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Advanced in Strengthening Prestressed Concrete Beams: A Comprehensive Review of Modern Techniques

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Abstract
Prestressed concrete (PSC) beams are widely used in construction worldwide, especially for bridges due to their high strength, durability, and efficient load-carrying capacity. However, over time, these structures face deterioration from various factors, such as material aging, fatigue, environmental factors, and increased service loads, requiring strengthening methods. Many studies have investigated various materials and schemes for improving the flexural and shear capacities of (PSC) beams. This review aims to explain external strengthening techniques for (PSC) beams, including steel plate bonding, external post-tensioning method, Fiber-Reinforced Polymers (FRP), and shape memory alloys (SMAs). A review was conducted to investigate the effects of various strengthening methods on the performance of (PSC) beams, focusing on crack propagation modes and specimen failure related to flexural and shear improvement techniques. Flexural strengthening enhances bending capacity and serviceability by reducing deflections and improving load resistance. In contrast, shear strengthening techniques aim to prevent diagonal shear cracks and brittle failures near support zones. A comparative analysis highlights each method's advantages, limitations, and applicable contexts, highlighting their impact on structural performance and longevity. The discussion also includes these techniques' knowledge gaps, challenges, and constraints while proposing future research directions to improve their effectiveness. This review study offers significant insights for engineers and researchers focused on enhancing the performance and durability of (PSC) beams by recent strengthening techniques.

Keywords: Prestressed concrete (PSC) beams, Strengthening, Flexure, Shear, failure mode.

1 Introduction

Prestressed concrete (PSC), introduced in the 1940s, is considered superior in durability and reliability for civil engineering applications [1], particularly for bridges [2, 3] where its benefits such as simplified construction methods, efficient mold casting, and economical aspects [4]. Compared to traditional reinforced concrete, (PSC) offers smaller member sizes, a high strength-to-weight ratio, higher resistance to deflection, preventing cracking loads [5-8], and effectively mitigating tensile stresses under service loads [9]. Prestressing is achieved in a structural by either pre-tensioning or post-tensioning tendons or wires, which are the primary means of tension reinforcement, with pre-tensioning favored in precast industry and post-tensioning in in-situ constructions [10]. Tendons can be classified into two main types, with steel and composition of fiber-reinforced polymer FRP tendons, with FRP encompassing carbon, basalt [11], aramid [12], and glass materials, identified as (CFRP), (BFRP), (AFRP), and (GFRP) [13]. However, over time, various factors such as environmental exposure [14], material aging, and overloading [15] can deteriorate the structural integrity and performance of (PSC) [16]. Strengthening (PSC) beams is essential for managing aging infrastructure and safety standards. Sustainable construction emphasizes cost-effective strengthening techniques over complete replacement to reduce environmental impact [17]. Advances in materials have enhanced the performance and durability of (PSC) beams for modern requirements. This review highlights external strengthening techniques for (PSC) beams as crucial for maintaining structural integrity and supporting societal resilience. The primary goal of this review is to evaluate techniques for strengthening (PSC) beams. It examines the mechanisms, advantages, and limitations to provide insights into their applications and effectiveness. Additionally, the article identifies research gaps and suggests future exploration areas. Ultimately, the review aspires to advance structural rehabilitation strategies, improving the safety, functionality, and longevity of (PSC) structures. The review was carried out using a structured search of major scientific databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar.

Relevant publications were retrieved using keyword combinations such as (prestressed concrete beams, external strengthening, steel plate bonding, FRP strengthening, external post-tensioning, near-surface mounted (NSM), and "shape memory alloys (SMA)). The search was limited to peer-reviewed journal articles published between 2000 and 2025 to capture recent advancements in strengthening techniques for prestressed concrete beams. After screening for relevance and eliminating duplicates, about 30 relevant references were selected for an extensive review and comparative analysis.

