Study of FRP Jacketing and Advanced Seismic Retrofitting

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Abstract -*This paper presents a dual-focused review encompassing two crucial aspects of structural engineering. The first segment explores the utilization of fiber-reinforced polymer (FRP) for confining concrete columns, aiming to enhance their strength and ductility by mitigating passive lateral confinement pressure. Existing numerical and analytical formulations describing the compressive behaviour of FRP-confined concrete under monotonic and cyclic loads are critically examined. The paper highlights the lack of well-defined strategies for modelling and the oversimplification of existing models, shedding light on the need for a comprehensive understanding of stress/strain levels in columns. Efforts are made to assess the effectiveness of various FRP combinations and explore potential future scopes to optimize the use of FRP-confined concrete in civil applications. The second segment provides a comprehensive overview of seismic analysis methodologies and retrofitting technologies, focusing on enhancing the resilience of structures. The discourse critically evaluates the typical approach of nonlinear static pushover analysis in assessing bridges and proposes the extension of the modal pushover method for more intricate structural configurations. The review delves into the advantages of retrofitting external sub-structures over conventional component-level methods and analyzes various methodologies, addressing key concerns and offering valuable perspectives for seismic engineering professionals*.

***Key Words*: Fiber Reinforced Polymer (FRP), Concrete Column Confinement, Seismic Analysis Methodologies, Retrofitting Technologies, FRP Jacketing, Seismic analysis.**

1.INTRODUCTION

The imperative shift of the construction sector towards sustainable development underscores the crucial significance of environmentally conscious building materials [1–5]. Several comprehensive literature reviews have extensively examined different materials and processes with the objective of enhancing the strength of concrete, taking into account both economic feasibility and environmental consequences [6–10]. It is worth mentioning that Fiber-Reinforced Polymer (FRP) composite materials, which have historically been employed in the aerospace and military industries, have experienced significant adoption in the field of civil engineering during the past three decades. This can be attributed to their remarkable mechanical characteristics that surpass those of conventional construction materials [11-15]. FRP materials possess corrosion-resistant properties and demonstrate adaptability, making them highly suitable for reinforcing pre-existing concrete elements or constructing new composite sections. These materials offer several advantages, such as decreased construction time and lower maintenance costs [16,17]. In recent years, there has been a notable increase in the utilisation of FRP columns. This trend can be attributed to their remarkable mechanical properties and the decreasing costs associated with fibrous materials [18,19]. The utilisation of fiber-reinforced plastic (FRP) profiles in beam and column applications is widespread. These profiles can be categorised into three main types: FRP tubes, FRP profiles, and hybrid columns that combine steel, concrete, and fiber-reinforced plastic tubes [20–22]. The main objective of Fibre Reinforced Polymer (FRP) columns is to utilise the inherent strength of FRP materials in order to induce transverse confining pressure within concrete columns. Simultaneously, there exists another classification of FRP profiles that seeks to provide structural column components that are lightweight [23,24]. The cost-effective production procedures of pultruded FRP profiles, which are now similar to those of steel profiles, have attracted significant interest in recent times [25]. Fiber-reinforced polymer (FRP) materials have demonstrated considerable promise in enhancing the strength, stiffness, and ductility of structural elements. Notably, there has been a notable increase in research attention dedicated to the investigation of "FRP columns," as seen by the publication of more than 1013 publications in this field in the year 2021 alone. The increasing interest and importance of FRP in civil engineering applications is highlighted by the growing trend shown in Figure 1. Simultaneously, the issue of seismic susceptibility continues to be a constant problem for structures, namely reinforced concrete (RC) bridges and buildings, located in regions that are susceptible to seismic events. The design of RC bridges in India has been historically characterised by several deficiencies, primarily attributed to the utilisation of old building codes. Consequently, these structures have been inadequately equipped to endure lateral seismic loads. The importance of mitigating seismic vulnerability has increased due to the introduction of seismic analysis methodologies that utilise non-linear static methods, which have received global attention.

