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Literature based Review

Advancing Seismic Resilience through Sustainable Structural Solutions: A Review of Material and Analytical Innovations in RC Design

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Abstract

Reinforced concrete (RC) structures, that are built with outdated seismic evaluations faced significant damage due to the earthquakes, which highlights the needs for resilient and sustainable strengthening solutions. In order to evaluate their efficacy in enhancing seismic behavior, this review summarizes recent developments in high performance materials like fibre reinforced polymer composites and engineered cementitious composites by applying nonlinear analytical techniques like pushover and nonlinear time-history analyses. Using Scopus, Web of Science, and Google Scholar, a focused literature search was carried out with an emphasis on important topics such as FRP-based retrofitting, engineered cementitious composites (ECC), and low-impact building materials that support sustainability objectives. Through lighter interventions, longer service life, and fewer repair requirements, innovations like FRP retrofitting and ECC-based detailing greatly improve ductility, energy absorption, and post-earthquake functionality while minimizing environmental impact, as the chosen studies show. The data also shows that proactive performance-based design (PBD), where nonlinear modeling enables educated retrofit decisions to meet targeted resilience targets, is increasingly replacing reactive repair solutions. Overall, this research emphasizes how crucial it is to combine cutting-edge seismic assessment techniques with sustainable material technologies in order to facilitate the construction of resilient, low-carbon RC infrastructure in earthquake-prone areas.

Keywords: - Engineered Cementitious Composites , Fiber Reinforced Polymer , Nonlinear Analysis, Seismic Resilience.

1. Introduction

Nowadays structures are analyzed and designed using easy linear or elastic analysis methods but in reality the response of structure is not elastic during high seismic conditions. To understand the complex inelastic response different researchers have proposed nonlinear analysis methods which provide a strong foundation for performance based design. New techniques were based on the design method to determine the real movement of the structure under seismic conditions, therefore for the new structures as well as for existing structure non linear pushover analysis is used which is very effective for design [1].To preserved the heritage and old buildings of concrete structure in high seismic zones has to be focused to avoid any disaster, due to the earthquake the structure witnesses the damage which has to be determined to set the benchmark for level of safety. For examining these factors linear elastic method is not efficient [2]. Pushover analysis is done by applying the x direction loads in a increasing manner which effect the structure when faced the ground shaking. Due to the lateral loads acting on it the buildings will face the loss in stiffness. A pushover analysis generate the non linear force displacement relationship [2] ,[3].

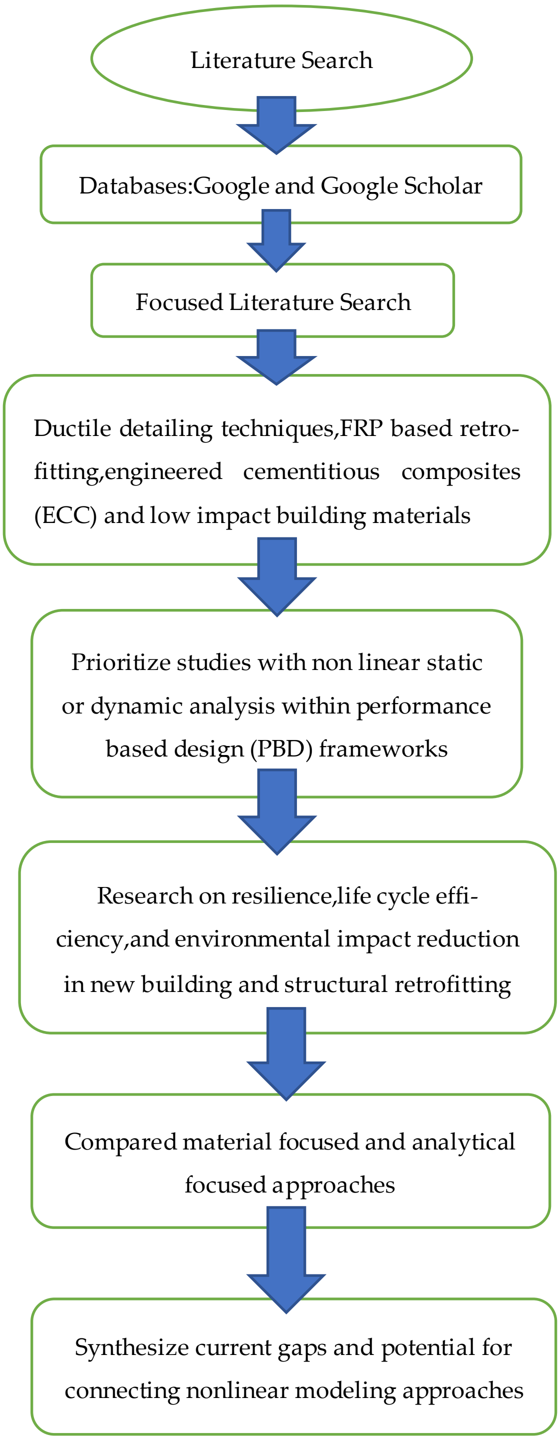
One of the technique is isolation for improving the seismic behaviour of buildings. Other is to cover the weaker elements with the FRP sheets which is efficient due to i) do not require the evacution of the occupants for a long period; ii) less polluting than other repairs methods; iii) increase the ductility and strength; iv) it does not increase the weight of the building.Some limitations of this technique should be also mentioned such as, for instance, the poor improvement of structural stiffness it brings or the high costs it typically entails.[4].Retrofitting is done to for the safety of the structures during the earthquakes, so that the kateral forces will cause less damage to the structures. Various techniques have been developed and implemented to achieve this goal, with each has unique advantages and applications[5]. Moreover, now it is more focusing on the effectiveness, sustainability and more energy efficiency. The purpose of this review is to have a detailed study of seismic retrofitting techniques for existing structures, focusing on recent innovations, methodologies, and materials used to enhance seismic performance, including fiber reinforced polymer composites, concrete jacketing, steel bracing systems, and advanced modelling techniques, with an emphasis on improving resilience in earthquake-prone areas[5],[6],[7].