2 Common Causes of Deterioration and Need for Strengthening Prestressed Concrete Beams

Prestressed concrete (PSC) is widely used in construction worldwide but faces similar deterioration challenges as reinforced concrete (RC) due to environmental, material degradation, and mechanical stresses. Influenced by various factors, as follows:

2.1. Overloading and impact loads significantly contribute to the deterioration of structural components, often occurring from changes in usage, an increase in traffic loads, or unexpected forces, such as seismic activity. Initial design inadequacies, construction errors, insufficient quality control, and inadequate maintenance practices make beams more prone to early failure [18]. Aging in (PSC) structures leads to increased crack propagation, negatively impacting load-bearing capacity and causing concrete degradation and loss of prestress in tendons [19].

2.2. (PSC) structures are generally resilient against environmental impacts; however, construction defects and environmental erosion lead to inevitable corrosion of strands within concrete, resulting in brittle fractures, and structural damage ultimately contributes to structural damage [20]. The degradation of concrete infrastructures has led to visible structural damage in some bridges. In addition, extreme environmental conditions such as freezing, thawing, and chloride penetration adversely affect durability, notably the corrosion of steel reinforcements and the formation of large cracks, leading to prestress loss [21]. Globally, numerous cases have been documented in which bridges have collapsed due to the deterioration of tendons or strands under various loads [22]. In concrete structures, corrosion is instigated by chloride, sulfate actions, or carbonation of the concrete, the findings demonstrate reductions in yield and ultimate strength as well as decreased ductility in the reinforcing steel, due to the degradation of mechanical properties of rebars and the weakened bond strength between the steel and the concrete [23], and reduced bearing capacity, which can lead to unpredictable failures [24].

2.3. Corrosion and fatigue, which are primarily caused by the natural aging of materials and live loading conditions, are the key processes behind critical deterioration [25]. Insufficient design considerations for anticipated future loads; accidental impacts from overweight vehicles; application of seismic retrofitting is essential to meet code specifications; fluctuations in temperature and moisture levels; and changes in usage pattern [17, 26]. The long-term behavior of prestressed concrete beams is influenced by creep and shrinkage, which may result in prestress losses and increased strains over time [27].

3 Overview of Strengthening Techniques

In the last two decades, various research initiatives have focused on the enhancement of prestressed concrete (PSC) beams through externally bonded reinforcement, improving their shear and flexural performance, extending their lifespan, and addressing deterioration or increased service demands [28]. An effective strengthening method should ideally ensure ease of implementation, efficiency, and economical [29], minimal service disruption of members, negligible dead weight addition or clearance loss, efficient labor practices, rapid installation, minimal impact on existing members, and adequate performance under service conditions [30]. Various externally bonded reinforcement (EB) techniques have been developed over the years as illustrated in Figure 1; however, each varies in applicability and effectiveness based on specific structural needs and challenges [31-33]. In this section, an overview is provided of the most commonly used techniques that are used for strengthening (PSC) beams, highlighting their mechanisms, advantages, limitations, and failure mechanisms.

