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REVIEW ARTICLE

FRP reinforced recycled aggregate concrete columns under static loading: a comprehensive review with machine learning perspectives

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Abstract: This review paper investigates the behaviour of fibre-reinforced polymer (FRP)-reinforced recycled aggregate concrete (RAC) columns under static loading conditions. The adoption of RAC, which uses recycled materials, is essential for sustainable construction, but its reduced mechanical properties pose challenges. To enhance RAC structural performance, FRP composites are applied to improve compressive strength, ductility, and energy dissipation capacity. FRP confinement mechanisms, including external wrapping and hoop reinforcement, provide lateral support, effectively increasing the axial load capacity of RAC columns and delaying failure mechanisms such as concrete crushing and FRP debonding. This paper examines over 100 studies, focusing on key parameters such as FRP material type (carbon, glass, aramid), the confinement effect of FRP, and the recycled aggregate replacement ratio. The review finds that FRP reinforcement significantly enhances RAC columns' compressive strength and ductility, with axial load capacity improving by up to 88.7% and energy dissipation increasing by 24.5%. However, the interaction between FRP and RAC remains complex, with increased recycled aggregate replacement ratios resulting in a decrease in compressive strength by approximately 19% at 100% replacement. Despite the positive outcomes, challenges such as long-term durability, environmental impact, and cost-effectiveness remain. The research identifies gaps, including the need for more studies on long-term performance, life-cycle assessments (LCA), and the development of predictive models for FRP-RAC columns. Key conclusions highlight that FRP reinforcement can boost column strength and ductility, but further investigation into environmental impacts and long-term behaviour is necessary. The review emphasizes future research directions to optimize FRP-RAC column design and sustainability.

Keywords: RAC column, FRP, static loading, confinement, durability, life cycle assessment

1 Introduction

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The increasing global demand for sustainable construction practices has spurred significant interest in utilizing recycled materials in concrete [1-3]. Recycled aggregate concrete (RAC), incorporating aggregates derived from demolished concrete structures, offers a promising solution to reduce reliance on natural resources and minimize construction waste. However, the mechanical properties of RAC can differ from conventional concrete, often exhibiting reduced strength and increased variability [4]. To address these limitations and enhance the structural performance of RAC elements, the application of fibre-reinforced polymers (FRP) has emerged as a highly effective technique. FRP composites, characterized by their high strength-to-weight ratio and excellent durability, provide external confinement and reinforcement, significantly improving the strength and ductility of concrete members, including those made with RAC [5]. This combination of RAC and FRP offers a synergistic approach, combining environmental benefits with enhanced structural performance.

The research journey into FRP-RAC columns has evolved over several stages. Initial investigations, primarily in the late 20th and early 21st centuries, focused on understanding the fundamental mechanical properties of RAC itself. Researchers explored the influence of various factors, such as the source and processing of recycled aggregates, the replacement ratio of recycled aggregates (i.e., the percentage of natural aggregate replaced with recycled aggregate), water-cement ratio, and curing conditions, on the compressive strength, flexural strength, elastic modulus, and durability of RAC [6-8]. These early studies laid the groundwork for subsequent research by establishing a baseline understanding of RAC behaviour and identifying key parameters influencing its performance.

Building upon this foundational knowledge, researchers began exploring the application of FRP to enhance the structural behaviour of RAC elements. Early studies on FRP-confined RAC columns, appearing in the early 2000s, demonstrated the effectiveness of FRP wrapping in improving the compressive strength and ductility of RAC columns, mirroring similar findings observed in conventional concrete columns [9-10]. These initial investigations explored the influence of key parameters such as the number of FRP layers, the type of FRP material (e.g., carbon, glass, or aramid), and the shape of the column cross-section (circular, square, rectangular) on the overall structural performance. Researchers also started investigating the interaction between the FRP and RAC, recognizing the importance of bond strength and the potential for debonding as a failure mechanism.

1.1 Overview of the need for sustainable construction materials and the role of RAC

The construction industry significantly impacts the environment through pollution and waste from material usage and energy consumption. Addressing these issues is crucial to protecting our planet for future generations [11]. Buildings consume nearly 16% of the world's freshwater and account for 25% of global wood harvesting. Moreover, the construction industry contributes roughly 40% of global carbon emissions, underscoring its role in environmental degradation driven by resource-intensive practices and waste generation [12-14]. This emphasizes the urgent need for sustainable practices. Globalization exacerbates resource depletion and environmental damage due to rising demands, making sustainable building practices essential for promoting environmental stewardship. The increasing awareness of the environmental challenges posed by traditional construction methods has led to a greater focus on sustainable building practices. Globalization further exacerbates resource depletion and environmental degradation due to rising demands, making sustainable construction even more crucial for promoting environmental stewardship [15]. The selection of sustainable materials has become a central aspect of this movement, though it remains a complex task due to the need to balance environmental, economic, and social considerations. By integrating RAC into construction practices, we can make significant strides toward more sustainable building practices. In addition to minimizing environmental degradation, RAC supports the goals of reducing reliance on non-renewable resources, conserving natural aggregates, and lowering carbon emissions associated with concrete production [16]. Sustainable buildings that prioritize the use of materials like RAC contribute to enhanced durability, lower operational costs, and improved human health, all while minimizing negative environmental impacts. This shift toward sustainable construction practices not only promotes a healthier future but also plays a crucial role in mitigating the ongoing effects of climate change [17].

1.2 Advantages of Fibre-Reinforced Polymer (FRP) in structural reinforcement

Fibre-Reinforced Polymer (FRP) reinforcement has gained recognition since the late 20th century as an innovative alternative to traditional steel bars in reinforced concrete structures. Longitudinal bars are primarily used to enhance tensile strength and are typically made of materials such as carbon (CFRP), glass (GFRP), or aramid (AFRP) fibres. CFRP is especially beneficial for structures requiring high strength and stiffness, while GFRP offers a more cost-effective solution, particularly in environments susceptible to corrosion, such as coastal or marine conditions. Hoops and spirals made from FRP provide shear reinforcement, enhancing the stability and ductility of concrete columns. Its outstanding corrosion resistance makes it particularly valuable in moist, chemical, or saline environments, enhancing durability and prolonging service life while reducing maintenance costs [18]. Reinforcement methods for FRP include longitudinal bars, hoops, and wrapping systems. A popular reinforcement scheme is the hybrid FRP-steel system, where FRP enhances corrosion resistance and ductility, while steel offers higher stiffness and bond strength [19]. This combination improves the overall seismic performance and energy dissipation capacity, making it ideal for use in earthquake prone regions. Additionally, FRP wrapped systems are employed to confine concrete, enhancing axial load capacity and preventing premature failure due to lateral deformation [20].

These FRP-reinforced recycled aggregate concrete (RAC) columns are especially well-suited for sustainable construction projects, as they combine the environmental benefits of recycled aggregates with the enhanced structural performance provided by FRP [21]. These columns have found applications in infrastructure projects, such as bridges, high-rise buildings, and seismic retrofitting, where long-term durability, corrosion resistance, and seismic resilience are essential

FRPs are advanced composite materials made of a polymer matrix reinforced with high-strength fibres like carbon, glass, or aramid, providing exceptional strength-to-weight ratios, corrosion resistance, and flexibility [22]. Recently, they have garnered attention for their ability to tackle challenges associated with traditional materials, especially in weight-sensitive applications.

1.3 Objectives and scope of the work

The primary objective of this review is to provide a comprehensive examination of the behaviour of fibre-reinforced polymer (FRP)-reinforced recycled aggregate concrete (RAC) columns under static and cyclic loading. This study aims to explore key influencing factors such as the type of recycled aggregate (RCA), the confinement effect of FRP, the FRP reinforcement approach, and the RCA replacement ratio. By analysing a wide range of experimental and numerical studies, the review seeks to provide valuable insights into the mechanical properties, structural performance, and long-term behaviour of FRP-RAC columns.

The scope of this work includes a critical evaluation of axial, lateral, and combined cyclic loading tests, as well as finite element and analytical modelling approaches. Special emphasis is placed on understanding how the confinement provided by FRP enhances the structural performance of RAC columns, particularly in improving their compressive strength and ductility. The review also includes an analysis of the durability and long-term performance of FRP-RAC columns under varying environmental conditions, providing a comparison of their cost-effectiveness and sustainability relative to traditional concrete structures. Novel to this work, the review integrates a comprehensive life-cycle assessment (LCA) approach, which compares the sustainability of FRP-RAC systems to conventional concrete structures, emphasizing the reduction of embodied energy and carbon footprint. The paper also identifies key gaps in the literature, particularly in the areas of long-term durability, life-cycle costs, and predictive modelling, and proposes future research directions to optimize FRP-RAC column design and performance.

2 Fundamentals of FRP-Reinforced Recycled Aggregate Concrete

Fibre-reinforced polymer (FRP)-reinforced recycled aggregate concrete (RAC) combines sustainability with enhanced structural performance. By replacing natural aggregates with recycled concrete aggregates, RAC reduces waste and conserves resources. While RAC may show different mechanical properties compared to conventional concrete, FRP reinforcement—applied as wraps or sheets—provides essential external confinement and reinforcement. This significantly enhances the compressive strength, ductility, and durability of the composite, making it both environmentally friendly and mechanically superior for various construction applications [23].

2.1 Mechanical properties of recycled aggregate concrete

RAC serves as a progressive and sustainable alternative to traditional concrete by replacing natural aggregates with recycled materials derived from construction and demolition waste. While the mechanical properties of RAC may differ from those of conventional concrete, these distinctions provide distinct advantages for contemporary construction practices.

2.1.1 Compressive strength

Recycled Aggregate Concrete (RAC) typically has lower compressive strength than standard concrete, but this can be improved by optimizing mix design and using high-quality recycled aggregates and supplementary cementitious materials. Research by Li et al. [24], Tang [25], Jin et al. [26], and Kou et al. [27] shows that increasing the amount of Recycled Concrete Aggregate (RCA) reduces concrete's compressive strength. **Fig. 1a** depicts the relationship between RCA replacement percentage and the relative compressive strength, indicating that as RCA content increases, the compressive strength of concrete generally decreases. Xiao et al. [28] examined RAC with RCA replacement rates of 0%, 30%, 50%, 70%, and 100%. They found that while normal concrete developed micro-cracks leading to macro-cracks post-peak stress, RAC exhibited similar initial behaviour but experienced quicker macro-crack formation, indicating shear failure. The stress-strain curvature improved with higher RCA content, though compressive strength generally decreased with increased RCA, and the prism-to-cube strength ratio was higher for RAC compared to normal concrete.

2.1.2 Tensile strength

Recycled Aggregate Concrete (RAC) generally has lower splitting tensile and flexural strength than conventional concrete, presenting an opportunity for innovation. The weaker bond between cement pastes and recycled aggregates can be improved through better mixing techniques, enabling sustainable construction without compromising performance. However, Shi-Cong Kou et al. [29] showed that after five years of water curing, recycled aggregate concretes had lower compressive strength but higher splitting tensile strength compared to normal aggregate concrete.

2.1.3 Modulus of elasticity

Fig. 1a illustrates the relationship between the percentage of RCA replacement and the relative compressive strength of concrete. As the RCA replacement percentage increases, there is a clear decrease in compressive strength, highlighting the negative impact of RCA on concrete ability to withstand compressive loads. The trend demonstrates the influence of factors such as aggregate porosity and reduced bonding between RCA and the cement matrix, resulting in reduced material strength at higher replacement levels.

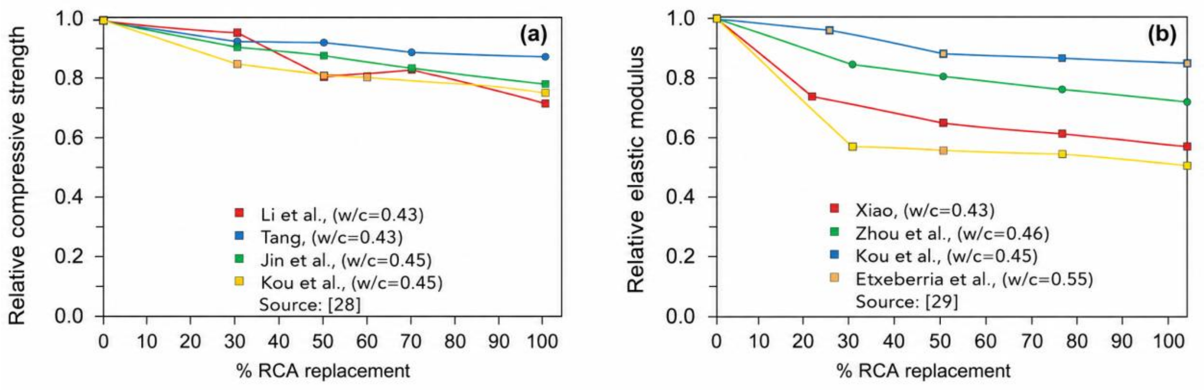


Fig. 1. Effects of RCA replacement on (a) compressive strength [28], (b) Elastic Modulus [29].