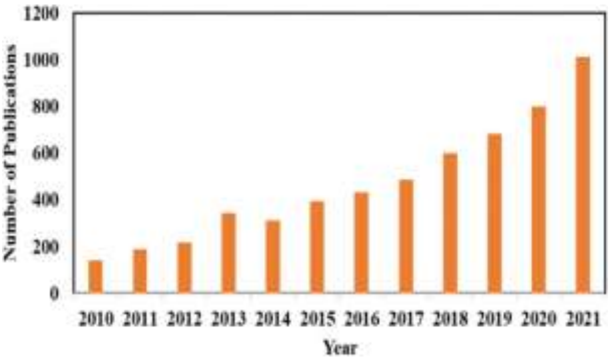


Fig.1 Publications in the last 12 years on FRP composite columns

This paper seeks to provide a comprehensive review, addressing two critical aspects of structural engineering. The first segment delves into the utilization of FRP materials in enhancing concrete strength, particularly in the context of columns. It explores the diverse applications, mechanical properties, and cost-effective fabrication processes associated with FRP materials, aiming to guide future research directions and applications in civil engineering. The second segment focuses on the seismic vulnerability of structures, emphasizing the need for robust seismic retrofitting technologies. The review encompasses pushover analysis of RC bridges, modifications to traditional analysis models, and advancements in seismic retrofitting technology. By synthesizing existing knowledge, identifying research gaps, and offering insights into the state-of-the-art in structural engineering practices, this paper aims to contribute to the advancement of sustainable and resilient infrastructure. The incorporation of transverse steel confinement greatly enhances the structural strength of concrete. Nevertheless, the occurrence of local buckling in columns results in a reduction of the effectiveness of lateral steel confinement, resulting in a decrease in both the capacity to bear axial loads and the ability to deform plastically [30–32]. As a result, the integration of Fibre Reinforced Polymer (FRP) within the framework functions to enhance confinement and mitigate the occurrence of outward local buckling. Despite the extensive discussion in the literature addressing the mechanical and physical characteristics of fiber-reinforced polymer (FRP) composites, there remains a lack of clarity regarding the ideal choice of fibre material and polymer matrix. This selection is a crucial determinant of both performance and cost-effectiveness.

In an effort to bridge this existing gap in knowledge, the present work aims to conduct a comprehensive assessment of recent research pertaining to the use of fiber-reinforced polymer (FRP) in concrete columns within civil constructions. In order to accomplish this objective, a variety of fibre materials including glass, carbon, aramid, bamboo [33,34], jute, and other types have been assessed within the realm of civil engineering applications. The purpose of this review is to offer recommendations for the appropriate selection of fibre types based on specific applications, as outlined in Table 1. Numerous investigations have been conducted to examine diverse approaches for forecasting the strength characteristics of Fibre Reinforced Polymer (FRP) composites, employing numerical or analytical models. However, there exists a necessity to amalgamate and integrate this knowledge. The objective of this work is to integrate various experimental, numerical, and analytical methodologies that have been offered in existing literature, with the purpose of assessing their efficacy in predicting desired results.

Table 1. review of different materials and advantages in FRP columns

Ref.	Material	Advantage
[7]	GFRP composites with crushed fired clay bricks	GFRP composite had a significant effect on the ultimate stress and strain of concrete specimens.
[14]	Concrete filled steel tubes	High compressive resistance, can be achieved by employing the ultra high strength concretes.
[19]	CFRP composite confinement	The axial stress of FRP confined concrete is lower than that of actively confined concrete under cyclic loading (Axial strain, lateral strain, and confinement pressure are all equal).
[24]	Aramid-FRP tubes and steel tubes	Ultimate axial strain and hoop rupture strain, are highly sensitive to instrumentation arrangement
[28]	RC columns with CFRP composites	Improvement in strength and ductility of confined RC columns.

[29]	Jute-polyester hybrid FRP	The hybrid confinement is effective in improving the compressive strength and strain capacity
[30-32]	Basalt based FRP	There is an increase of the strain reduction factor as the hybrid effect increases.
[35]	CFRP-wrapped conereteccylinders	Numerical research revealed that the compressive strength, stiffness, and ductility of CFRP-wrapped concrete cylinders were much higher.
[36]	CFRP/GFRP composite confinement	The Diameter increased to 350" " mm and the ultimate strength increased up to 2157.44%.
[37]	Natural fibre-reinforced polymer (NFRP) jackets	Proposed a new strength model to predict the compressive strength of natural fibre-reinforced polymer jackets.
[38]	CFRP-confined gangue aggregate concrete column	Proposed analytical formulation to systematically study the interaction mechanism between hybrid FRPs.