Mainly the social and economics infrastructures are built on residential and commercial structures. Housing are constructed using the concrete, steel, wood and stone. Originally utilized for minor parts like windows, doors, canopies, profiles, and other decorative elements, fiber reinforced polymer (FRP) composites are now used for entire buildings[8],[9].FRP with the composite like glass, aramid, carbon, and basalt are used In the structural engineering applications. Furthermore differnet types of additives were used with the polymer to improve its performance like wettability and fabrication, which further reduce the costs. This way, the FRP composites can be employed for both internal and external applications in RC structures[10]. The increasing demand of FRP enhance the engineering technique and efficiency in civil engineering. Both rehabilitation repair, strengthening, and retrofit and creative new building techniques utilizing full FRP or hybrid FRP concrete systems are part of structural renewal due to which long-term structural performance and durability are enhanced as a result[11].In the industry, engineers are emphasizes on the material ductility, costs and the structural performance of reinforced Engineered Cementitious concrete or Reinforced engineered cementitious concrete .At this point, it is clear that a milestone has been reached where there is a broad international community, involving academic, industrial and govern mental concerns engaged in ECC science and technology development. [12].

2. Research Methodology

In order to examine how sustainable material advances and analytical methods lead to improved seismic performance in reinforced concrete structures; this review uses an organized methodological framework. Using Scopus, Web of Science, and Google Scholar, a focused literature search was carried out with an emphasis on important topics such ductile detailing techniques, FRP-based retrofitting, engineered cementitious composites

(ECC), and low-impact building materials that support sustainability objectives. To guarantee technological relevance to contemporary seismic engineering practice, studies incorporating nonlinear static or dynamic analysis within performance-based design (PBD) frameworks were given priority. Research on resilience, life-cycle efficiency, and environmental impact reduction in both new building and structural retrofitting was prioritized in the selection criteria. In order to compare how well the reviewed works improved seismic behavior while achieving sustainability goals, they were divided into material-focused and analytical-focused approaches. In order to enhance resilient RC infrastructure, the final synthesis identifies current gaps and potential in connecting nonlinear modeling approaches with creative sustainable design ideas.



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3. Sustainable Material and Retrofitting Innovations for Enhanced Seismic Performance

Owens Glass company was the first one to introduced the patented fiber glass, and its matrial mostly used in the military and aerospace industries. Numerous research studies have been conducted since then to study the potential applications of FRP composites in structural engineering[10]. Fibre reinforced concrete is divided into two further categories i) internal applications such as rods, tendons and FRP bars, and external applications includes FRP plates, fabrics and wraps. For the retroffiting, strengthening purpose industries focuses on the FRP prestressed concrete structures. A tree diagram shows the composite of the FRP composites with its applications in figure 1(a),(b).