RAC exhibits a lower elastic modulus compared to conventional concrete due to its increased porosity and reduced stiffness. This can result in larger deformations under load. **Fig. 1b** illustrates that elastic modulus versus replacement percentage would also show a decreasing trend, indicating the lower stiffness of RAC compared to conventional concrete. This trend may be more pronounced at higher replacement levels [29].

2.2 Microstructural characteristics

Recycled Concrete Aggregate (RCA) possesses distinctive advantages due to the adhered mortar on its surface, which includes cement paste and fine aggregates. This adherence contributes to RCA's heterogeneity, characterized by variations in composition, density, and strength, impacting performance in specific applications. RCA's increased porosity and water absorption can enhance workability in concrete mixtures. Additionally, remnants of interfacial transition zones (ITZ) from the original concrete, despite being weaker, can positively influence the mechanical properties and durability of recycled aggregate concrete (RAC). Lastly, inherent cracks within RCA, a result of the demolition process, can serve as beneficial pathways for water and aggressive agents, and the quantity of adhered mortar is crucial for determining the overall performance of RAC. **Fig. 2** illustrates the Interfacial transition zone for RCA.

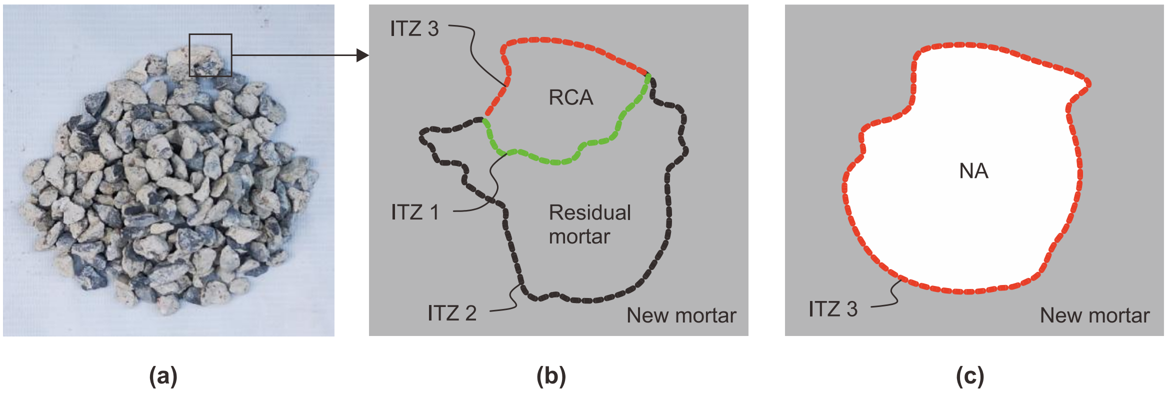


Fig. 2. Interfacial transition zone (ITZ) between new cement mortar and aggregates (a) recycled coarse aggregates, (b) schematic view of ITZ around RCA between residual and new mortar, (c) schematic view of new mortar with natural aggregate [34].

While the ITZ is known to be weaker than the bulk material due to its higher porosity and lower bond strength, quantitative data on the ITZ is scarce in general discussions. Recent studies have sought to characterize the ITZ more precisely using advanced techniques. For instance, Du et al. [30] used X-ray microtomography (XMT) to provide three-dimensional images of the ITZ. Their research focused on quantifying the thickness of the ITZ in RAC with varying amounts of recycled aggregates. They found that as the RCA replacement ratio increased, the thickness of the ITZ also increased, negatively impacting the material's strength and durability. This suggests that a thicker ITZ may lead to weaker bonding between the recycled aggregate and new mortar, ultimately reducing the overall performance of the concrete. However, the interface between RCA and new mortar has the lowest microhardness, an area for improvement. Additionally, Poon et al. [31] utilized microhardness testing to measure the bond strength at the ITZ. Their findings indicated that the ITZ has a lower microhardness compared to the surrounding mortar, demonstrating that the bond strength between the recycled aggregate and new cement paste is weaker. Furthermore, SEM was used to observe the morphology and thickness of the ITZ, providing clear visual evidence of the differences between the new cement paste and the old, adhered mortar. These findings emphasize the critical role of the ITZ in the overall mechanical performance of RAC. Tam et al. [32] identified two ITZs in RAC: one between RCA and new mortar, and another with old mortar, which is porous and cracked, representing a weak link.

Globally, Etxeberria et al. [33] confirmed the adhered old mortar as the weak point, while Nagataki and Gokce et al. suggested this isn't always indicative of RAC quality [34]. Rasheeduzzafar and Khan [35] emphasized that the weakest link often depends on the strength and quality of the old and new mortars, highlighting the need for innovative improvements in RAC.

2.3 Overview of FRP reinforcement

Fiber-reinforced polymers (FRP) are composite materials made from a polymer matrix reinforced with high-strength fibres like glass, carbon, aramid, or basalt. They are increasingly used as alternatives to traditional steel reinforcement in concrete due to their high strength-to-weight ratio, corrosion resistance, and ease of installation. FRP typically consists of thermosetting resins, such as epoxy or polyester, bonded with these fibres, enhancing strength and stiffness. The versatile nature of FRP allows for customization based on specific structural needs, with various types including Glass Fiber-Reinforced Polymer (GFRP), known for its cost-effectiveness and corrosion resistance; Carbon Fiber-Reinforced Polymer (CFRP), recognized for its superior strength-to-weight ratio; and Aramid Fiber-Reinforced Polymer (AFRP), valued for its high performance in demanding applications [36].

Hybrid Fiber Reinforced Polymer (FRP) systems integrate two or more different types of fibres, such as carbon, glass, or aramid, to harness a synergistic combination of their unique properties. By blending these fibres, hybrid systems can achieve an optimal balance of strength, stiffness, and ductility that is often unattainable with a single fibre type. This versatility allows for enhanced performance in various structural applications, including bridges, buildings, and other critical infrastructures. The tailored characteristics of these hybrid materials enable engineers to address specific design challenges effectively, providing solutions that enhance durability while potentially reducing weight and overall material costs. As a result, hybrid FRP systems are increasingly being recognized for their value in innovative engineering designs [37]. Moreover, it is crucial to consider other significant factors like creep, the tendency of the material to slowly deform under constant load over time, fatigue which refers to how cyclical loading can weaken the material, and long-term durability, ensuring that the material will perform well over extended periods in various environmental conditions. For professionals seeking guidance in the design of concrete structures reinforced with FRP, established design standards such as ACI 440.1R-15 [38] and CSA S806-12 [39] offer valuable insights and recommendations to ensure safe and effective construction practices.

2.4 FRP types

Fiber-reinforced polymer (FRP) composites are increasingly used as an alternative to steel reinforcement in concrete structures due to their superior mechanical properties, corrosion resistance, and versatility. Different forms of FRP reinforcement include longitudinal bars, stirrups, unidirectional and bidirectional wraps, and hybrid systems. Longitudinal FRP bars, made from carbon, glass, or aramid fibres, enhance tensile strength in beams, columns, and slabs. FRP stirrups provide shear reinforcement, while unidirectional and bidirectional wraps are used for external strengthening, improving load capacity and ductility. Hybrid FRP bars and wraps combine different fibre types to optimize performance, making them suitable for various structural applications [40]. Different types of FRP bars and sheets can be seen in **Fig. 3**.

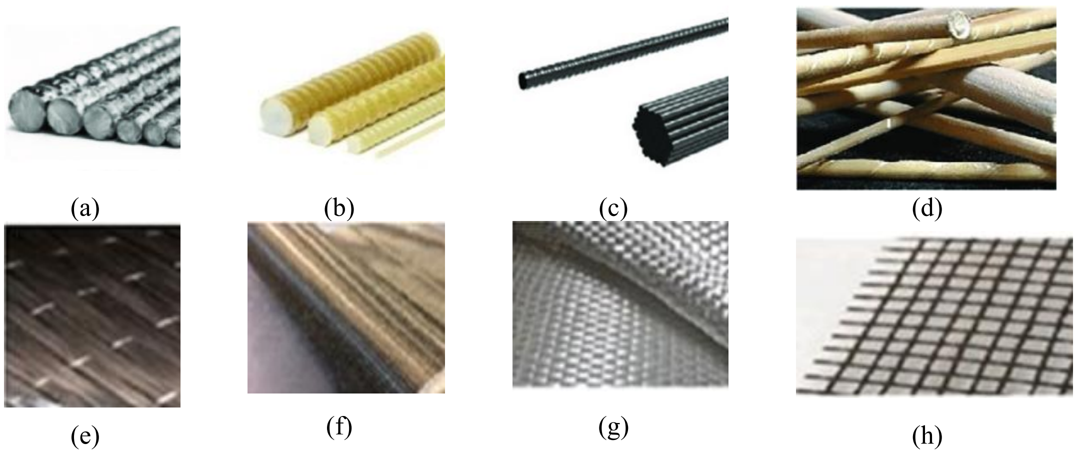


Fig. 3. Different types of FRP bars: (a)BFRP, (b) GFRP, (c) CFRP, (d) AFRP (e) UN sheet CFRP, (f) UN sheet BFRP, (g) UN sheet GFRP, (h) CFRP grids [40].

2.5 Mechanical properties and advantages over steel reinforcement

Fiber-reinforced polymers (FRPs) are composite materials comprising high-strength fibres in a polymer matrix, exhibiting varied mechanical properties based on factors such as fibre type, matrix material, and volume fraction. Notably, FRPs have high tensile strength, particularly with carbon fibres, and their compressive strength can be enhanced through optimized fibre alignment [40]. They also demonstrate good flexural strength, impact resistance, and fatigue resistance, though performance may be affected by certain conditions [43]. Additionally, FRPs are highly resistant to corrosion, making them suitable for harsh environments, and offer significant advantages in applications due to their exceptional mechanical characteristics [41-43]. Fiber-reinforced polymer (FRP) offers several advantages over traditional steel reinforcement in concrete structures, including a high strength-to-weight ratio that simplifies handling and reduces dead loads. Its corrosion resistance enhances durability, especially in coastal environments, while its electromagnetic neutrality suits sensitive applications. Customizable properties, easy installation, and improved resistance to seismic and blast forces make FRP a smart, sustainable choice for modern construction [41]. Comparison of mechanical properties of different types of FRP are tabulated in **Table 1**.

Table 1. Comparison of mechanical properties of different FRP types [45]

Classes	Yield strength (MPa)	Density (g/cm^3)	Tensile strength (MPa)	Specific gravity	Elastic modulus (GPa)	Strain at break %	Elongation (%)
Steel	500	7.70-8.10	350-450	7.8	200	0.2	2.0
AFRP	1700-2500	1.28-2.60	1720-2540	1.38-1.39	41-125	1.9-4.4	2.5
GFRP	600-1400	2.11-2.70	480-1600	1.5-2.5	35-51	1.2-3.1	3.2
BFRP	1000-1600	2.15-2.70	1035-1650	27-2.89	45-59	1.6-3.0	2.3

2.6 Challenges in combining RAC with FRP reinforcement

Combining Recycled Aggregate Concrete (RAC) with Fibre-Reinforced Polymer (FRP) reinforcement presents challenges that must be addressed for optimal structural performance and durability. Key issues include incompatibility between FRP and RAC, variability in the properties of recycled aggregates leading to inconsistent performance, and the need for long-term durability studies to understand their interaction. Additionally, limited design guidelines and the higher cost of FRP compared to traditional steel reinforcement can hinder widespread adoption, especially in cost-sensitive projects. Addressing these challenges is crucial for the broader use of RAC-FRP systems in construction [46].