I. FIBRE REINFORCED PLASTIC/POLYMER (FRP) JACKETING

The application of Fibre Reinforced Polymer (FRP) jacketing shown in Figure 2, is generally accepted as a seismic retrofitting technique on a global scale, owing to its multitude of advantages in comparison to traditional approaches like as Reinforced Concrete (RC) and steel jacketing. The advantages of this technology encompass accelerated installation, less labour requirements, limited modification to the original structure's geometry and aesthetics, a high ratio of strength to weight, and features that are favourable to occupants. However, it is important to acknowledge that there are still certain limits that continue to exist in the use of externally bonded Fibre Reinforced Polymer (FRP) materials. These limitations mostly stem from the restricted effectiveness of the bonding between the FRP and the substrate, typically resulting in a maximum efficiency of approximately 30-35%. This reduced efficiency is primarily attributed to the occurrence of early debonding. Moreover, Fibre Reinforced Polymer (FRP) demonstrates limitations when exposed to elevated temperatures or moisture-laden conditions and is accompanied by a comparatively elevated expense. In general, Fibre Reinforced Polymer (FRP) is commonly affixed to columns through the application of epoxy resins.

A. FRP Jacketing for Enhanced Confinement in Concrete Retrofitting

There has been a recent focus on the utilisation of FRP jacketing as a viable alternative for the structural application of Recycled Aggregate Concrete (RAC). The principal benefits associated with fiber-reinforced polymer (FRP) composites are their cost-efficiency, superior strength, and stiffness properties. The utilisation of Glass Fibre Reinforced Polymer (GFRP) composites and crushed fire clay bricks as coarse aggregates has been demonstrated in prior studies, resulting in notable improvements in both the ultimate load-bearing capacity and stiffness of circular concrete columns [12]. Fibre Reinforced Polymer (FRP) jacketing has demonstrated notable efficacy in enhancing the performance of structural elements subjected to compressive loads or possessing circular or annular cross-sectional geometries. This technique offers significant benefits, including enhanced confinement and corrosion resistance for embedded concrete, as supported by previous studies [23–27]. This section delves deeper into the examination of how various fibre kinds affect the compressive behaviour of concrete columns.

Figure 2 FRP jacketing

B. Carbon Fibers for Confinement in Concrete Structures

Concrete structures exhibit intrinsic properties such as high strength, resistance to corrosion, and resistance to deformation, rendering them appropriate for the construction of high-rise buildings [28–33]. Nevertheless, the inherent brittleness of these materials imposes some limitations on their potential uses, hence requiring the implementation of lateral confinement techniques in order to enhance their performance. The utilisation of conventional techniques that employ high-tensile steel tubes is confronted with obstacles such as excessive material consumption and elevated expenses [34–39]. The utilisation of Carbon Fibre Reinforced Polymer (CFRP) materials, which possess a notable strength-to-weight ratio, serves as a potential solution to these aforementioned concerns. However, it is important to note that these materials may be susceptible to sudden and catastrophic rupture failures. The effective confinement of FRP concrete structures can be achieved through the combination of carbon fiber-reinforced polymer (CFRP) sheets and steel tubes. The study done by Chen et al. (2019) investigated the axial compression behaviour of recycled aggregate/natural aggregate concrete constrained with CFRP. The researchers observed comparable compressive behaviour among specimens of varying sizes. The efficacy of CFRP confinement was not considerably affected by the incorporation of recycled material. Several studies have reported differing levels of effectiveness, which can be attributed to various factors, including the replacement rates of recycled brick aggregate (RBA) [26, 27]. This research highlights the potential of CFRP in enhancing the strength of concrete, while also recognising the various elements that can affect the effectiveness of confinement. Figure 3. represents the different failure modes observed in the experiment where the different size of aggregate was used by different authors.

Figure 3 Different failure modes (a) Failure modes based on sample size [22] (b) Progressive failure of a CFRP confined concrete of 150 * 150 * 300 mm dimension [26] (c) Comparison of confined and CFRP confined samples [27]

C. Comparative Analysis: Carbon vs. Glass Fiber Confinement

In this study, we want to compare the effectiveness of carbon and glass fibre as confinement materials.