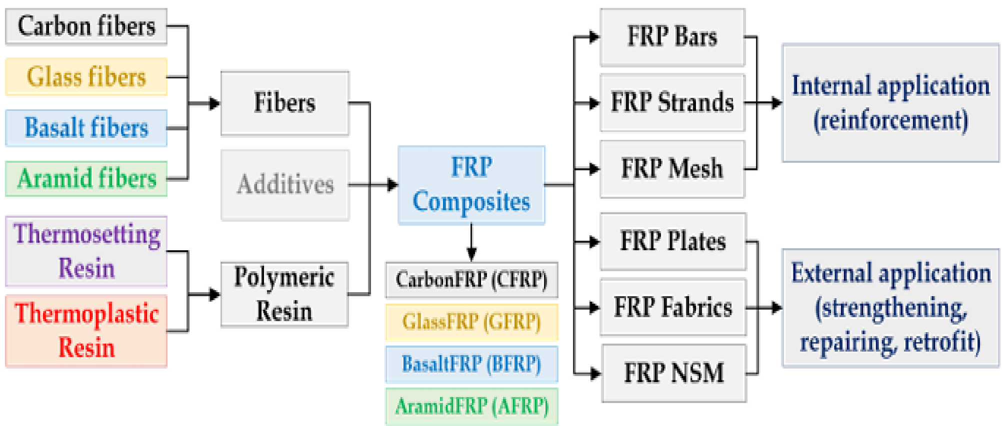


Figure 1. FRP composites used in concrete structures [10].

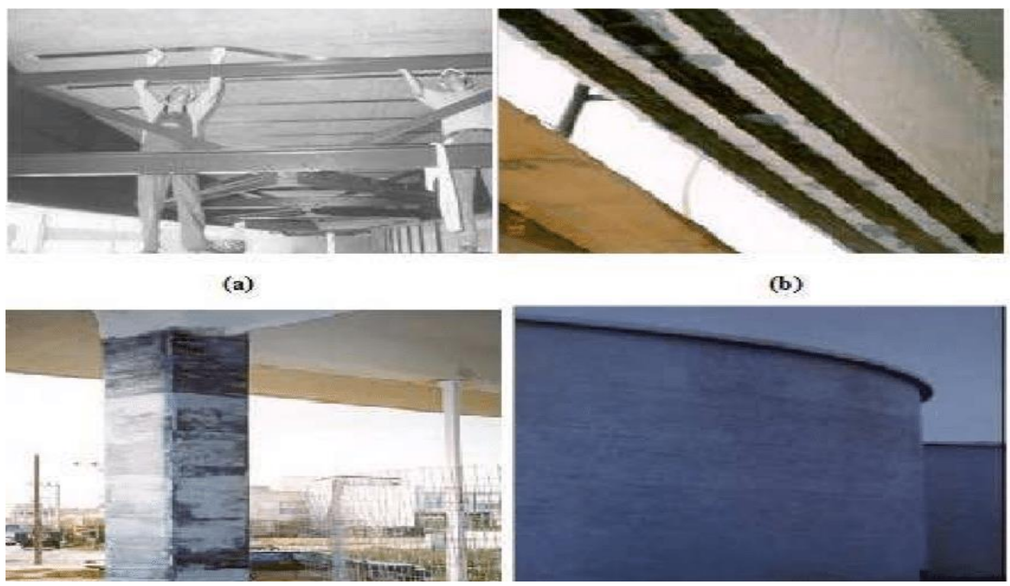


Figure 2. FRP Composite strengthening[13]

The FRP composite is used internally where the steel reinforcement get corode and weak to cover the economic and safety of the structure. For lowering the environmental impacts like global warming, chemical reactions FRP composites are suitable for these conditions. [10],[14]. Furthermore, when we notice the the external application of FRP composites as primarily been implemented for the retrofitting of structures when lack of design techniques is noticed, after experiencing the extreme events such as fire and seismic the elements load bearing capacity is modified for those which start to deteriorate after these events.