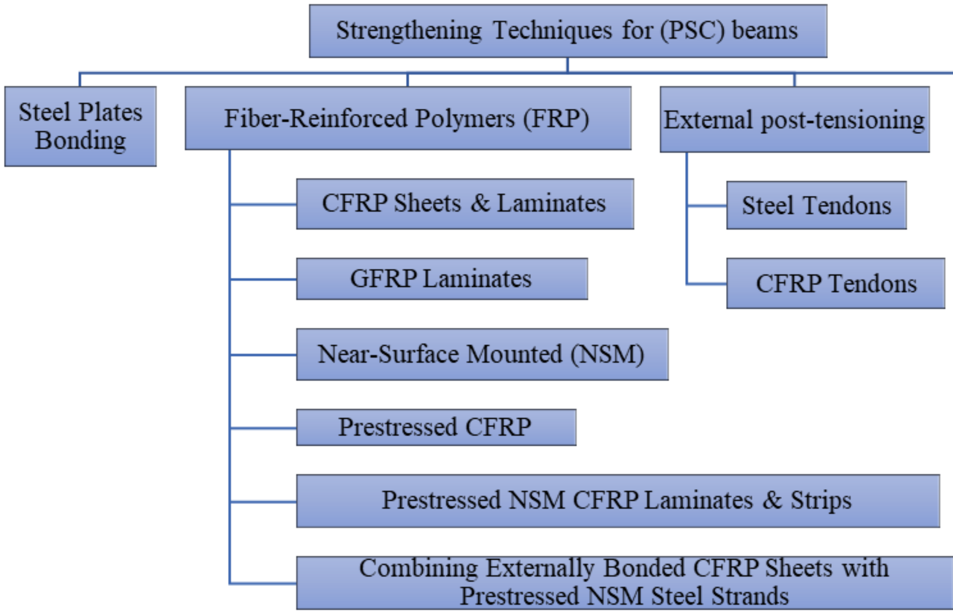


Figure 1: Available strengthening techniques for (PSC) beams present in this article.

3. 1Steel Plates Bonding

3. 1. 1 Overview:

The use of steel plates to enhance the strength of concrete elements began in the 1960s as a cost-effective alternative to structural demolition. Since then, steel has been applied in various forms, including rods, bars, tendons, plates, strand splice systems, and steel jackets to enhance structural concrete members [17]. Typically, steel plates are bonded to the concrete part of the member using specialized adhesives or epoxy resins, anchored to enhance tensile strength, functioning similarly to steel bars in augmenting structural integrity [34-36].

3. 1. 2 Advantages, Challenges and Limitations:

Currently, steel plate reinforcement is widely used due to its advantages, which are its established mechanical properties, quick installation, minimal disruption, slight alteration in dimensions, the accessibility and cost-effectiveness of steel plates, along with their consistent stress distribution and favorable plasticity, and effective strengthening capabilities, make them a preferred choice and particularly in prestressed bridges [34-36]. Despite its advantages, the method has limitations. The disadvantage of this technique suffers from inadequate corrosion resistance at the interface between steel and epoxy in aggressive environments, leading to potential strength loss and debonding, as well as on-site handling challenges due to their weight and it can add significant dead load to the structure. Consequently, the inherent corrosion issues and handling difficulties render steel materials suboptimal for bridge applications exposed to severe environmental conditions and significant in situ costs [37, 38]. Debonding, a critical issue resulting from stress concentration at plate ends, arises from inadequate surface preparation, thermal expansion differences, or adhesive creep. Additionally, bonding steel plates may not significantly improve ductility, potentially exposing the structure to brittle failure [39].

3. 1. 3 General behavior for flexural and shear strengthening, and failure modes in recent studies:

Steel Plates Bonding technique is used for shear or flexural strengthening of concrete members, with performance influenced by factors such as bolt arrangement and plate dimensions; its effectiveness is contingent upon surface preparation, adhesive properties, and environmental conditions [17, 40]. The steel plates act as external reinforcement, it has demonstrated significant improvements in load-carrying capacity, stiffness, deformation control under live loads, serviceability, crack resistance, and enhanced bending and shear performance of girders, without adversely affecting structural aesthetics or clearance [41]. Among the limited studies on the performance of strengthening (PSC) beams. As indicated in Table 1, the application of bonding steel plates to prestressed concrete beams has led to notable improvements in both flexural and shear capacities, with improved load-bearing performance and modified failure mechanisms.

Table 1: Summary of the principal experimental findings from recent studies of strengthening PSC beams with steel plates bonding.

No.	Author	PSC Beam Section	Concrete Strength (MPa)	Strengthening Configuration	Strengthening Schemes	Ultimate Load / Shear Capacity Increase (%)	Failure Modes
1	Eisa et al., (2024) [42]	Rectangular	40	Flexural	Bottom steel plate (U-shape)	48	Flexural failure; U-shape reduced crack propagation
					Bottom steel plate	13	Flexural failure; compressive failure due to crack progression
2	Eisa et al., (2024) [42]	Rectangular	40	Shear	U-shaped steel plate with anchors	60	Shear failure; reduced crack propagation
					Steel plate (straps) with anchors	13	Shear failure; ineffective in limiting crack propagation
3	Jiang et al., (2024) [43]	T-shaped	41	Shear	Vertical strips	24.7	Shear failure; Stirrups & plates yielded; concrete fractures
					Inclined strips	21.5	Shear failure; stirrup yielding, steel plate debonding