The axial compressive behaviour of glass and carbon fiber-reinforced polymer tubes within recycled aggregate concrete, using recycled clay brick aggregate, was thoroughly investigated by Gao et al. [45]. The researchers produced glass fibre reinforced polymer (GFRP) and carbon fibre reinforced polymer (CFRP) tubes by utilising unidirectional glass and carbon fabrics that were strengthened with epoxy resin. These materials were then placed within polyvinyl chloride (PVC) moulds, with varying numbers of layers being employed. Brick aggregates were substituted by natural aggregates at different proportions. Figure. 4 represents a typical stress-strain curve for GFRP and CFRP composites and from the experimental results. The results of their study shown a notable increase in the compressive strength of concrete encased with recycled clay brick aggregate (RCBA), especially when using a 6-layer glass fibre reinforced polymer (GFRP) tube. Nevertheless, an analysis of stress-strain curves indicated notable differences between carbon fibre reinforced polymer (CFRP) and glass fibre reinforced polymer (GFRP) tube-confined concrete.

Specifically, CFRP exhibited reduced axial strain while displaying increased compressive strength. The study utilised visual depictions of unsuccessful specimens to illustrate specific failure mechanisms and evaluate the efficacy of different confinement materials, with a particular focus on the contrasting mechanical characteristics of GFRP and CFRP confined concretes [41], Figure. 5 shows the failed specimens of neat, CFRP and GFRP confined concretes.

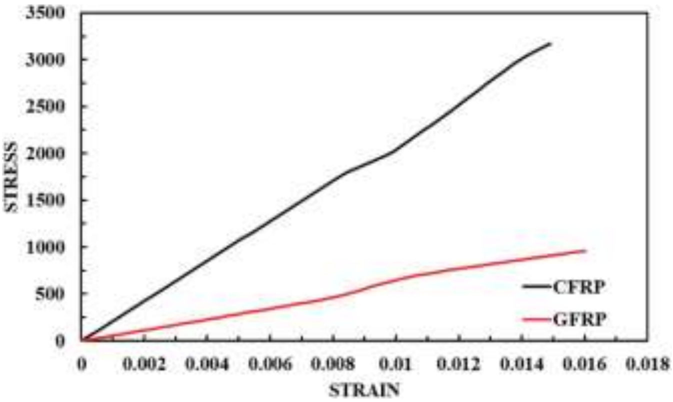


Figure 4 Tensile stress-strain curves of GFRP and CFRP composites [45]

Figure 5 Failed specimens under compressive load (a) Plain (b) GFRP confined concrete (c) CFRP confined concrete [45]

D. Hybrid FRP Composites Columns

Hybrid fiber-reinforced polymer (FRP) columns integrate conventional structural components such as steel and concrete with FRP profiles, resulting in adaptable structural elements. The research primarily centres around two areas: the application of FRP composites for retrofitting existing concrete columns [42–46] and the construction of new high-performance composite columns [46–48]. The employment of fiber-reinforced polymers (FRP) in the confinement of concrete is to mitigate the risk of steel profile buckling. Scholars have conducted investigations on the development of hybrid FRP column members that are both cost-effective and high-performing. These studies have involved the utilisation of different combinations of unidirectional and bi-directional fibres, capitalising on the strengths of each component to improve the structural performance [49–52].

E. Exploring the Potential of Hybrid FRP Columns

In structural applications, it is common to utilise concrete-filled steel tubes as columns. However, these columns are susceptible to inelastic outward local buckling in close proximity to the end of the column. Researchers have proposed and tested the use of Fibre Reinforced Polymers (FRP) as jackets or wraps in steel structures to prevent buckling. These studies have shown promising results in both retrofitting and reinforcing existing structures, as well as in new construction projects. Hybrid fiber-reinforced polymer (FRP) columns, which incorporate fillers, steel tubes, and steel I sections, are designed to provide lightweight structural solutions. Table 2 provides a comprehensive overview of several hybrid fiber-reinforced polymer (FRP) combinations that have been described in the existing body of literature.

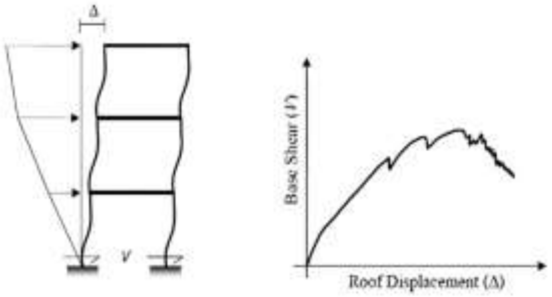
Table 2. Review of existing hybrid frp column

Citation	FRP hybrid components	Reinforcement Method	Dimension	
			Diameter	Height
[29]	Jute polyester hybrid FRP composites	Wrapping of fibre sheets	150mm	300 mm
[30]	CFRP Basalt FRP GFRP	Wet layup	150 mm	300 mm
[52]	CFRP Aramid FRP GFRP Polypara phenylene Benzo bis-Oxazole (PBO)	FRP jackets formed using wet lay-up process	150 mm	300 mm