Table 1. Comparison of different fibres

Property	GFRP Bars	CFRP Fabrics	Basalt Fibre (BFRP / BFRM)
Reference	[10]	[10]	[15]
General Mechanical Performance	Good overall performance, tensile 550 to 1380 Mpa, modulus 44.8 to 60 Gpa, Serviceability governs.	Very high strength and stiffness; excellent for strengthening; bond degradation under moisture.	High strength, increased ductility, good crack control, good chemical and thermal resistance.
Tensile Strength	550 to 1380 MPa depending on product.	Not numerically specified; high strength.	Mesh tensile capacity 45 kN/m. Basalt fibres commonly 1000 to 1500 Mpa.
Flexural Strength / Performance	Flexural governed by serviceability, retains >70% strength under alkalinity.	Water exposure decreases flexural strength; resin moisture absorption critical.	BFRM increases flexural capacity 25 to 40%; improves crack resistance and ductility.
Durability Performance	Good retention in water, saline, alkaline environments (67 to 93%).	Moisture reduces bond; adhesive failure becomes dominant.	Enhanced durability, better crack resistance, stable load behavior under repeated loading.
Sustainability	Lower environmental impact than steel.	Not discussed as sustainable.	Environmentally friendly, natural volcanic rock; chemically additive free, recyclable, lower embodied energy than CFRP.
Strength to Weight Efficiency	Density ¼ steel in high strength to weight.	High strength-to-weight; easy installation.	Higher strength to weight ratio, lighter than steel, good energy absorption.
Cost / Availability	Slightly more expensive than steel but near parity.	No cost data.	basalt is described as low cost and widely available natural material.

In addition to the previously mentioned advantages of FRP materials, their strength-to-weight ratio, ease of installation, and suitability for irregular surfaces are additional reasons that have contributed to their popularity as a strengthening technique [10],[14].FRP composites are used for the external structural elements like beams ,coloumn and slab, to enhance the flexural, shear strength of the elements without increasing their weight.

Table 2. Comparison of different fibres

Application	Internal Application	External Application	Material Specifications
AASHTO	LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete (2nd ed.)	Guide Specifications for Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements (1st ed.)	ASTM International D7205/D7205M-06(2016). D7914/D7914M. D7957/D7957M-22
ACI	ACI 440.22. Code Requirements for Structural Concrete Reinforced with Glass FRP Bars (1st ed.)	ACI 440.2R-17. Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures	ACI SPEC-440.5-22. Construction with Glass Fiber-Reinforced Polymer Reinforcing Bars

CSA	CSA S806-12 (R2017). Design and construction of building structures with fibre-reinforced polymers	CSA S806-12 (R2017). Design and construction of building structures with fibre-reinforced polymers	CSA S807-19. Specification for fibre-reinforced polymers
JPCI	Recommendation for Design and Construction of Concrete Structures using Fiber Reinforced Polymers (FRP)	-	-

Ali Abbaszadeh and Omar Chaallal examine the potential of externally bonded Fiber Reinforced Polymer (EB-FRP) composites for improve self-centering and lessen residual drift in Single Shear Walls (SSWs), which are essential for withstanding seismic stresses but frequently undergo irreversible deformation. They assessed three EB-FRP configurations (R1-SSW, R2-SSW, and R3-SSW) under various seismic characteristics using nonlinear time-history analyses on 20- and 15-story buildings in Vancouver and Montreal. The findings demonstrate that EB-FRP greatly improves post-earthquake performance by reducing residual inter-story drift. All things considered, EB-FRP offers an affordable, minimally invasive way to reinforce current SSWs and increase seismic resilience. Gangarao Hota and Ruifeng Liang offer an overview of fiber reinforced polymer (FRP) composites, focusing their corrosion resistance, more strength-to-weight ratio, and high durability that make them crucial 21st-century construction materials. The study analyzes over 25 years of research and field applications across highways, bridges, utility systems, renewable energy, green buildings, and advanced retrofitting. FRPs offer noncorrosive, lightweight, and ecologically beneficial alternatives to standard materials, with qualities that can be customized to performance needs. All things considered, their application represents a significant change in civil infrastructure by enhancing long-term cost effectiveness, sustainability, and durability.[8],[9]