Eisa et al., (2024) [42] conducted an analysis on the impact of bonded steel plate strengthening schemes affect the flexural and shear properties of rectangular (PSC) beams, using bottom steel plate configurations for flexure and various shear strength schemes with anchors, showing failure modes in Figures 2 and 3. Failure of the beams were observed as Plate debonding, and concrete cracking.

a) Flexural strengthened (PSC) beam by U-shaped steel plate

b) Flexural strengthened (PSC) beam by steel plate

Figure2: Observed failure mode of test specimens tested by Eisa et al., (2024) [42].

a) Shear strengthened (PSC) beam by U-shaped steel plates b) Shear strengthened (PSC) beam by U-shaped steel plates straps

Figure 3: Typical failure mode of test specimens tested by Eisa et al., (2024) [42].

Furthermore, Jiang et al., (2024) [43] tested (PSC) Tee beams, with various schemes of strips, demonstrating shear failure as shown in Figure 4.

a) strengthened (PSC) beam with vertical strips b) strengthened (PSC) beam with inclined strips

Figure 4: Typical failure mode of test specimens reported by Jiang et al., (2024) [43].

3. 2 External post-tensioning method

3. 2. 1 Overview:

The external post-tensioning pre-stressing method introduced in the mid-20th century, was initially utilized to strengthen bridges, but it can be used for both the enhancement of existing and new structures [44]. This method involves the installation of extra tendons outside the concrete cross-section, anchored at the ends of the beam and modified in a trajectory through saddles or deviators [45]. The principles governing externally post-tensioned methods are fundamentally similar to those of internally post-tensioned techniques [46]. The main difference between the two techniques is the influence of tendon eccentricity and the frictionless condition due to increased component diversion [47]. High-strength steel tendons and fiber-reinforced polymer FRP tendons are mainly used in external post-tensioning [48]. Steel tendons, including strands and wires, are commonly used due to their high tensile strength, ductility, economical material cost, material availability, and relative ease of installation. However, they are prone to corrosion in harsh environments, to mitigate this issue, it is essential to adopt protective measures such as the application of sheathing or coatings [49]. Nevertheless, these approaches are not durable or cost-effective solutions [50]. In this context, fiber-reinforced polymer FRP tendons, such as carbon fiber (CFRP), glass fiber (GFRP), and aramid fiber (AFRP) have emerged as a compelling alternative for traditional steel strands in both new constructions and the retrofitting of existing structures [51] due to their superior corrosion resistance, high tensile strength, lightweight properties, and fatigue resistance [52] though they exhibit brittle failure modes and higher initial costs [21]. The use of hybrid systems that combine steel and FRP materials is prevalent in specialized applications, aiming to effectively balance the properties of strength, durability, and ductility.

3. 2. 2 Advantages, Challenges and Limitations:

The principal advantages of external prestressing include adaptability, reduced disruption on existing structures, and convenience of maintenance or future enhancements. Furthermore, this technique contributes to the extended service life of structures by improving their capacity and durability. Nonetheless, this technique has certain limitations, the exposed tendons are susceptible to environmental deterioration, requiring adequate protection. Secondary consequences, including the eccentricity of tendons and the increase in long-term deflections, can affect performance. This technique requires careful design and installation to guarantee that stress is transferred appropriately and that the system is compatible. Despite its limitations, the application of external prestressing is one of the most effective techniques for strengthening pre-existing prestressed concrete beams, particularly in retrofitting aging or under-designed structures [51]. Its advantages outweigh its challenges when appropriately designed, implemented, and maintained. In recent decades, the application of externally prestressed strands has been used to enhance the strength of reinforced concrete structures by numerous experimental studies [53-56] significantly improves flexural behavior, increasing the load-carrying capacity, and decreasing deflections. Investigation indicates that the flexural performance of externally prestressed concrete beams using fiber-reinforced polymer FRP or steel tendons exhibits no notable differences, aside from minor variations attributed to the differing moduli of elasticity of the two materials [57,58].

3. 2. 3 General Behavior for flexural and shear strengthening, and failure modes in recent studies:

The use of external prestressing for the enhancement and rehabilitation of (PSC) beams and girders has been investigated in the last decades, among the few studies investigating the strengthening of (PSC) beams with external prestressing, Table 2 highlights that these beams has resulted in significant improvements load-bearing capacity and modified failure mechanisms reported in these studies.