3 Static Loading Behaviour of FRP-Reinforced RAC Columns

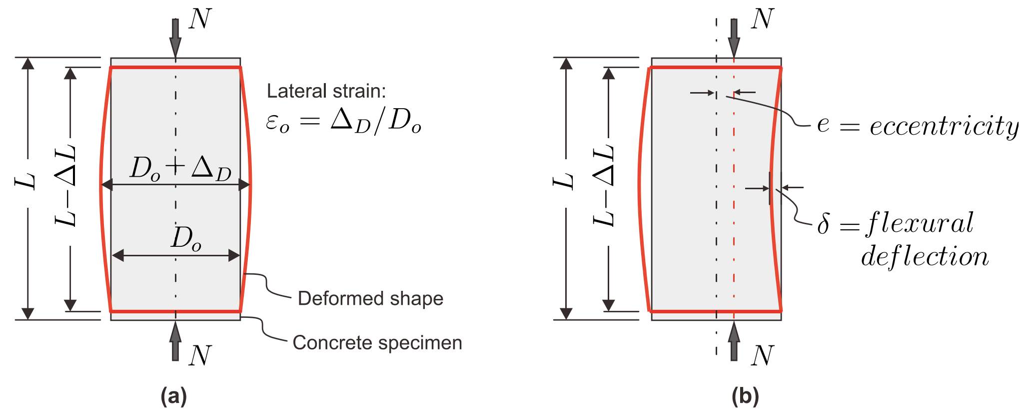


Fig. 4. Type of deflection of columns subjected to: (a) concentric loading (b) eccentric loading.

Various researchers [47-53], have examined the static behaviour of fibre-reinforced polymer (FRP)-confined recycled aggregate concrete (RAC) members, categorizing tests into concentric and eccentric loading configurations. Concentric loading is characterized by axial loads that produce corresponding deformation and lateral dilation (see **Fig. 4a**), while eccentric loading involves axial loads with an associated eccentricity, resulting in deformation and lateral flexural deflection (refer to **Fig. 4b**). In this review study, FRP-RAC columns will be discussed under both concentric and eccentric loads.

Under static loading, FRP-reinforced RAC columns demonstrate enhanced compressive strength and ductility due to lateral confinement provided by FRP wraps, exhibiting a bilinear or multi-linear stress-strain behaviour with significantly increased ultimate strain capacity [54]. The column's performance is influenced by recycled aggregate properties, where higher-quality aggregates and lower replacement ratios generally improve strength and stiffness, though FRP confinement can compensate for lower RAC strength. Common failure modes include FRP rupture, concrete crushing, and debonding, dependent on FRP material and configuration, with increased FRP layers and hoop-wrapped fibres enhancing confinement and strength [55]. Experimental observations confirm improved load-carrying capacity and energy absorption compared to unreinforced columns, highlighting the effective interaction between FRP and RAC.

3.1 Key performance indicators under static loading

To evaluate the performance of Recycled Aggregate Concrete (RAC) columns reinforced with Fibre-Reinforced Polymer (FRP) under static loading, several key indicators should be assessed. Axial load capacity indicates the maximum compressive load the column can withstand, with FRP confinement enhancing structural integrity and minimizing lateral deformations and buckling, leading to improved robustness and durability [46, 56]. Ductility reflects the material's ability to stretch under tensile stress, with FRP enhancing this property for safer load reactions [57]. Energy absorption capability indicates how well the structure dissipates energy during deformation, making RAC-FRP columns resilient to severe loading. Stiffness, influenced by FRP arrangement, impacts overall structural performance [48]. Long-lasting durability is bolstered by FRP's corrosion-resistant properties, ensuring extended service life. Sustainability indicators include the proportion of recycled aggregates in the mix, highlighting resource substitution, and the reduced embodied energy and carbon footprint associated with FRP compared to traditional steel reinforcement [58].

3.2 Strength and stiffness degradation

The strength and stiffness of Recycled Aggregate Concrete (RAC) columns reinforced with Fibre-Reinforced Polymer (FRP) can degrade over time due to various factors. Understanding these factors is essential for designing durable structures. Key aspects of the degradation in RAC-FRP columns include:

3.2.1 Impact of recycled aggregates

Recycled aggregates typically contain adhered mortar, microcracks, and exhibit higher porosity than natural aggregates. These characteristics contribute to lower compressive strength, reduced stiffness, and diminished durability in RAC compared to conventional concrete. Consequently, RAC columns may experience a more rapid decline in strength and stiffness, especially under sustained loads or cyclic stress. The weaker ITZ between recycled aggregates and new cement matrix further accelerates microcracking and stiffness reduction.

3.2.2 Effects of environmental influences

Environmental exposures such as freeze-thaw cycles, chloride penetration, moisture ingress, and elevated temperatures can exacerbate the degradation of RAC. Due to its increased water absorption, RAC is more susceptible to such environmental deterioration. However, the application of FRP confinement significantly mitigates these effects by restricting crack propagation and providing additional lateral confinement, thus helping to preserve the structural integrity and prolong service life.

3.2.3 Energy dissipation capacity

The energy dissipation capacity of Recycled Aggregate Concrete (RAC) columns reinforced with Fibre-Reinforced Polymer (FRP) is affected by factors such as hysteretic behaviour, ductility, damage mechanisms, and environmental exposure. FRP confinement enhances hysteretic performance, increases energy absorption during seismic events, and improves ductility by delaying concrete crushing, allowing for larger deformations. Damage mechanisms like concrete cracking, FRP debonding, and fibre rupture are influenced by fibre type, orientation, and concrete properties [57, 59].

3.2.4 Failure modes and deformation behaviour

Common failure modes in FRP-RAC columns include concrete crushing at the column ends, rupture of the FRP wrap, and shear cracking. The presence of recycled aggregates tends to promote more ductile failure mechanisms compared to conventional concrete. FRP reinforcement enhances post-peak behaviour by improving deformation capacity and providing a more gradual strength reduction, which is especially beneficial in seismic design. Overall, FRP confinement effectively compensates for the inherent tensile weaknesses of RAC, improving strength and stiffness retention over the life of the structure.

3.3 Testing process of FRP-RAC columns

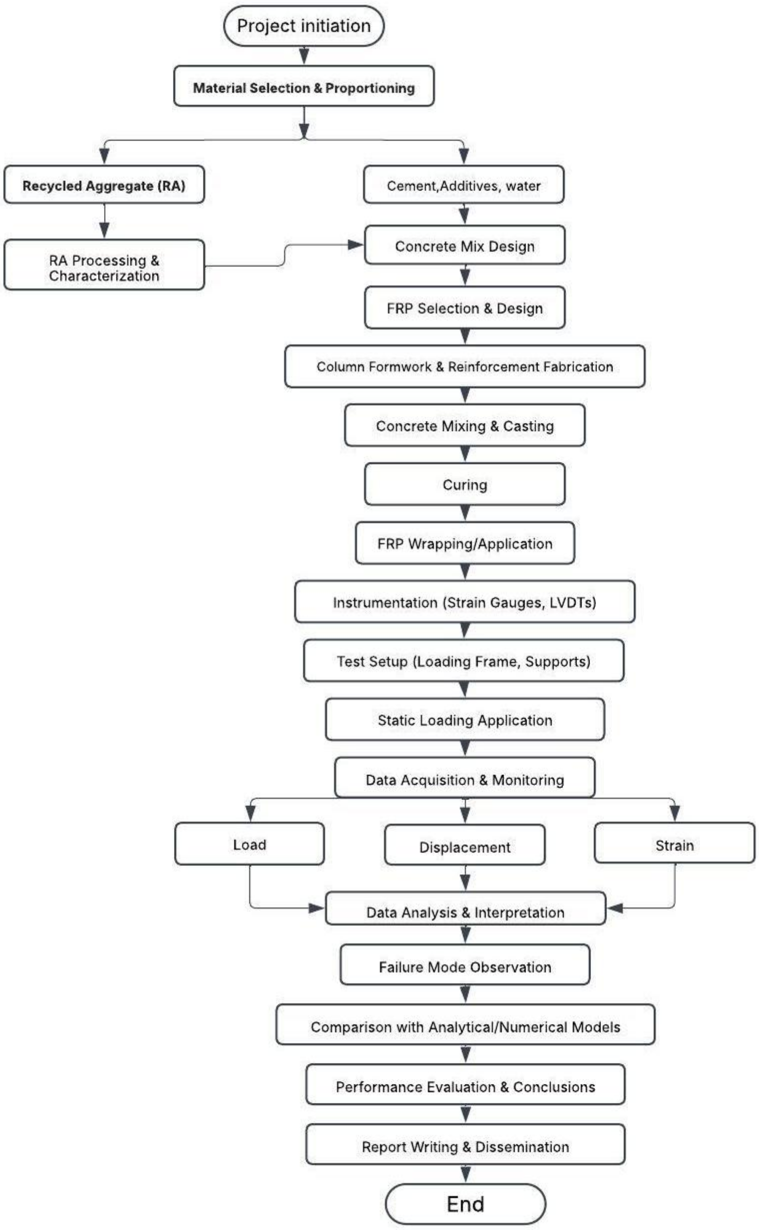


Fig. 5. Flow chart of the process of building and testing FRP-RAC columns.

Testing FRP-RAC columns requires careful specimen preparation, including controlled concrete mixing with recycled aggregates and precise FRP application. Rigorous experiments involve axial compression, lateral loading, and sometimes flexural testing, using strain gauges and LVDTs to collect data on load, strain, and displacement. Data analysis assesses load-carrying capacity, stress-strain behaviour, and failure modes, evaluating FRP confinement efficacy and the columns' structural performance. The chart in **Fig. 5** shows various stages of preparing and doing tests on the FRP-RAC column.

3.4 Overview of studies on FRP-RAC columns

Table 2. A detailed summary of research on FRP-RAC columns

Authors	Year	Concrete Type	Key Results	Failure types
Liu et al. [60]	2023	RAC (Sea-sand)	Thicker and larger diameter FRP tubes in the core region contributed to a better column load capacity.	steel outer tube buckled and cracked along the weld seam, Tensile rupture of inner FRP tube
Raza et al. [61]	2021	RAC	GFRP reinforced normal aggregate concrete (NAC) in terms of loading capacity, ductility, and failure modes.	Failures in GRAGC columns were mainly due to ruptured GFRP spirals and crushed longitudinal GFRP bars, indicating ductile behavior beneficial for structural integrity.
Chen et al. [74]	2021	High-strength	Increasing the thickness of GFRP tube is an effective way to restrain the global and local buckling of the encased steel section.	Type I shows initial elastic and plastic deformation with micro-crack propagation, Type II involves recovery and hardening post peak in high-strength concrete, and
Alashker and Raza [48]	2022	recycled aggregate geopolymer concrete (RAGC)	FGSTCs had a horizontal load capacity 16.9% greater and energy loss 24.5% higher than their natural aggregate equivalents	Circumferential fractures in the GLT cracks in the STT, and flattened RAGC were all common failure and cracking patterns in all of the specimens
Rafique et al. [62]	2021	RAC	GRFC columns confined with GFRP spirals portrayed higher axial strength and higher ductility indices	The failure modes include buckling of longitudinal GFRP bars
Xiao et al. [63]	2015	RAC	Compressive strength and initial elastic modulus increased with strain rate, but peak strain showed no clear dependence	The failure modes observed were the specimens failed with a few visible cracks, the specimens cracked into several large pieces, and the specimens were crushed into fine fragments
Hadi [64]	2007	NC	FRP straps are effective in producing columns with higher capacity and ductility compared with reinforced concrete columns	The failure mode of the strengthened specimens occurred with the rupture of the FRP jacket in the maximum tensile region
Choi and Yun [65]	2012	RAC	Axial load of the column is consistently greater than the predicted nominal strength, regardless of whether recycled aggregate is used	Type 1 specimens and at the contact surface with the steel plate for the Type 2, Type 3, and Type 4 specimens
Liu et al. [51]	2018	RAC	The energy dissipation capacity of RAC columns and NAC columns are approximately the same except in the failure stage	The failure process of RAC columns is similar to that of NAC columns
Fang et al. [66]	2019	RAC	Larger columns exhibited slightly lower normalized strength.	RAC-filled GFRP-steel columns, flexural cracks appeared as displacement increased, with no debonding