This review about the durability of fiber-reinforced polymer (FRP) composites in concrete structures is presented by Jesús D. Ortiz, who focuses on how mechanical impacts (creep rupture, fatigue) and environmental conditions (water, alkalinity, temperature) affect their performance. The study assesses existing design guidelines for FRP-reinforced and strengthened concrete and looks at important FRP materials including glass/vinyl-ester bars and carbon/epoxy textiles. Results indicate that, in the absence of numerous stressors, the majority of exposures result in a tensile strength drop of no more than 20%. This information encourages the appropriate use of FRPs to guarantee the long term dependability and durability of FRP concrete and strengthened concrete systems[10],[14].Using Fiber-Reinforced Polymer (FRP) sheets, a quick and lightweight method that enhances the seismic performance of buildings built to antiquated norms, Juan-Carlos Vielma-Perez investigates the efficacy of pre-seismic reinforcing. The work employs nonlinear static and dynamic calculations to assess how FRP strengthening improves global structural behavior prior to an earthquake, with a focus on an existing Italian residential structure. Such pre-seismic reinforcement can greatly enhance performance, according to the results, highlighting the need of nonlinear analysis for pre-planning and verifying retrofit schemes.[4]

The vast amount of research has done on Engineered cementitious composite (ECC) for the commercial development due to the micromechanics based design theory. ECC is known because of its good tensile strain capacity which is far better than the normal concrete. Even with a relatively low fiber volume fraction (less than 2-3%), this design methodology produces a versatile material that may be treated using techniques like casting, extrusion, or spraying. To facilitate the usage of ECC, a sizable database of its mechanical and physical characteristics is being created.

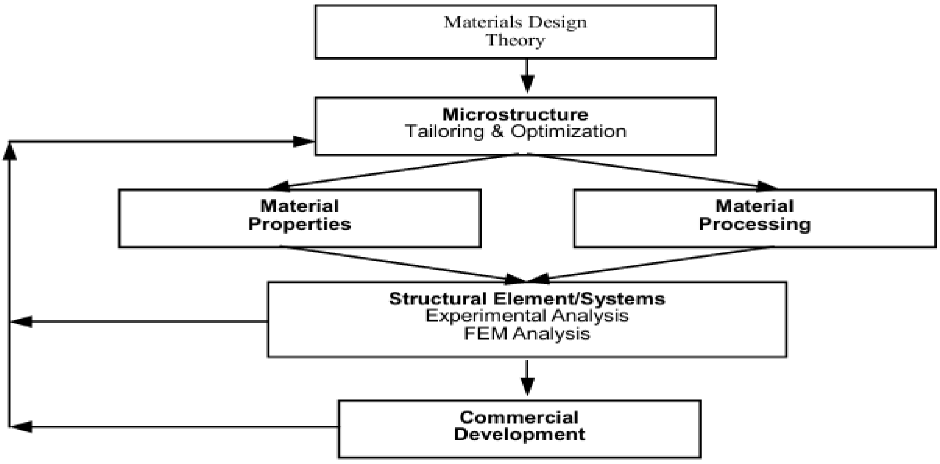
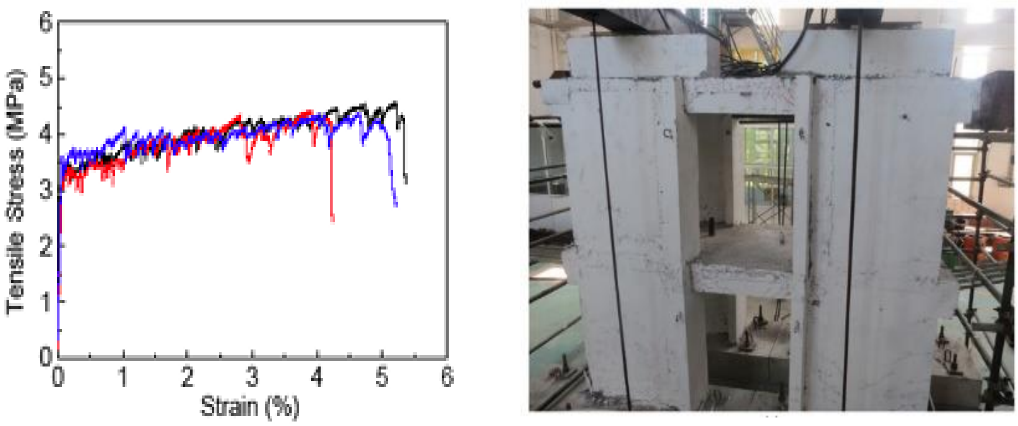


Figure 2. Flow-chart of important elements of the research and development of Engineered Cementitious Composites. Investigations into structural applications [12]