Table 2: Overview of external post-tensioning strengthening techniques for PSC beams

No.	Author	PSC Beam Section	Concrete Strength (MPa)	Strengthening Configuration	Load Capacity Increase (%)	Crack Behavior & Failure Mode
1	Chen et al., (2024) [59]	I-shaped	72	External Prestressed (CFRP)Tendons: level of prestressing: 15%	31	Concrete crushing; CFRP tendons intact; plastic deformation observed
				External Prestressed (CFRP)Tendons: External post-tensioned Level of prestressing: 30%	39	
				External Prestressed (CFRP)Tendons: External post-tensioned level of prestressing: 50%	54	
2	Xue et al., (2020) [21]	T-shaped	52	External Prestressed (CFRP)Tendons	40	Flexural failure; compression zone crushing; no CFRP rupture
				External Prestressed steel Tendons	40	
3	Abbas & Al-Mahaidi, (2017) [6]	I-shaped	37.8	External Prestressed steel Tendons	118.1	Flexural failure; wider cracks near midspan;
4	Herbrand & Classen, (2015) [45]	I-shaped	42.0	External Prestressed steel Tendons	Not quantified	Reduced crack widths. Transition from brittle shear to ductile flexure failure

In more recent studies, Chen et al. (2024) [59] carried out a research study on (PSC) beams strengthened with external unbonded (CFRP) tendons by various prestress levels (15%, 30% and 50%), with Figure 5 illustrates the crack pattern of a (PSC) beam strengthened using external post-tensioning techniques. The most ideal failure mode for a strengthened (PSC) beam involves the crushing of concrete, while the (CFRP) tendons retain their structural integrity.

a) Reference (PSC) beam

b) Strengthened (PSC) beam

Figure 5: Failure mode of test specimens as observed in Chen et al. (2024)'s experiments [59].

Xue et al. (2020) [21] compared the performance of strengthening (PSC) beams by using external post-tensioned tendon types (steel and (CFRP)). The failure mode depicted in Figure 6 showed pure flexural failure across all samples, with cracks concentrated in the compression zone.

a) (PSC) beam with internal Steel tendon (S-N-U)

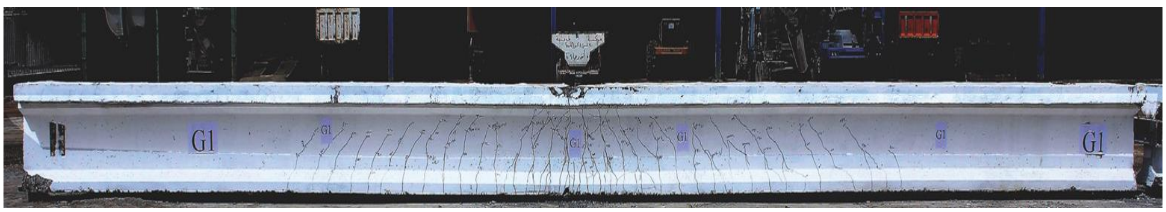
b) Strengthened (PSC) beam by external steel tendon (S-S-U)

c) (PSC) beam with internal (CFRP) tendon (C-N-U)

d) Strengthened (PSC) beam by external (CFRP) tendon (C-C-U)

Figure 6: Typical failure patterns of specimens tested by Xue et al. (2020) [21].

Abbas and Al-Mahaidi (2017) [60] conducted research to examine the behavior of strengthened (PSC) I-shaped full-size girders with an external posttensioned method by additional external strands, tested under continuous loading to failure, showing typical crack patterns in Figure 7.



a) control (PSC) girder

b) strengthening (PSC) girder

Figure 7: Observed crack pattern of girder tested by Abbas and Al-Mahaidi (2017) [60].

Further, Herbrand and Classen (2015) [45] conducted an experiment aimed at investigating the effect of additional external tendons pre-stressing on the shear capacity of (PSC) beams.