Authors	Year	Concrete Type	Key Results	Failure types
Wang et al. [67]	2019	RAC	RRC column lateral load capacity decreases with increased RCA replacement using AWM, while ETWM shows the reverse	The failure mode of all the test specimens was solely flexural-dominated failure
Li et al. [54]	2021	seawater sea-sand recycled aggregate concrete (SSRAC)	CFRP-confined SSRAC columns exhibit strength influenced by corner radius and RA replacement	Specimens with different RA replacement ratios showed similar failure modes, with CFRP rupture near the corners
Guo et al. [68]	2018	Normal Concrete	FRP-confined circular columns exhibit enhanced strength and deformation	The failure modes of the tested specimens, including unconfined concrete and FRP-wrapped columns
Tang et al. [3]	2020	RAC	RACFCTs show improved behaviour over RACFSTs due to the GFRP outer tube, especially at high slenderness ratios, and demonstrate strong ductility	Two different failure modes were observed in RACFST and RACFCT columns based on their slenderness ratio
Yuan et al. [69]	2024	RAC	GFRP-confined RACFST stub columns demonstrate good axial compressive properties	The failure modes of GFRP–confined RACFST stub columns indicated that as loading increased
Ali et al. [70]	2020	Normal	Diagonal tension failure was observed in the circular steel and FRP-reinforced	The model accurately predicted the behaviour of circular concrete piles with shear capacity ratios
Wang et al. [71]	2016	Normal	Lateral strain at the corners of square columns decreases with size, leading to the recommendation that the effective rupture strain	Post-test, diagonal failure surfaces and severe concrete crushing were evident, with internal steel reinforcements bending outward and longitudinal bars buckling.
Ren et al. [72]	2021	RAC	The replacement ratio of RCA minimally affects the buckling behaviour of slender FCSRC columns under eccentric loads	The failure modes of slender columns varied with height but not significantly with GFRP tube thickness

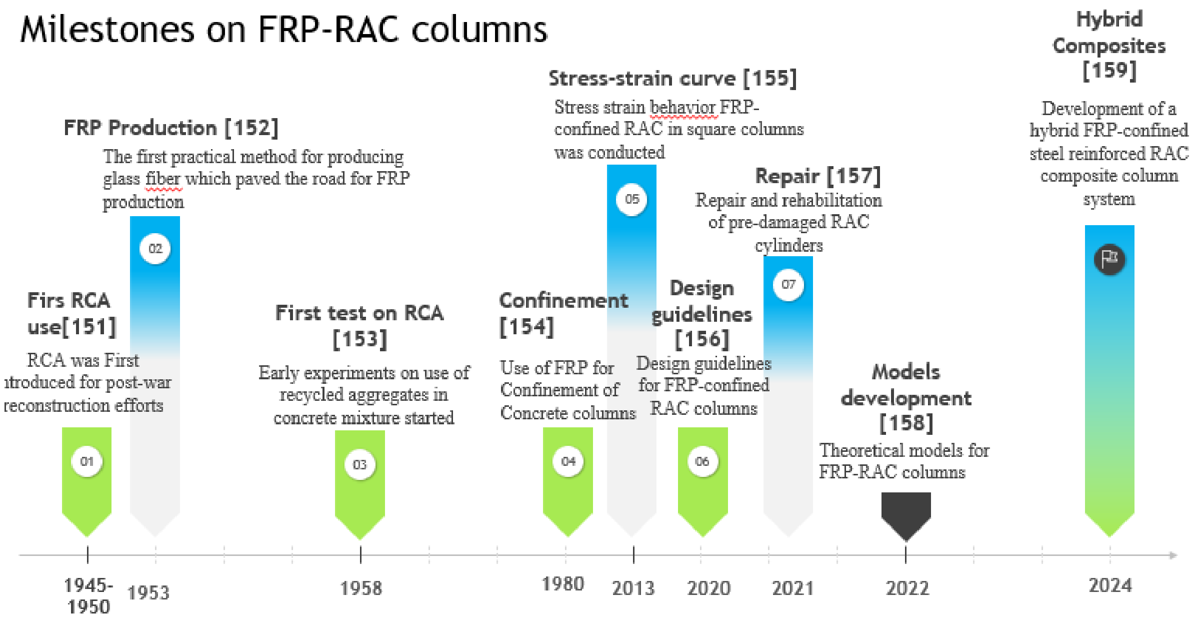


Fig. 6. Timeline of milestones on FRP-RAC columns.

This review summarizes findings from 90 studies on the behaviour of FRP-RAC columns, examining various factors that affect their structural performance. A detailed summary of research on

FRP-RAC columns is listed in **Table 2**. The studies analyse different types of FRP (GFRP, CFRP), confinement methods (hoops, spirals, tubes, hybrid steel-FRP), concrete types (normal, RAC with various aggregates, geopolymer), loading conditions (axial, eccentric, cyclic, impact), and column shapes (circular, square, rectangular). **Table 3** consolidates these variables. **Table 3** summaries the comparative study of different loading conditions, fibre type and failure modes to explicitly understand the behaviour of FRP RAC columns. The review aims to present a detailed overview of the mechanical properties, failure mechanisms, and durability of FRP-RAC columns while highlighting trends, inconsistencies, and research gaps. It also underscores the significance of life-cycle assessment (LCA) and sustainability in designing FRP-RAC structures to promote eco-friendly construction practices. **Fig. 6** effectively illustrates the critical milestones in the research on Fibre-Reinforced Polymer-Recycled Aggregate Concrete (FRP-RAC) columns, providing a comprehensive timeline that showcases the progression of key findings, experimental methodologies, and innovative applications in this emerging field.

Table 3. Comparative study of different types of FRP under different loading conditions

References	FRP type	Loading condition	Failure mode	Column geometry
Xu et al. [47]; Fang et al. [55]	GFRP	Cyclic	Debonding	Circular
Alashker and Raza [48]; Rashid and Bahrami [56]	CFRP	Cyclic	FRP rupture	Square
Ren et al. [46]; Li et al. [54]	AFRP	Cyclic	Concrete crushing	Rectangle
Rashid and Bahrami [56]	BFRP	Concentric	Debonding	Circular
Liu et al. [57]; Sbahieh et al. [58]	GFRP	Eccentric	Concrete crushing	Square
Tao et al. [59]	CFRP	Concentric	Debonding	Rectangle
Liu et al. [60]	AFRP	Eccentric	Concrete crushing	Square
Raza et al. [61]	GFRP	Eccentric	FRP rupture	Circular
Rafique et al. [62]	CFRP	Eccentric	Debonding	Square
Xiao et al. [63]	BFRP	Cyclic	Concrete crushing	Rectangle
Hadi [64]; Choi and Yun [65]	GFRP	Concentric	FRP rupture	Circular
Fang et al. [66]; Wang et al. [67]	GFRP	Eccentric	Concrete crushing	Square
Guo et al. [68]	GFRP	Cyclic	Debonding	Circular
Yuan et al. [69]	GFRP	Concentric	Concrete crushing	Rectangle
Ali et al. [70]	GFRP	Eccentric	FRP rupture	Square
Wang et al. [71]	GFRP	Eccentric	Debonding	Circular
Ren et al. [72]	GFRP	Cyclic	FRP rupture	Square

3.4.1 FRP Confinement and Combined Reinforcement

The reviewed studies consistently demonstrate the effectiveness of FRP confinement in enhancing the mechanical properties of concrete columns, including those utilizing recycled aggregates (RAC) [60], [73-75], [12], [39], [76], [77]. Both GFRP and CFRP have shown significant improvements in compressive strength and ductility, with CFRP generally exhibiting higher performance [75, 78]. However, the cost-effectiveness of GFRP makes it a viable option for many applications. Several studies explored the benefits of combined reinforcement, incorporating both steel and FRP [46, 66, 69, 70, 79, 80, 81, 82]. The combination often leads to synergistic effects, with steel providing increased stiffness and preventing premature concrete crushing, while FRP enhances confinement and ductility. However, optimizing the ratio of steel to FRP remains a critical area for further research. Furthermore, the configuration of the FRP (hoops, spirals, tubes) plays a significant role in confinement effectiveness [18, 66, 80, 83, 84]. Tubes, particularly when combined with steel [66, 70, 74] appear to offer exceptional confinement, but their cost and constructability should be considered.

3.4.2 Influence of Concrete Type and Loading Conditions

The use of recycled aggregates in concrete columns is a promising approach for sustainable construction [12, 48, 61, 77, 79, 83, 85]. While RAC may exhibit slightly lower compressive strength compared to normal concrete, FRP confinement can effectively compensate for this difference [62, 79, 86]. The type of recycled aggregate (e.g., recycled concrete, brick, coral, sea-sand) can also influence the mechanical properties [87-89]. Geopolymer concrete, as a more sustainable binder, has shown promising results in FRP-confined applications [48, 61], but further research is needed to understand its long-term performance. The loading conditions significantly impact the behaviour of FRP-RAC columns. Eccentric loading reduces strength and stiffness [46, 64, 90, 91], while cyclic loading can lead to fatigue failure of the FRP [51, 67]. Seismic performance is a critical consideration [48, 66, 82], and research in this area is crucial for ensuring the safety of FRP-RAC structures in seismic regions. Impact loading [74] also requires further investigation.

3.4.3. Durability, Repair, and Environmental Impact

Durability is a crucial concern for FRP-RAC structures, particularly in harsh environments [85]. Research on the long-term effects of freeze-thaw cycles, chemical exposure, and elevated temperatures is essential for ensuring the longevity of these structures. The use of FRP for repairing and rehabilitating damaged RAC columns [92] shows promise for extending the service life of existing infrastructure. From a sustainability perspective, the environmental impact and life-cycle assessment (LCA) of FRP-RAC construction are important considerations [93-95]. The use of recycled aggregates reduces the demand for natural resources, and FRP materials, while having their environmental footprint, can contribute to the overall sustainability of structures by increasing their lifespan and reducing the need for repairs.

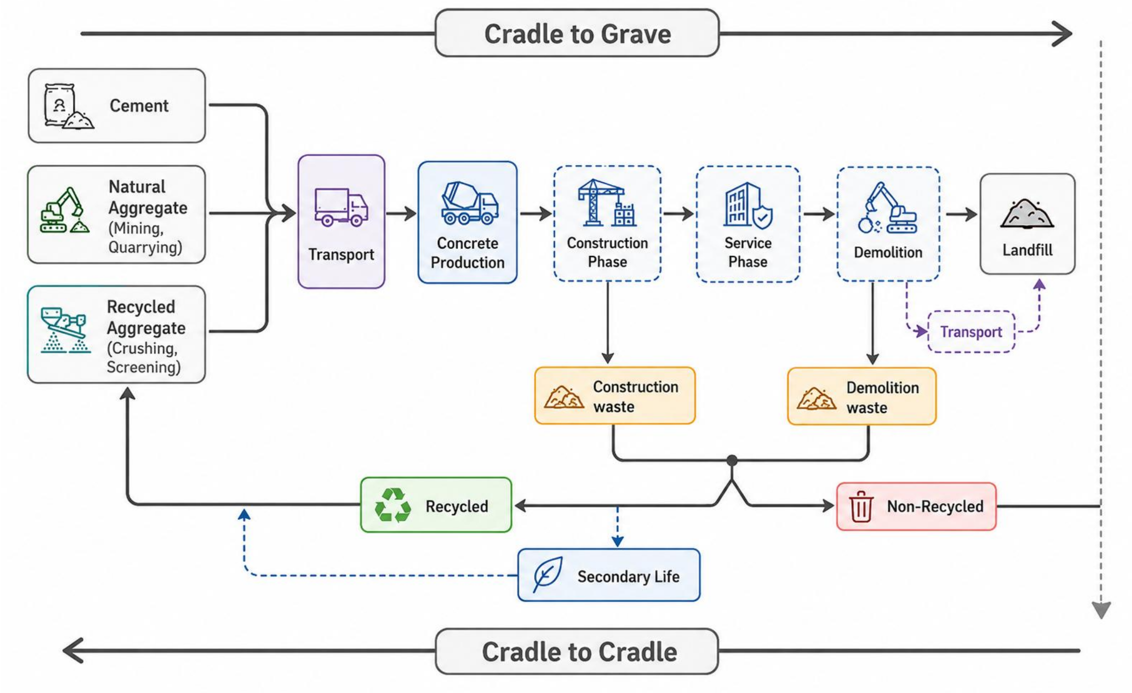


Fig. 7. Typical methodology of Life Cycle Assessment (LCA) [98].

3.4.4. Life Cycle Assessment

Life-cycle assessment (LCA) is essential for evaluating the sustainability of FRP-RAC structures by providing insights into their environmental impacts throughout their life cycle. The overview of the following LCA methodology is derived from the guidelines provided in ISO 14040 (2006) [96] and ISO 14044 (2006) [97]. It comprises four distinct analytical phases: (1) defining objectives and boundaries; (2) developing the life cycle inventory (LCI); (3) evaluating impacts; and (4) interpreting the findings. The scope covered NCA and RCA production, including cement proportions, aggregate transport, and waste disposal, reflecting the actual processes in the life cycle of NAC or RAC production.

Fig. 7 illustrates the system boundaries for this LCA methodology [98].