ECC is very appealing for a variety of structural applications, including those that call for improved seismic performance, due to its high ductility. Rational approaches to structural design with ECC are being established by experiments and constitutive models incorporated into FEM codes. The long-term advantages are anticipated to propel its commercialization worldwide, especially in nations like Japan, Korea, and the US, despite the initial raw material cost being more than that of regular concrete. In order to improve the material through a constant feedback loop, ongoing R&D focuses on cutting costs, creating specific variants of ECC with special features (such light weightedness), and encouraging cooperation among all stakeholders. A decade of advancements in engineered cementitious composites , an ultra-ductile fiber-reinforced material intended for widespread, economical application in building, are reviewed by Victor C. Li. The paper details the improved ductility, toughness, and structural performance of ECC and emphasizes the crucial role of micromechanics in its design through an extensive review of theoretical and experimental studies. When compared to regular concrete, applications in structural systems, repairs, and retrofits show notable improvements in capacity, stiffness, and energy absorption. Future obstacles and chances to advance ECC development and implementation are also noted in the review. [16],[12]



(**a**) (**b**)

Figure 3 a) Uniaxial tensile stress-strain curves of an ECC reinforced with 2% PVA-REC15 fibers, showing high tensile ductility of about 5%.[12]. b) ECC/RC Composite Coupled Shear Walls[17]

Pushover analysis is an analysis method in which the structure is subjected to increasing lateral forces with an constant height-wise distribution until a target displacement is reached [18].. The applied lateral loads were accelerations in the x direction representing the forces that would be experienced by the structures when subjected to ground shaking[2].These parametrs gives the force- deformation potential locations such as plastic hinges in pushover analysis. As shown in Figure 4 below, five points labelled A, B, C, D, and E are used to define the force deformation behaviour of the plastic hinge, and three points labelled IO (Immediate Occupancy), LS (Life Safety) and CP (Collapse Prevention) are used to define the acceptance criteria for the hinge.[19],[20]

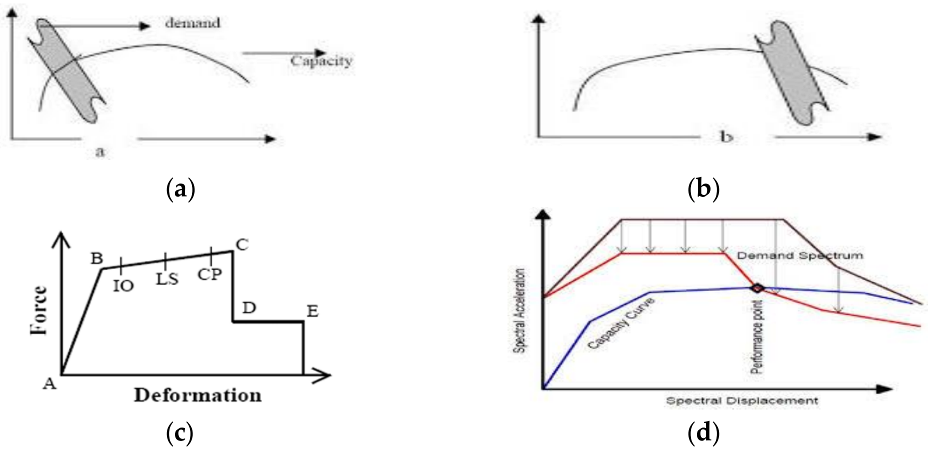


Figure 4 Seismic demand and capacity graphs (a) safe design; (b) unsafe design [2]. c) Load –Deformation curve[19]. d) Capacity curve, Demand Spectrum and Performance Point[1]

Performance-Based Seismic Design (PBSD) is emphasized by Nishant and Siddhant Rana, who focus on the importance of examining the building inelastic behavior for better seismic investigation. They describe how Pushover Analysis, a non-linear static technique that has been in use since the 1970s, tracks the force-displacement behavior of a structure by applying constant gravity loads and gradually rising lateral forces. This method creates capacity curves that may be compared with seismic demand, exposes the evolution of deterioration, and highlights important elements. All things considered, pushover analysis is a useful and straightforward method for forecasting non-linear seismic behavior and directing retrofit plans for already-existing structures.[1],[3]. Following the 2003 Boumerdes earthquake, which exposed serious structural flaws, A. Kadid and A. Boumrkik examine the seismic performance of Algerian reinforced concrete frame buildings. They evaluated performance under increasing seismic demand by measuring base shear capacity, displacement response, and hinge development on 5, 8, and 12-story frames using nonlinear static pushover analysis. The findings demonstrate that well-designed frames can function satisfactorily, although poor material quality and weak-column/strong-beam pairings were the main causes of reported failures. In order to fully comprehend the general behavior of RC frame buildings in Algeria, the study emphasizes the necessity for more case studies.[2],[21]