[55]	S-GFRP tubes and steel tubes	Wet layup process in the hoop direction	60.3 to 114.3 mm	181 to 305 mm
[56]	(Aramid) FRP tubes and steel tubes	Layup process	150 mm	300 mm
[57]	GFRP tubes and steel tubes	Filament winding	300 mm	1350 mm
[58]	CFRP tubes and steel tubes	Layup process	60 to 150 mm	180 to 300 mm
[59]	CFRP tubes and steel tubes	Layup process (Alternate layer arrangement)	153 mm	300 mm
[60]	GFRP wrap, steel tube	Wet-layup with fibres in the hoop	200 mm	400 mm

II. PUSHOVER ANALYSIS

Pushover analysis employs a static nonlinear methodology, that involves incrementally increasing the amplitude of the lateral load while keeping a predetermined distribution pattern along the vertical axis of the building (Figure 6a). The displacement of the building occurs until the "control node" attains the desired level of displacement or until the building experiences structural failure. Throughout the process, it is clear to see the order in which the structural components fracture, plastic hinge, and collapse. The graph in Figure 6b. illustrates the correlation between base shear and control node displacement across all pushover analyses. Pushover analysis offers comprehensive understanding of the complete structural reaction until failure [64]. Pushover analysis is conducted using several load patterns in order to determine the most appropriate load pattern for the analysis of bridges [68]. The capacity curve, which represents the relationship between base shear and top displacement of the structure, is typically derived by pushover analysis. In order to assess the suitability of a structure to withstand seismic loads of a specific magnitude, it is necessary to measure its capacity against the related requirements for a given scenario event. The comparison might be predicated upon either force or displacement [62].



a) b)

Figure 6 a) Building model, b) Pushover curve

III. SEISMIC RETROFITTING

The earthquake risk of a particular place is determined by the estimated aggregate impact of many factors [74, 75], including the anticipated number of lives lost, individuals hurt, property damaged, and economic activity disrupted as a result of an expected powerful earthquake. In recent decades, India has encountered a number of significant earthquakes. As per the guidelines outlined in IS 1893 (Part I:2016), approximately 56% of India's landmass is susceptible to moderate to severe earthquake shaking intensity. This distribution is further broken down into specific zones, with 12% falling within Zone V, 18% within Zone IV, 26% within Zone III, and the remaining 44% within Zone II. Over the past 25 years, a number of significant to moderate earthquakes have taken place within the country.

A. Need for Seismic Evaluation of Existing Buildings

The seismic susceptibility of an existing building is determined in the following scenarios:

i. The structural design and detailing of the structure may not have been adequately implemented to withstand seismic effects.
ii. The building's design may have taken into consideration seismic forces, predating the release of the present seismic standards. The building's lateral strength fails to meet the requirements for seismic forces outlined in the updated seismic zones

or the increased design base shear. The level of detailing employed does not meet the specifications outlined in the existing regulations, which are intended to assure both ductility and integrated action of the components.

iii. The structure appears to be of substandard quality.
iv. The building's condition has evidently worsened over time.
v. The structure has undergone alterations, extensions, or changes in its usage, resulting in an increased susceptibility. For instance, supplementary levels have been constructed.
vi. The soil exhibits a significant propensity for liquefaction.

B. *Objectives of Seismic Retrofit*

The objectives of seismic retrofitting are numerical representations aimed at achieving the objectives of retrofitting. In the case of a non-engineered construction, it is possible that the objective may lack quantifiability. The underlying goal is to ensure sufficient lateral strength by the implementation of measures that have been empirically validated and proven beneficial in previous seismic events. It is imperative that the retrofitted structure exhibits sufficient structural integrity to withstand a major seismic event without experiencing any form of collapse.

Objectives of seismic retrofit can be summarized as follows:

i. Public safety: The primary objective of public safety is to safeguard human life by ensuring that a structure does not pose a risk of collapsing on its occupants or individuals passing by, and that the structure allows for safe evacuation. In the event of significant seismic activity, the structure may incur substantial economic losses, necessitating its complete demolition and subsequent reconstruction.
ii. Structural Resilience: The objective is to ensure that the structure, while maintaining its safety for evacuation, may necessitate significant repairs (rather than complete replacement) before it becomes fully functional or deemed suitable for habitation. Typically, the lowest level of retrofitting is implemented on bridges.
iii. Structural functionality: The core structure remains intact and retains its full utility for its intended primary purpose.
iv. Structure unaffected: The optimum level of refit for historic structures of high cultural significance is one that does not alter the structure's original design or layout.