The reviewed studies [93, 94, 95, 98] consistently emphasize LCA's role in optimizing material selection and minimizing environmental burdens. Several studies [88, 90, 93] compare the environmental impacts of RAC with natural aggregate concrete, highlighting benefits such as reduced natural resource depletion and landfill waste. However, the carbon-intensive processes related to FRP production are also significant [99]. LCA helps to balance the advantages of RAC with the environmental implications of FRP materials. For example, some research [93] shows that multi-generation recycled aggregate concrete can further lower environmental impacts, while LCA quantifies the associated trade-offs. The complexities of LCA are underscored by factors like the functional unit, emissions allocation, and CO_2 uptake [94]. The comparative LCA review in [95] stresses the need to consider various impact categories beyond global warming potential for a fuller environmental profile of RAC versus natural aggregate concrete. In FRP-RAC contexts, LCA aids in selecting low-impact FRP types, optimizing FRP reinforcement, and informing end-of-life strategies, ultimately fostering a more sustainable construction sector. Integrating LCA into the assessment of FRP-RAC performance is crucial for promoting environmentally responsible construction practices.

3.5 Ductility and failure modes

The failure modes in FRP-confined RAC columns involve interactions among concrete behaviour, steel reinforcement, and FRP response. Common mechanisms include concrete cracking and crushing [74, 80, 87] steel yielding in reinforced columns [46, 55, 74], and FRP rupture or debonding [83, 87, 100]. In axially loaded columns, micro-cracks in the concrete core develop and propagate as the load increases [46], with FRP confinement activating to delay further deterioration [69, 87, 100]. Eventually, the FRP reaches its tensile limit and ruptures, often leading to a load drop [83, 87]. Steel reinforcement can influence this process, with yielding occurring before FRP rupture [46, 66, 75]. Eccentrically loaded columns experience additional complexities, including concrete cracking, tensile cracking, and steel buckling [46, 85, 90]. FRP confinement enhances ductility and mitigates brittle failure. Seismic loading introduces fatigue in FRP and concrete degradation [67, 101]. Factors such as FRP type [52, 73, 102], concrete strength [61, 79, 100], steel configuration [69, 74, 80], loading conditions [46, 85, 90], and column geometry [103] influence these failure mechanisms. A thorough understanding of these modes is crucial for accurate predictive modelling and the design of durable FRP-RAC structures as shown in **Fig. 8**.

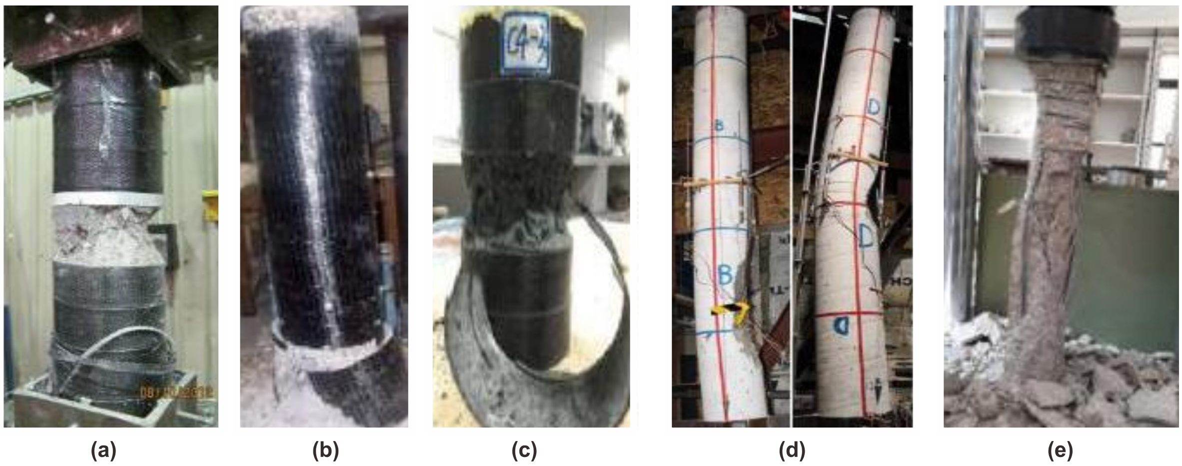


Fig. 8. Failure modes of RAC FRP-reinforced columns [63, 64, 64].

To prevent or mitigate these failure modes, it is essential to carefully design RAC-FRP columns considering factors such as the properties of the recycled aggregates, the type and amount of FRP reinforcement, and the loading conditions. Proper installation techniques, quality control measures, and regular maintenance can also help ensure the long-term performance and durability of these structures.

3.6 Confinement

FRP externally wrapped concrete columns differ from those reinforced with FRP spirals or ties, as the latter often experience cover spalling before confinement activates. The confinement mechanisms of FSCC and FTCC resemble that of FRP-partially confined concrete (FPCC) with non-uniform confinement along the column. **Fig. 9** illustrates these mechanisms [104]. Confinement using steel or FRP significantly improves the mechanical performance of recycled aggregate concrete (RAC) columns, with FRP interlocking multi-spirals enhancing efficiency and post-peak behaviour in square columns, particularly in marine environments [55].

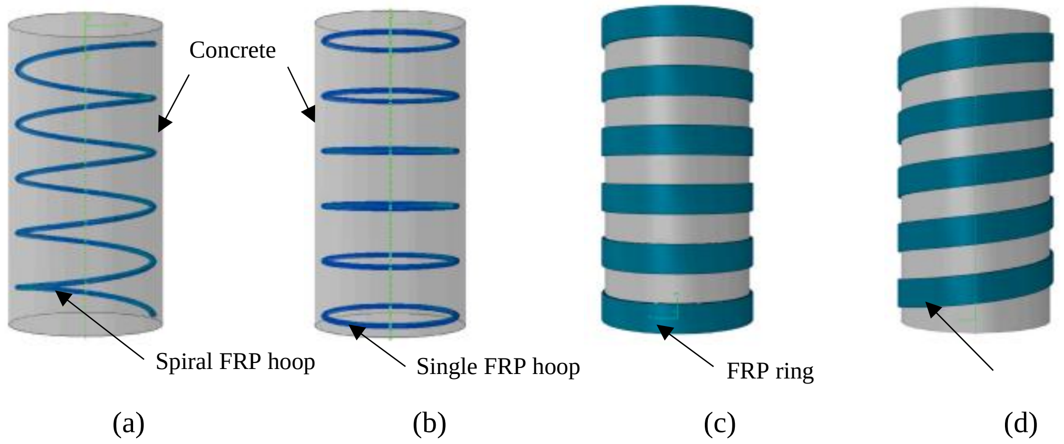


Fig. 9. Concrete columns that utilize both internal and external FRP confining systems: (a) FRP-spiral confined concrete (FSCC), (b) FRP-tie confined concrete (FTCC), (c) FRP-ring confined concrete, (d) FRP-strip confined concrete.

External FRP tubes in recycled aggregate geopolymer concrete-filled double-skin tubular columns boost seismic performance through effective double confinement [48]. Reducing the pitch of GFRP hoops increases ductility in RAC columns [52], and the effectiveness of GFRP reinforcement is influenced by the recycled aggregate replacement ratio [102]. FRP-confined RAC columns exhibit higher axial strain at peak stress and gradual post-peak strength degradation, improving load-bearing capacity and ductility [67]. Confinement techniques also mitigate corrosion in seawater sea-sand concrete (SWSSC) columns and enhance axial compression [54, 55]. The integration of recycled materials with GFRP reinforcement compensates for reduced mechanical properties [60], while studies on FRP-confined steel-reinforced concrete reveal increased axial stiffness but reduced deformation capacity [74]. Reinforced recycled concrete (RRC) columns demonstrate acceptable seismic performance under cyclic loading [65, 87] highlighting the critical role of confinement in enhancing the performance and durability of RAC columns.

In concrete circular columns confined with FRP under concentric compression, the FRP shell applies a consistent lateral confining pressure around the entire circumference of the column. This confining pressure at the point of column failure, known as the ultimate failure pressure (flu), can be theoretically determined using **Eq. (1)**.

$$f_{\mathrm{l,u}} = \frac{2E_{\mathrm{f}}t_{\mathrm{f}}\varepsilon_{\mathrm{fu}}}{D} \tag{1}$$

The elastic modulus, total nominal thickness, and ultimate tensile strain of the fibres are represented as E_{f}, t_{f}, and $\varepsilon_{\mathrm{fu}}$, respectively, while D denotes the diameter of the column. **Fig. 10** illustrates the typical axial stress versus axial strain curves for both unconfined and confined concrete. The graph shows that the axial stress-strain curves for confined concrete feature an initial ascending segment, which is then followed by a second segment. Depending on the confinement parameters, the stress-strain curve can exhibit a fully ascending second segment or one that has a descending trend. Fallah pour et al. [105] also demonstrated that the ultimate axial strain of FRP-confined concrete can be calculated as follows:

$$\varepsilon_{\mathrm{cu}} = \gamma\varepsilon_{\mathrm{co}} + k_2\left(\frac{k_l}{f_{\mathrm{co}}^{'}}\right)^2 \varepsilon_{\mathrm{fu}}^{\beta} \tag{2}$$

In this context, k_2 represents the enhancement coefficient for the ultimate axial strain, $\varepsilon_{\mathrm{fu}}^{\beta}$ denoting the ultimate tensile strain of the fibres, while γ, α, and β are constant values utilized for calibrating the model. FRP confinement models for RAC columns adapt existing frameworks like those by Lam & Teng [106] and Mander et al. [107], addressing factors such as RAC's lower stiffness and higher variability. Key considerations include FRP properties (tensile strength, stiffness, thickness), column geometry, RAC characteristics (replacement ratio, interfacial transition zone quality, seawater effects) [54], and experimental validation to ensure model accuracy [73]. Models must also account for the effectiveness of confinement based on column shape and interaction with steel reinforcement [80].

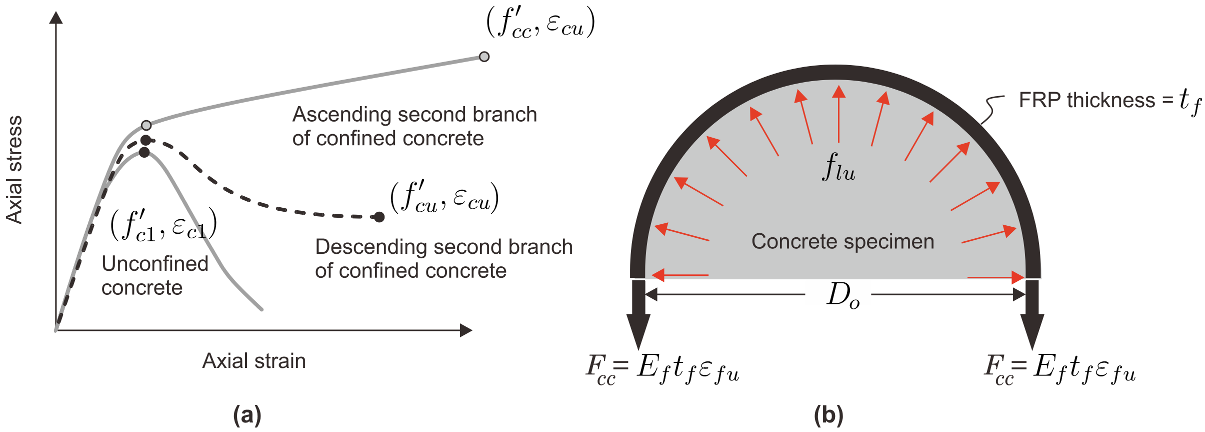


Fig. 10. Stress-strain curve of confined section: (a) Typical axial stress-axial strain curves for confined and unconfined concrete, (b) The confining action of the FRP jacket to concrete $\boldsymbol{E_f}$, $\boldsymbol{t_f}$, $\boldsymbol{\varepsilon_{fu}}$, and $\boldsymbol{f_{lu}}$ are the elastic modulus, total nominal thickness, ultimate tensile strain of fibres, and ultimate lateral confining pressure, respectively [105].