Jhon In his analysis of current developments in seismic retrofitting, Philip P. Camayang highlights the significance of this technique for improving the resilience of buildings in seismically active areas. In addition to machine learning and sophisticated modeling for optimal design, the study looks at contemporary methods such as FRP composites, concrete jacketing, steel bracing, and new materials like shape memory alloys. Results show that these techniques greatly increase structural strength and lessen seismic damage. All things considered, the analysis reaffirms the need for creative retrofitting techniques to fortify both modern and historic structures.[5]

4. Comparison

Table 4. Summary of the Literature Review papers

Researchers	Focus Area	Analysis Method	Seismic Performance Outcomes	Sustainability Benefits
Li (2003)	ECC for structural & retrofit applications	Experimental + theoretical review	Ultra ductility, superior crack control	Extended service life; reduced repair demand
Abbaszadeh & Chaallal (2020)	EB FRP strengthening of SSWs	Nonlinear time-history	Reduced residual drifts; improved self centering	Low intrusive retrofit; lightweight
Hota & Liang (2017)	FRP for resilient infrastructure	Field implementation review	Higher durability and performance in harsh conditions	Low embodied energy; corrosion free
Ortiz et al. (2024)	FRP RSC durability under environmental loads	Durability review	≤20% strength reduction under exposure	Increased longevity of RC elements
Vielma-Perez et al. (2018)	FRP seismic retrofit of RC buildings	NL static + dynamic	Increased global building resilience	Reduced demolition waste; low added mass
Rana & Rana (2021)	Performance based pushover methodologies	Review + modeling assessment	Accurate damage prediction and capacity evaluation	Optimization reduces material use
Kadid & Boumrkik (2008)	RC frame seismic performance (Algeria)	Pushover analysis	Good response when ductile detailing present	Prevents failures lower reconstruction needs
Camayang (2022)	Innovative retrofit technologies	Comprehensive review	Improved structural strength and failure mitigation	Supports sustainable adaptive reuse

5. Conclusions

After reviewing all important aspects related to material and new innovations techniques it is recommended that the high use of the performance materials like FRP and ECC, which enhance the ductility ,corrosion resistance and energy dissipation while decreasing the environmental impacts and increase the service life. Although both Fiber-Reinforced Polymer (FRP) and Engineered Cementitious Composite (ECC) are advanced building materials, their performance, behavior, and composition are different. FRP is a lightweight, corrosion-resistant composite with a very high tensile strength that is perfect for retrofitting or strengthening structures. It is built from fibers (such as carbon or glass) inserted in a polymer matrix. Conversely, ECC is a unique kind of fiber-reinforced concrete that is intended to have ductile, crack-controlled behavior; it may experience significant deformation without failing and produces numerous tiny microcracks rather than massive ones. When comparing the two, ECC offers better flexibility and crack-control capabilities, while FRP typically delivers stronger tensile strength and outstanding longevity because of its corrosion resistance. [22],[23].Compared to FRP products, which are often made worldwide, ECC is more specialized and less readily available. Futhermore ECC is the superior option for long-term durability in cement-based structures because of its remarkable crack resistance, whereas FRP is the superior option for pure strength, lightweight application, and wide availability. Secondly, Pushover and nonlinear time history simulations allow for performance based design strategies for optimal and effective strengthening solutions, as well as accurate assessment of damage progression.

1. Abbreviations

The following abbreviations are used in this manuscript:

FRP	Fibre reinforced concrete
ECC	Engineered Cementitious composite
PBSD	Performance Based Design
IO	Immediate occupancy
LS	Life Safety
CP	Collapse Prevention

References

[1]Rana, N. and S. Rana, *Non-linear static analysis (pushover analysis) a review.* International Journal of Engineering and Technical Research (IJETR), 2015. **3**(7): p. 2321-0869.

[2] Kadid, A. and A. Boumrkik, Pushover analysis of reinforced concrete frame structures. 2008.