C. *Seismic Retrofit Strategies/Technique*

This section provides an explanation of the methodology employed in formulating a retrofit strategy [63] after identifying defects in the existing buildings and establishing apparent performance objectives. The retrofit strategies can be categorised into global and local initiatives. A comprehensive retrofit strategy is implemented on a global scale with the aim of enhancing the seismic resistance of buildings. The primary objective of a local retrofit technique is to enhance the seismic resistance of a specific structural part, while minimising any substantial impact on the overall resistance of the entire structure. In order to develop a sustainable and cost-effective retrofit plan [68], it may be imperative to integrate local and global retrofit ideas.

i. Adding Shear Wall

Shear walls may be incorporated into buildings using either framed structures or flat slabs or plates. In the latter category of structures, the absence of traditional frames can result in significant deficiencies in both lateral strength and stiffness. It is imperative to ensure that a sufficient foundation is provided for the installation of a new shear wall. It is imperative to ensure that the reinforcing bars of the wall are adequately secured to the bounding frame. Shear walls are designed to withstand two distinct types of forces, namely shear forces and uplift forces. The previously stated arrangement facilitates the transmission of horizontal forces to the shear wall. The act of transferring loads in this context induces shear forces that are distributed uniformly along the vertical extent of the wall, spanning from the upper to the lower connections of the shear wall. The ability of the lumber, sheathing, and fasteners to withstand shear stresses is crucial in preventing the wall from experiencing tearing or shearing.

ii. Adding Infill Wall

The implementation of infill walls in the ground storey presents an attractive option for retrofitting structures that possess open ground levels. In the event that a plinth beam is not present, it is necessary for the new foundation of the infill wall to be securely connected to the pre-existing footings of the neighbouring columns. Alternatively, a plinth beam may be added in order to provide additional support to the wall. The inclusion of infill in a frame contributes to an increase in both the lateral load resistance and the energy dissipation capability. The option being discussed, which involves a building with an open ground story, is considered to be feasible. Infill walls with reinforced concrete masonry units can operate as shear walls.

iii. Adding Bracing

Steel braces can be incorporated into a frame structure to enhance its lateral stiffness, strength, ductility, energy absorption, or a combination of these factors. These braces can be conveniently installed on the outside frames of a building with no disturbance to its functionality. In the case of an open ground story, the placement of braces within suitable bays can effectively preserve the practical utility. The relationship between the braces and the pre-existing frame is a crucial factor to take into account. One method for placing bracing involves the incorporation of a steel frame within the allocated bay. Alternatively, the braces have the potential to be directly affixed to the frame through the utilisation of plates and bolts.

iv. Base Isolation

Base isolation refers to a set of structural components incorporated into a building with the purpose of effectively separating the building's structure from the vibrations of the ground. It helps to protect the structural integrity of the building and improve its ability to withstand seismic activity. Base isolation is a technique that aims to minimise the transfer of ground motion to a building, while also maintaining the building's proper alignment with its foundation.

IV. CONCLUSION

In conclusion, this paper offers a comprehensive review of the use of various Fiber-Reinforced Polymers (FRPs) as confining materials in concretes and diverse methods employed to assess their impact. Over the last three decades, research in this area has significantly progressed, leading to enhanced structural applications. However, a notable challenge arises with FRP profiles, where buckling can adversely affect axial performance, necessitating modifications in cross-sections to optimize mechanical properties. Shifting focus to structural engineering, particularly nonlinear pushover analysis, this review underscores notable advancements in methodologies such as multi-mode approaches and adaptive analogies. These developments signal a transition toward more accurate seismic effect capture. Additionally, the rapid global adoption of external sub-structure retrofitting technology, originating in Japan, holds promise for enhancing structural-system-level performance with minimal disruption. In essence, the collaborative exploration of these knowledge gaps presents opportunities for international consensus and the refinement of seismic engineering practices. Addressing these areas will contribute to establishing definitive design guidelines and enhancing the global resilience of structures in the face of seismic challenges. Researchers are encouraged to pursue further studies in these domains, fostering a collective effort to advance seismic engineering practices.

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