3.7 Recycled aggregate replacement ratios

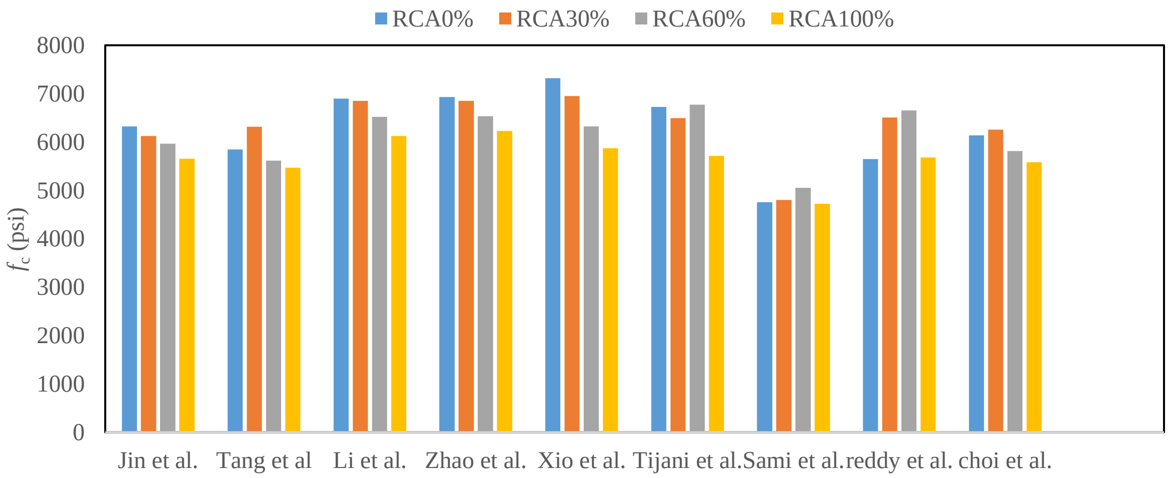


Fig. 11. Effects of RCA replacement ratios on compressive strength of unconfined columns.

The replacement ratio of Recycled Concrete Aggregates (RCA) in Recycled Aggregate Concrete (RAC) columns reinforced with Fibre-Reinforced Polymer (FRP) affects their strength and behaviour. Various studies have reported differing outcomes. Wu et al. [41] found that increasing the RCA replacement ratio from 0% to 100% decreased the compressive strength of RAC-filled FRP tubes by 4.5%, 13%, and 19% for 30%, 60%, and 100% RCA replacements, respectively. Guo et al. [108] noted similar trends, observing a 7.7% reduction in peak stress at 30% RCA replacement and a 12.5% decrease at 50% RCA replacement. Bai [15] suggested that the type of FRP and RCA replacement ratio did not significantly influence the active confinement pressure and strain efficiency factors, indicating that models for FRP-confined conventional concrete may apply to FRP-confined RAC columns. Additionally, Qian et al. [109] found that RCA replacement had minimal effect on the behaviour of FRP-confined steel-reinforced RAC columns, aside from the ultimate load-carrying capacity, which is influenced by factors like load eccentricity and column height. Effects of RCA replacement ratios on compressive strength of unconfined columns is shown in **Fig. 11**. Overall, while increasing the RCA replacement ratio tends to reduce compressive strength and axial stiffness, the effectiveness of FRP confinement and the applicability of existing models appear largely unaffected. Studies [88, 96] show that higher RCA replacement ratios (e.g., 70-100%) significantly reduce compressive strength and axial stiffness, with reductions in compressive strength by up to 19% at 100% RCA replacement. This is due to the lower quality of recycled aggregates and increased porosity, which negatively impacts the bond between cement paste and aggregates. The negative effects of higher RCA replacement can be mitigated by strengthening with FRP reinforcement. Specifically, FRP can enhance the ductility and energy absorption capacity of RAC columns, even with high RCA content, compensating for the loss in compressive strength.

3.8 FRP reinforcement configurations and properties

The effectiveness of Fibre Reinforced Polymer (FRP) reinforcement in Reinforced Autoclaved Concrete (RAC) columns is influenced by multiple factors including the type of FRP material used, the reinforcement configuration, and the inherent properties of the RAC. Various configurations exist for FRP reinforcement, each with distinct benefits and applications. Fully wrapped configurations provide the best confinement and significantly enhance compressive strength and ductility [3, 64, 71]. Partially wrapped configurations offer some advantages but are less effective than fully wrapped solutions [89]. Strip wrapping and grid wrapping configurations serve specific purposes, such as localized confinement and shear strength improvement [51], respectively. Understanding these configurations is essential for optimizing the performance of FRP-reinforced RAC columns.

3.8.1 Interaction between FRP and RAC

The interaction between FRP and RAC is crucial for the overall performance of the composite column. The FRP provides confinement to the RAC core, which helps to increase its compressive strength and ductility. The RAC, in turn, provides support to the FRP, preventing it from buckling. The bond between FRP and RAC is also essential for the effective transfer of stresses between the two materials. Some studies have been conducted on the bond behaviour between FRP bars and RCA in FRP-RAC columns [88, 110, 111]. One of the important tests to investigate the bond behaviour of FRP bars and RAC is the pull-out test. The typical configuration of the pull-out test is depicted in **Fig. 12**.

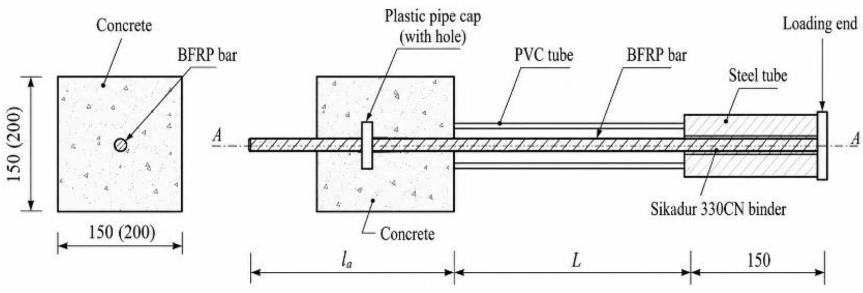


Fig.12. Typical configuration of pull-out test of FRP bars [110].

The FRP bar pull-out test involves embedding an FRP bar in a concrete block and applying a controlled tensile force to the bar's protruding end until failure occurs. The test measures the load and the bar's slippage relative to the concrete, allowing for the determination of the bond strength and the failure load [110]. The bond performance in concrete is primarily influenced by concrete strength, with increased strength leading to higher bond strength. Additionally, the surface shape of BFRP bars significantly affects bond mechanisms, with R-shaped bars demonstrating the best bond behaviour due to effective mechanical interlocking. **Eq. (3)** is applicable for determining the bond stiffness, where fc represents the compressive strength of the concrete [110].

$$K_s = \frac{0.68 f_c^{0.5} + 68.29}{d} \quad (3)$$

Eq. (4) was established in the design guide ACI 440.1R-06 [38] and [110] to estimate the development length required for FRP bars.

$$l_{\mathrm{d,c}} = \frac{\gamma \frac{f_{\mathrm{f}}}{0.083}\sqrt{f_{\mathrm{c}}} - 340}{13.6 + \frac{C}{d}} d \quad (4)$$

In this context, γ is used to denote the position of FRP bars, with a value of γ equal to 1. Meanwhile, C refers to the thickness of the concrete cover, which has a ratio of C to d set at 3.5.

3.9 Axial load ratios and cross-sectional shapes

The axial load ratio indicates the fraction of a column's load-carrying capacity that is utilized, typically expressed as a percentage or ratio. At lower ratios, columns exhibit minimal deformations and cracking, with limited activation of FRP confinement. As the ratio rises, more significant deformations occur, making FRP confinement critical to prevent concrete crushing and maintain integrity. The most common column shapes (circular, square, and rectangular) each have distinct behaviours; circular columns provide uniform confinement and strength, while square and rectangular columns can experience stress concentrations at corners but benefit from FRP wrapping to improve performance. Other shapes may exhibit varied behaviours based on their geometry and FRP configuration.

3.10 Comparative analysis of FRP-RAC columns against conventional RC columns

FRP-RAC (Fibre-Reinforced Polymer Recycled Aggregate Concrete) columns provide a sustainable alternative to conventional reinforced concrete columns, utilizing recycled aggregates and FRP reinforcement to enhance strength and ductility. These columns often demonstrate superior compressive strength and ductility due to the confinement by the FRP, allowing for potentially slenderer designs that reduce material use. While FRP-RAC columns may have higher initial costs and require specialized construction techniques, their durability in harsh environments and improved seismic performance are significant advantages [48]. In contrast, conventional concrete columns are generally more economical but suffer from issues like steel corrosion and lower performance levels [112]. Key considerations include the inherent variability in RAC properties, the effectiveness of FRP confinement based on column shape [54], and the interactions between steel reinforcement and FRP [80], emphasizing the need for experimental data for model validation [73]. The choice between these options should consider project-specific requirements, balancing cost, performance, and sustainability goals. Comparative analysis of FRP-RAC columns against conventional RC columns is shown in **Table 4**.

Table 4. Comparative Analysis of FRP-RAC columns against conventional RC columns

Feature	FRP-RAC Columns	Conventional Concrete Columns
Sustainability	High (utilizes recycled materials)	Lower (relies on natural resources)
Strength	Higher (due to FRP confinement)	Lower
Ductility	Higher (due to FRP confinement)	Lower
Durability	Potentially higher (FRP protects RAC)	Lower (steel rebar susceptible to corrosion)
Cost	Higher (FRP material and specialized labour)	Lower
Complexity	More complex design and construction	Simpler design and construction

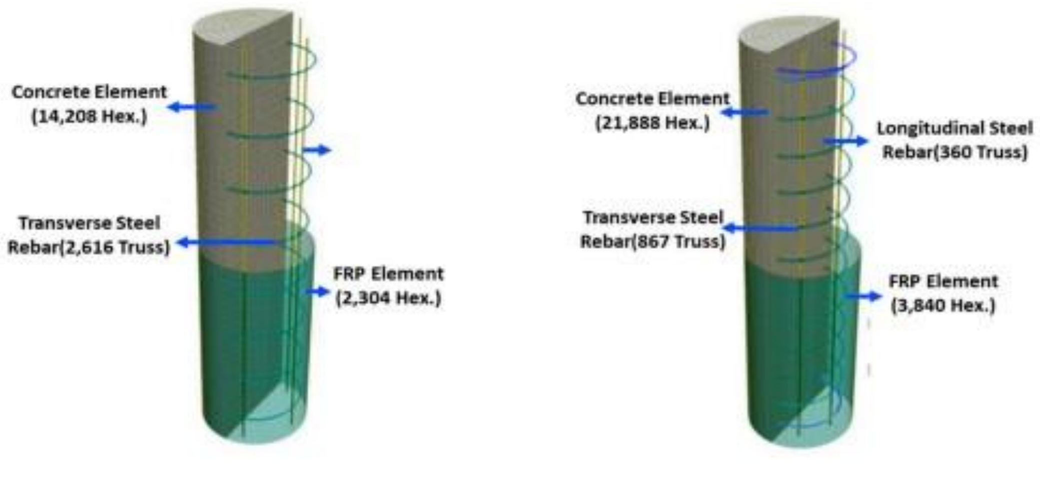
4 Predictive Models for Static Performance

4.1 Overview of Predictive Models:

4.1.1 FEM models

Predictive models for FRP-RAC columns can be categorized into three main types: Empirical/Regression-Based Models, which use statistical techniques to relate column performance to various parameters like RAC replacement ratio and FRP type; Analytical/Mechanics-Based Models, which are grounded in the mechanics of materials and consider the stress-strain behaviour of both concrete and FRP; and Numerical Models (Finite Element Analysis —FEA), which utilize numerical techniques to analyse the behaviour of the column by discretizing it into small elements, providing detailed insights. Each of these models has unique characteristics that can be advantageous in certain scenarios, but they also come with limitations. A clearer understanding of the strengths and weaknesses of each model is necessary for selecting the right approach for the design and analysis of FRP-RAC columns. Raza et al. [61] used ABAQUS FEA to model FRP-confined concrete columns, finding that increasing column diameter and GFRP reinforcement significantly boosted ultimate strength. FEA models showed good agreement with experimental data. Mohammadi et al. studied large rupture strain FRPs, demonstrating their ability to enhance strength and ductility through passive confinement. They calibrated the Concrete Damage Plasticity Module (CDPM) and developed a novel plastic dilation angle model for non-circular columns.

Inaccurate modelling of FRP-reinforced concrete can lead to incorrect strength predictions, highlighting the need for advanced constitutive models [113]. While a stress-strain model was used to estimate the seismic response of RC columns retrofitted with FRP jackets, it often failed to predict ultimate lateral displacements. Adjusting the model for the eccentricity ratio improved predictions. Additionally, Piscesa et al. [114] developed a 3D nonlinear FEM for conventional steel stirrups and FRP-wrapped columns, where factors like boundary conditions and Poisson's ratio significantly affected the lateral modulus, as shown in finite element models with circular ties and spirals for reinforcement. **Fig. 13** shows the 3D finite element mesh model.



