghunath Kale, Rohit S. Gunjal, Sadhu B. Nagargoje, Dinesh M. Pandit, Parmeshwar M. Pawar, Krushna S. Gore. (2026). Seismic Performance Evaluation and Retrofitting of Reinforced Concrete Structures: A Comprehensive Literature Review. *International Journal of Civil Engineering and Technology (IJCIET)*, 17(4), 1-24.

Abstract Link: https://iaeme.com/Home/article_id/IJCIET_17_04_001

Article Link: https://iaeme.com/MasterAdmin/Journal_uploads/IJCIET/VOLUME_17_ISSUE_4/IJCIET_17_04_001.pdf

✉ **editor@iaeme.com**