[3] Deierlein, G.G., A.M. Reinhorn, and M.R. Willford, *Nonlinear structural analysis for seismic design.* NEHRP seismic design technical brief, 2010. **4**: p. 1-36.

[4] Vielma-Perez, J.-C., M.C. Porcu, and M.A. Gómez, *Non-linear analyses to assess the seismic performance of RC buildings retrofitted with FRP.* Revista Internacional de Metodos Numericos para Calculo y Diseno en Ingenieria, 2020. **36**(2): p. 1-13.

[5] Camayang, J.P.P. and J.A. Padilla. *Seismic Retrofitting: Techniques and Innovations for Structural Resilience*. in *IOP Conference Series: Earth and Environmental Science*. 2025. IOP Publishing.

[6] Golias, E., et al., *Effectiveness of the Novel Rehabilitation Method of Seismically Damaged RC Joints Using C-FRP Ropes and Comparison with Widely Applied Method Using C-FRP Sheets—Experimental Investigation. Sustainability 2021, 13, 6454*. 2021, s Note: MDPI stays neutral with regard to jurisdictional claims in published ….

[7] Pohoryles, D.A., et al., *Seismic retrofit schemes with FRP for deficient RC beam-column joints: State-of-the-art review.* Journal of Composites for Construction, 2019. **23**(4): p. 03119001.

[8] Hota, G. and R. Liang. *Advanced fiber reinforced polymer composites for sustainable civil infrastructures*. in *Proceedings of the International Symposium on Innovation & Sustainability of Structures in Civil Engineering*. 2011. Xiamen University.

[9] Pang, M., S. Yang, and Y. Zhang, *Experimental study of cement mortar-steel fiber reinforced rammed earth wall.* Sustainability, 2012. **4**(10): p. 2630-2638.

[10] Ortiz, J., et al., *FRP-Reinforced/Strengthened Concrete: State-of-the-Art Review on Durability and Mechanical Effects. Materials 2023, 16, 1990*. 2023.

[11] Van Den Einde, L., L. Zhao, and F. Seible, *Use of FRP composites in civil structural applications.* Construction and building materials, 2003. **17**(6-7): p. 389-403.

[12] Li, V.C., *On engineered cementitious composites (ECC) a review of the material and its applications.* Journal of advanced concrete technology, 2003. **1**(3): p. 215-230.

[13] Gunaslan, S.E. and A. Karasin, *Confining concrete columns with FRP materials.* Eur. Sci. J. ESJ, 2017. **13**: p. 464-470.

[14] Yan, F., Z. Lin, and M. Yang, *Bond mechanism and bond strength of GFRP bars to concrete: A review.* Composites Part B: Engineering, 2016. **98**: p. 56-69.

[15] Protchenko, K. and E. Szmigiera, *Post-fire characteristics of concrete beams reinforced with hybrid FRP bars.* Materials, 2020. **13**(5): p. 1248.

[16] Fukuyama, H., et al., *Structural performance of beam elements with PVA-ECC.* Proc. of High Performance Fiber Reinforced Cement Composites 3 (HPFRCC 3), 1999: p. 531-542.

[17] Yang, J., et al., *Research on Optimization Design of Prefabricated ECC/RC Composite Coupled Shear Walls Based on Seismic Energy Dissipation.* Buildings, 2024. **14**(4): p. 951.

[18] Mohod, M.V., *Pushover analysis of structures with plan irregularity.* J Mech Civ Eng, 2015. **12**(4): p. 46-55.

[19] Govind, M., K.K. Shetty, and K.A. Hegde, *Non linear static pushover analysis of irregular space frame structure with and without t shaped columns.* International Journal of Research in Engineering and Technology, 2014. **3**(3): p. 663-667.

[20] Council, A.T., *Seismic evaluation and retrofit of concrete buildings.* Report No. SSC 96-01: ATC-40, 1996. **1**.

[21] Prestandard, F., *commentary for the seismic rehabilitation of buildings (FEMA356).* Washington, DC: Federal Emergency Management Agency, 2000. **7**(2): p. 518.

[22] Cai, J., J. Pan, and X. Zhou, *Flexural behavior of basalt FRP reinforced ECC and concrete beams.* Construction and Building Materials, 2017. **142**: p. 423-430.

[23] Ge, W., et al., *Experimental study on flexural behavior of ECC-concrete composite beams reinforced with FRP bars.* Composite Structures, 2019. **208**: p. 454-465.