(a) (b)

Fig. 13. The 3D finite element mesh model (a) features circular ties as transverse reinforcement, while (b) includes spirals for the transverse reinforcement [114].

Lo et al. [115] employed 2-D finite element methodologies on the cross-sections of axially loaded FRP-confined rectangular concrete columns without assumptions about non-uniformity, with failure under triaxial compression defined by **Eq. (5)**.

$$(\xi,\rho,\theta)=\left(\sqrt{1.5}\,\frac{\rho}{f_c}\right)^2+m\left[\frac{\rho}{\sqrt{6}f_c}\gamma(\theta,e)+\frac{\xi}{\sqrt{3}f_c}\right]-c=0 \qquad (5)$$

In this context, ξ refers to the hydrostatic length, ρ to the deviatoric length, and θ to the Lode angle. The results indicate that aspect ratio and corner roundness minimally impact yield strength and strain but significantly influence post-yield behaviour.

4.1.2 Evaluation of predictive models

Predictive models for FRP-RAC columns can be divided into three categories, each with distinct strengths and weaknesses. Empirical/Regression-Based models are simple and quick to apply, making them suitable for initial design stages. They rely on experimental data to predict column behaviour, offering fast results without requiring computational resources [117]. However, their applicability is limited to the data they were trained on, and they often lack insight into the material interactions and underlying mechanisms, making them less reliable for conditions outside the experimental range. Analytical/mechanics-based models, on the other hand, provide a deeper understanding of material behaviour through fundamental principles of mechanics. They can adapt to different loading conditions and offer more accurate predictions in certain contexts. However, they often involve simplifying assumptions about material behaviour and stress distribution, which can reduce their accuracy. These models can also be complex to apply and interpret [118]. Numerical Models from FEA offer the highest accuracy by simulating detailed material interactions and complex geometries. They are versatile in handling various loading scenarios and can account for real-world structural complexities. Nevertheless, FEA models are computationally expensive and require significant resources. They also require calibration with experimental data to ensure their reliability, which can be a limitation if data is scarce for specific materials or configurations.

4.1.3 Analytical models.

Concrete specimens expand under axial compression. An FRP jacket confines this transverse expansion, creating triaxial compression that enhances strength and ductility. Richart et al. [116] first studied this effect, testing axially loaded concrete cylinders under lateral fluid pressure, and proposed a formula to estimate the maximum strength f'_{cc} of confined concrete as shown in **Eq. (6)**, which is widely applicable to existing strength models [116].

$$\frac{f'_{\mathrm{cc}}}{f'_{\mathrm{c}}} = 1 + k_1 \frac{f_{\mathrm{l}}}{f'_{\mathrm{c}}} \tag{6}$$

In this context, f'_{cc} cc, and f'_c refer to the compressive strengths of confined and unconfined concrete, respectively. Additionally, fl represents the lateral confining pressure, while k_1 denotes the coefficient that measures the effectiveness of confinement. Zeng et al. [60]. proposed a load-capacity model for RAC-filled steel tube columns with FRP-confined concrete cores, derived from axial compression tests. It considers various parameters, such as the FRP core configuration, diameter-to-thickness ratio of the FRP tubes, compressive strengths of RAC and SSC, and column cross-sectional shape. Their proposed equation is as follows in **Eq. (7) – Eq. (10)**.

$$N_{\mathrm{cu}} = N_{\mathrm{su}} + N_{\mathrm{fu}} \tag{7}$$

$$N_{\mathrm{su}} = (1 + 1.27\xi_{\mathrm{s}})A_{\mathrm{sc}}f_{\mathrm{sc}} \tag{8}$$

$$N_{\mathrm{fu}} = (1 + 1.27\xi_{\mathrm{s}} + 1.28\xi_{\mathrm{s}})A_{\mathrm{fc}}f_{\mathrm{fc}} \tag{9}$$

$$\xi_{\mathrm{s}} = A_{\mathrm{s}}f_{\mathrm{y}}/A_{\mathrm{sc}}f_{\mathrm{sc}} \quad \xi_s = A_{\mathrm{f}}f_{\mathrm{f}}/A_{\mathrm{fc}}f_{\mathrm{fc}} \tag{10}$$

where N_{cu} is the load capacity of the proposed column, N_{su} is the load capacity of a RAC-filled steel tube column, N_{fu} is a large diameter SSC-filled-FRP tube column, A_{f} is the cross-sectional area of the sandwich concrete after deducting the total cross-sectional area of the FRP tube, f_{sc} represents the compressive strength of the concrete filled in the steel tube, and f_{fc} is the compressive strength of the concrete filled in the FRP tube.

Xiao et al. [117] introduced a unified active-confinement model for high-strength concrete, noting that silica fume reduces confinement efficiency. They proposed basalt fibre composites as alternatives to epoxy-based FRPs [118]. Wang et al. [119] created a cyclic axial stress-strain model for CFRP-confined RC columns, accounting for internal steel reinforcement. Concrete-filled FRP tubes enhance confinement and reduce brittleness with an inner steel wire mesh [120]. Huang et al. [121] reviewed stress and strain models for GFRP-confined concrete, emphasizing unconfined concrete strength's significance, while Pimanmas et al. [122] presented a strength model for natural fibre-reinforced jackets, highlighting the benefits of increased shell thickness. **Table 5** illustrates the review of existing analytical models. Empirical models rely on experimental data and may lack predictive ability outside tested parameters [67]; analytical models depend on the validity of assumptions, with more complex versions offering greater accuracy but increased difficulty; and numerical models, like FEA [78], can achieve high accuracy with careful calibration and validation, though they face challenges such as computational costs and the complex behaviour of recycled aggregate concrete (RAC) with fibre-reinforced polymers (FRP). Comparison of model types is shown in **Table 6**.

4.2 Inclusion of recycled aggregate properties in predictions

Developing accurate prediction models for FRP-confined Recycled Aggregate Concrete (RAC) columns requires considering the unique properties of recycled aggregates, such as the replacement ratio, which affects mechanical behaviour [54], and the interfacial transition zone (ITZ), which has a weaker bond strength compared to natural concrete. Models should also account for higher porosity and water absorption in recycled aggregates, impacting durability and bond effectiveness in moist environments [82]. The variable quality of recycled aggregates must be reflected in model parameters, influencing strength and workability [125]. Integrating these factors into prediction models involves modifying existing stress-strain relationships, adjusting parameters based on recycled aggregate properties, introducing empirical coefficients from experimental testing, and employing numerical modelling techniques like finite element analysis. By addressing these considerations, models can yield more reliable assessments of FRP-confined RAC column behaviour, enhancing design and construction practices.

Table 5. Review of existing analytical models

Reference	Year	Ultimate stress	Strain
Saafi et al. [123]	1999	$f'_{cc}/f'_{c} = 1 + 2.2(f_{l}/f'_{c})^{0.84}$	-
Lam and Teng [106]	2002	$f'_{cc}/f'_{c} = 1 + 2(f_{l}/f'_{c})$	-
Toutanji and Matthys [124]	2005	$f'_{cc}/f'_{c} = 1 + 2.3(f_{l}/f'_{c})^{0.85}$	-
Di-Ludovico et al. [118]	2010	$f_{cc} = \left[1 + 2.94\left(\frac{f_{FPP}}{f_{cu}}\right)\right] f_{cu}$	$\varepsilon_{cc} = \left[1 + 0.037\left(\frac{f_{frap}}{f_{cu}}\right)^{1.06}\right] \varepsilon_{cu}$
Xiao et al. [117]	2010	$f_{cc} = \left[1 + 3.24\left(\frac{f_{fre}}{f_{cu}}\right)^{0.80}\right] f_{cu}$	$\varepsilon_{cc} = \left[1 + 17.40\left(\frac{f_{crp}}{f_{cu}}\right)^{1.06}\right] \varepsilon_{cu}$
Wang et al. [119]	2012	$f_{cc} = \left[0.20 + 3.47\left(\frac{f_{crep}}{f_{cu}}\right)^{0.64}\right] f_{cu}$	$\varepsilon_{cc} = \left[2 + 73.31\left(\frac{f_{frp}}{f_{cu}}\right)^{1.07}\right] \varepsilon_{cu}$
Gao et al. [120]	2015	$f_{cc} = \left[1 + 4.08\left(\frac{f_{FRP}}{f_{cu}}\right)\right] f_{cu}$	$\varepsilon_{cc} = \left[2 + 19.60\left(\frac{f_{FRP}}{f_{cu}}\right)^{0.45}\right] \varepsilon_{cu}$
Huang et al. [121]	2016	$f_{cc} = \left[1 + 1.69\left(\frac{f_{fup}}{f_{cu}}\right)^{0.63}\right] f_{cu}$	$\varepsilon_{cc} = \left[2 + 13.20\left(\frac{f_{crap}}{f_{cu}}\right)^{0.60}\right] \varepsilon_{cu}$
Pimanmas et al. [122]	2019	$f_{cc} = \left[1 + 3.0\left(\frac{f_{FRP}}{f_{cu}}\right)\right] f_{cu}$	$\varepsilon_{cc} = \left[1 + 6.40\left(\frac{f_{FRP}}{f_{cu}}\right)\right] \varepsilon_{cu}$
Wang et al. [119]	2022	$f_{cc} = [1 + (5.3\rho_{k} + 0.036)\rho_{\varepsilon}] f_{cu}$	$\varepsilon_{cc} = [169 + 17.5\rho_{k}^{0.98}\rho_{\varepsilon}^{1.45}]\varepsilon_{cu}$

Table 6. Comparison of model types

Model Type	Strengths	Weaknesses
Empirical	Simple, easy to apply	Limited to the range of experimental data
	Suitable for early-stage design	Lack of insight into material behaviour
Analytical	Provides mechanistic understanding of material behaviour	Assumptions may reduce accuracy
	Adaptable to different loading conditions	Complex to apply and interpret
Numerical (FEA)	High accuracy and precision	Computationally expensive and resource intensive
	Versatile for complex structures and loading scenarios	Requires calibration with experimental data

4.3 Recommendations for Improvement of Models

To enhance prediction models for FRP-confined recycled aggregate concrete (RAC) columns, several key areas need attention. Firstly, it is crucial to accurately quantify the quality of recycled aggregates. Additionally, refining the modelling of the interfacial transition zone (ITZ) and investigating size effects are important [65]. Environmental factors, such as long-term durability and the effects of corrosion, especially in aggressive conditions, should also be taken into account [48]. Improving the modelling of the interaction between FRP and concrete, including bond-slip behaviour and effectiveness of confinement, is vital [61]. Furthermore, expanding experimental validation with diverse datasets and real-world conditions will enhance model accuracy [52]. Finally, employing advanced techniques like machine learning and finite element analysis will help capture complex material interactions more effectively [104].

5 Durability and Long-Term Performance

Table 7. Long-term performance of recycled aggregate concrete

Study	RCA replacement percentages	Compressive strength	Elastic modulus	Drying shrinkage
Poon and Kou [128]	20%	6.58–6.79% lower	4.32–17.05% lower	5.91–10.37%
	50%	12.55–16.47% lower	9.63–26.10% lower	11.82–17.53% larger
	100%	21.60–37.13% lower	17.94–39.53%	20.82–33.33% larger
Teranishi et al. [129]	50%	57.8% lower	30.5% lower	
Sagoe-Crentsil et al. [130]	100%	10% lower		35% larger
Topcu [131]	30%	31.8% lower		53.4% larger
Roos [132]	100%	34% lower	36.4% lower	
Dhir et al. [133]	30%		1.85% lower	0.67% larger
	50%		3.70% lower	4.86% larger
	100%		3.70% lower	12.92% larger
Yanagi et al. [134]	30%	0.3–11.2% lower	0–18.7% lower	0.4–30.9% larger
	50%	1.2–16.8% lower	2.8–25.1% lower	0.1–29.9% larger
	100%	4.1–19.7% lower	1.1–25.8% lower	5.9–40% larger

The long-term durability of FRP-reinforced concrete columns is complex and affected by environmental and load factors. Although FRP has advantages like corrosion resistance, its performance can diminish over time due to moisture, UV exposure, alkaline conditions, and sustained loads. Understanding these degradation mechanisms is crucial for predicting the lifespan of FRP structures. Guidelines such as ACI 44 [38] address material degradation under various environmental conditions. Geng et al. [126] conducted a study examining the time-dependent behaviour of recycled aggregate concrete (RAC)-filled steel tube columns. The findings indicate that the long-term deformation of these columns increases by 22% when natural coarse aggregate (NCA) is substituted with recycled concrete aggregate (RCA).

Duo et al. [127] evaluated the long-term durability of GFRP and BFRP by analysing 557 experiments. They found that GFRP bars generally exhibit better corrosion resistance than BFRP bars in harsh environments, particularly in alkali, salt, and acid solutions. The quality of recycled aggregates and the corrosion resistance of FRP composites both play significant roles in the concrete's durability. Proper design and detailing of FRP reinforcement can enhance the structural integrity and durability of RAC columns. The bond between FRP and RAC is crucial for long-term performance, influenced by surface preparation and the specific type of FRP. Studies indicate that RAC columns with FRP reinforcement exhibit enhanced seismic performance and energy dissipation, with the energy loss of FRP-RAC columns being 24.5% higher than natural aggregate equivalents [48]. A summary of the long-term performance of recycled aggregate concrete is listed in **Table 7**.

5.1 Experimental insights into durability under cyclic loading conditions

Experimental studies on FRP-reinforced RAC columns under cyclic loading reveal that progressive damage, bond degradation, and material fatigue are key durability concerns, heavily influenced by the ITZ, aggregate quality, and FRP configuration. While FRP confinement enhances energy dissipation and delays cracking, cyclic loading induces gradual stiffness degradation and potential failure through FRP rupture, concrete crushing, or bond failure. The long-term durability of FRP-RAC columns remains a topic of ongoing investigation, with several studies showing conflicting findings. While FRP offers corrosion resistance and increased durability, its performance can degrade over time due to moisture, UV exposure, alkaline conditions, and sustained loading. For instance, research indicates that GFRP and CFRP reinforcement show promising results in resisting freeze-thaw cycles and chemical exposure, enhancing the long-term stability of RAC columns. However, some studies suggest that FRP materials may degrade due to UV radiation or alkaline environments, potentially compromising the structural integrity of FRP-RAC columns in the long term. The quality of recycled aggregates also significantly impacts the bond strength and the overall durability of these columns, as it affects the interaction between FRP and the concrete. Further studies are required to understand the cumulative effects of multiple environmental factors, such as freeze-thaw cycles, chemical exposure, and moisture variations, to predict the service life of FRP-RAC columns more accurately. Additionally, a comprehensive life-cycle assessment (LCA) would help evaluate the environmental impact and sustainability of FRP-RAC constructions, offering insights into their long-term performance and maintenance needs compared to conventional concrete.

6 Design Recommendations

6.1 Optimal configurations for FRP-RAC columns

Optimal configurations for FRP-reinforced RAC columns require balancing several factors, including the choice of FRP material (CFRP, GFRP, AFRP), configuration (layers, orientation, corner radius), RAC properties (replacement ratio, aggregate quality), and structural designs based on loading conditions. High-load applications in harsh environments prefer CFRP-wrapped circular columns with quality RAC, while moderate conditions may benefit from GFRP-wrapped square columns. Seismic regions benefit from combined FRP and steel reinforcement. Increasing the corner radius enhances FRP confinement effectiveness [54]. Additionally, using FRP interlocking multi-spirals can provide extra confinement benefits [55].

A comprehensive design approach for FRP-reinforced RAC columns involves meticulous attention to several critical aspects: maximizing confinement efficiency through optimal column geometry, with circular shapes preferred for uniform stress distribution; precise selection of FRP materials, accounting for their mechanical properties and environmental susceptibility, as outlined in ACI 440.2R [38]; strategic layering and fibre orientation to achieve desired confinement pressure, favouring continuous wraps for enhanced performance; and ensuring strong interface behaviour by employing proper surface preparation and adhesive selection, especially vital when utilizing RAC which may exhibit different bonding characteristics. Furthermore, integrating research on RAC-FRP interactions, accessible via platforms like ResearchGate, is essential for addressing the unique challenges posed by recycled aggregates, such as variations in compressive strength and water absorption, thereby guaranteeing long-term durability and structural integrity.

6.2 Seismic Resilience

FRP-reinforced RAC columns demonstrate enhanced seismic resilience through improved ductility, energy dissipation, and strength, allowing for larger deformations and reduced damage during earthquakes compared to conventional RC columns. This is achieved via FRP confinement that delays concrete crushing and maintains structural integrity, while the material's durability minimizes long-term damage and repair costs. Stable hysteresis behaviour under cyclic loading, as seen in [47, 135, 136], further validates their effectiveness.

7 Machine Learning for Performance Prediction and Optimisation

A merged dataset of 1842 stress–strain curves has made it possible to fine-tune models trained on normal concrete so they reach a mean 4 % RMSE on RAC targets with < 200 new samples, using transfer-learning protocols first demonstrated by Liu et al. [137]. Embedding classical confinement equations as soft constraints in physics-informed neural networks trims extrapolation error by a further

20 % [138], while hybrid XGBoost–PSO optimisers push the median RMSE below 4 MPa across 330 mixed-lab tests [139]. Data augmentation with GAN-generated synthetic specimens now reduces the need for costly large-diameter RAC wraps by about 30 % [140]. Strict 10-fold stratified and *author-wise* cross-validation, followed by an external blind check on a 126-specimen FRP-steel-tube benchmark, shows that Bayesian quantile forests achieve 90 % coverage of true strengths [141]. Explainable-AI analyses repeatedly rank ρ_E and $f'co$ as the top two drivers of confined strength, giving transparent design levers [142], and the first digital-twin demonstrator streams field strain-gauge data to update model predictions in near-real-time [143]. These advances collectively reposition ML from a black-box curiosity to an integrated, uncertainty-quantified layer that accelerates FRP-RAC column design while preserving engineering traceability.

Table 8. Summary of Machine Learning in Reinforced Concrete, Fiber-Reinforced Plastics, and Confinement Techniques

Study	Data source	Dataset size	Method	Input parameters	Output parameters	Evaluation metrics	Key findings
Tao et al. [144]	Literature	490	XGBoost, MARS, RF, and ELM	D, H, E_f, t_f, $\varepsilon_{h,rup}$, f'_{cc}, and f'_{co}	f'_{cc}/f'_{co}	R^2, MAPE, RMSE, MAE, NSE, and WI	XGBoost achieved the best prediction and parameter-ranking performance, with $R^2 = 0.955$.
Milad et al. [145]	Literature	729	XGBoost, MARS, and RF	D, ε_{co}, ε_{cu}, f'_{co}, f'_{cc}, E_f, $\varepsilon_{h,rup}$, ρ_ε, and ρ_K	$\varepsilon_{co}/\varepsilon_{cu}$	R^2, RMSE, MAE, RD, Nash, and KGE	MARS provided the best overall prediction accuracy, while RF performed best for strain-enhancement prediction.
Zhao et al. [146]	Literature	582 for f'_{cc}; 582 for ε_{cu}	XGBoost, TGAN, and BAS	T, RA%, w_{eff}/C, ρ_{frp}, $\varepsilon_{h,rup}$, E_{frp}, f_{frp}, f_{co}, ε_{co}, and H	f'_{cc} and ε_{cu}	R^2, RMSE, MAE, and MAPE	BAS-XGBoost enhanced by TGAN accurately predicted the axial behaviour of FRP-confined recycled aggregate concrete columns and provided interpretable design equations.
Xue et al. [147]	Literature	293	GP, MPMR, and DNN	b, h, r, t_w, f'_{co}, and E_{CFRP}	K_s	R, R^2, MAE, RMSE, IA, FV, FA2, CV, DW, and NMBE	Leveraging Genetic Programming (GP) accurately predicted the lateral confinement coefficient, achieving $R^2 = 0.89$.
Onyelowe et al. [148]	Experiment	330	ANN-BP, ANN-GA, ANN-GRG, GP, and EPR	b, h, r, t, F_{co}, F_{tf}, and E_f	F_{cc}	R^2 and RMSE	ANN models outperformed GP and EPR in predicting confined compressive strength. GP and EPR provided explicit equations.
Hanteh et al. [149]	Literature	281	MARS, ELM, and PSO	d, L, f'_{co}, t, f_l, and f_f	f'_{cc}	R, RMSE, and MAPE	MARS-PSO achieved the highest accuracy, with R = 0.9961 for the testing dataset. Confinement pressure was the most influential parameter.
Fallah Pour and Gholampour [150]	Literature	836 for f'_{cc}; 571 for ε_{cu}; 443 for $\varepsilon_{h,rup}$; 260 for ε_{c1}; 230 for f'_{c1}	ANN	D, H, E_f, t_f, f_f, ε_{co}, f'_{co}, K_l, K_l/f'_{co}, ε_{fu}, and K_2	f'_{cc}, ε_{cu}, $\varepsilon_{h,rup}$, ε_{c1}, and f'_{c1}	MAE, AAE, M, RMSE, and MSE	ANN models accurately predicted hoop rupture strain and transition-zone parameters and effectively captured lateral confinement effects.

Table 8 benchmarks seven peer-reviewed ML studies (2022-2025) on FRP-wrapped recycled-aggregate concrete (RAC) columns. Most of the ML studies listed in Table 8 train on medium-to-large literature datasets (≈ 300–830 specimens) and therefore converge on tree-based ensembles (especially XGBoost) which post the tightest normalised errors (≈ 4 % RMSE) when estimating the confined strength $f'cc$ of FRP-wrapped columns [144], [145]. When the sample size drops below 250 rows, authors compensate with data-synthesis (XGBoost + TG-GAN, [146]) or physics/transfer learning (PINNs or TL-XGBoost, [147]), but still cannot outperform the ensemble “upper tier.” Only one paper adds new experimental data (330 non-circular RAC columns, [148]), and just two studies work with 100 % recycled-aggregate specimens ([146], [148]), underscoring the field’s dependence on normal-aggregate evidence. While three investigations now predict ductility measures such as ε_{cu} or $\varepsilon_{h,rup}$ ([145],

[146], [150]) or confinement coefficients K_S ([147]), strength prediction remains dominant, and none of the seven papers report calibrated 90 % prediction-interval widths, leaving model uncertainty implicit. Feature sets are mostly limited to basic geometry and unconfined strength $f'co$; only two rows include stiffness ratios ρ_E (the variable SHAP analyses rank highest for interpretability ([149], [150]). Together these patterns signal that ensemble learners currently rule predictive accuracy, but richer RAC testing, routine uncertainty reporting, and broader sectional diversity are still critical research gaps.

8 Conclusions and future work

This review paper examines the behaviour of FRP-reinforced recycled aggregate concrete (RAC) columns under static loading. It covers a variety of topics, including the fundamentals of FRP-reinforced RAC, the static loading behaviour of these columns, predictive models for FRP-RAC columns, their durability and long-term performance, design recommendations, as well as research gaps and future directions. Here are the main findings from this paper:

- FRP-RAC columns have higher sustainability, strength, ductility, and potentially higher durability. However, they also have a higher cost and more complex design and construction.
- The replacement ratio of Recycled Concrete Aggregates (RCA) in Recycled Aggregate Concrete (RAC) columns affects their strength and behaviour. Various studies have reported differing outcomes.
- The effectiveness of Fibre Reinforced Polymer (FRP) reinforcement in Reinforced Autoclaved Concrete (RAC) columns is influenced by multiple factors, including the type of FRP material used, the reinforcement configuration, and the inherent properties of the RAC.
- The interaction between FRP and RAC is crucial for the overall performance of the composite column. The FRP provides confinement to the RAC core, which helps to increase its compressive strength and ductility.
- GFRP bars generally exhibit better corrosion resistance than BFRP bars in harsh environments, particularly in alkali, salt, and acid solutions. As a result, it is highly recommended to use BFRP bars for RAC columns if they are subjected to harsh environmental conditions.
- A comprehensive model for predicting the bond behaviour between FRP layers and the RAC column is lacking, necessitating further research to develop an accurate predictive model.

Despite significant advancements in the study of FRP-RAC columns, several research gaps remain. Future studies should focus on the long-term performance of FRP-RAC columns, particularly under cyclic loading and in harsh environmental conditions, to better understand their durability. Research into the interaction between FRP and RCA, specifically ITZ, is also needed to explore how different FRP types affect the performance of RAC with varying recycled aggregate replacement ratios. Additionally, further investigations into the LCA and economic feasibility of FRP-RAC columns are essential to evaluate their sustainability and cost-effectiveness. Development of predictive models for simulating the behaviour of FRP-RAC columns and enhancing design guidelines is another critical area. Lastly, the seismic performance of FRP-RAC columns in earthquake-prone regions should be explored, along with the potential for hybrid FRP systems that combine different FRP types to optimise material performance for specific applications.

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Credit authorship contribution statement

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Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

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