3. 3 Fiber-Reinforced Polymers FRP

3. 3. 1 Overview:

Since 1990, FRP has been used for structural enhancement in the USA. In 1996, FRP was recognized globally as a structural support material. FRP is widely used for strengthening existing reinforced concrete and new civil structures [62-63]. Within FRP composites, the resin is used as an interface agent and referred to as a matrix or epoxy. FRP composites are classified according to fiber type, including Carbon (CFRP), Basalt (BFRP), Glass (GFRP), and Aramid (AFRP) [64-67].

3. 3. 2 Advantages, Challenges and Limitations:

(FRP) composites are recognized for their excellent mechanical properties, corrosion resistance, and lightweight characteristics [68]. These advanced materials consist of high-performance fibers within a polymer matrix. This combination results in materials characterized by a favorable strength-to-weight ratio, fatigue resistance, flexibility, simple construction method, and exceptional durability, making them suitable for structural enhancement [50, 69]. (FRP) composites, despite their advantages, face significant challenges. The high costs remain a significant barrier to use especially for large-scale infrastructure projects. Environmental influences like moisture and alkali exposure can lead to the degradation of certain (FRP) types over time [70]. Debonding issues are also critical. The mode of failure identified during the flexural testing was (FRP) rupture and de-bonding [71]. Moreover, (FRP) materials exhibit poor fire resistance [72]. Also, issues associated with EBR systems include environmental harm and premature failure [70, 73]. In addition, the absence of universally accepted design standards for prestressed applications further complicates the deployment of (FRP) systems, presenting challenges for engineers in achieving consistent and reliable solutions [74].

3. 3. 3 General Behavior for flexural and shear strengthening, and failure modes in recent studies:

In recent years, the application of (FRP) in strengthening (PSC) beams and girders has garnered significant attention in contemporary engineering research due to their advantageous properties. As summarized in Table 3, experimental studies applying different FRP types and configurations demonstrate significant enhancements in flexural and shear behavior of (PSC) beams, along with improved ductility and a postponement of failure modes.

A. (CFRP) Sheets and Laminates

Externally bonded sheets and laminates made of Carbon Fiber Reinforced Polymer (CFRP) [75] are commonly used to strengthen (PSC) beams due to the properties of (CFRP) including being lightweight, easy to install, and non-corrosive. Researchers conducted experimental investigations to examine the influence of (CFRP) on (PSC) beams, Xuân Vinh et al. (2023) [76] conducted an experimental study focused on the flexural behavior of (PSC) beams reinforced with (CFRP) sheets of designated dimensions. The failure modes of the unstrengthened and strengthened beams are illustrated in Figure 8.

a) control (PSC) beam

b) strengthening (PSC) beam

Figure 8. Typical failure of unstrengthened and strengthened (PSC) beam specimens reported by Xuân Vinh et al. (2023) [76].

Nguyen-Minh et al. (2018) [77] analyzed how varying (CFRP) sheet ratios influenced the flexural performance of (PSC) T-beams and tendon performance. Three different strengthening strategies were used, including varying applications of CFRP layers and U-wrapped anchors, affecting tendon strain and failure modes as shown in Figure 9, with earlier failure of U-wraps near loading points.

a) Control (PSC) beam (un-strengthened)

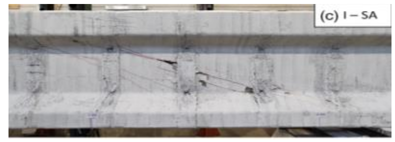
b) (PSC) beam strengthened with (CFRP) layers

c) and d) (PSC) beams strengthened with (CFRP) layers with (CFRP) U-wrapped anchors non-uniformly and uniformly distributed within the shear span respectively

Figure 9. Failure mode of test specimens tested by Nguyen-Minh et al. (2018) [77].

Kang and Ary (2012) [78] assessed the effects of (CFRP) quantity and strip spacing on the shear behavior of (PSC) beams on I-beam specimens. The failure mode of (CFRP) was primarily by the fracturing of the strips under ultimate loading conditions.

Yaqub et al. (2023) [79] evaluates (PSC) I-girders strengthened with (CFRP) using epoxy bonded in-fill blocks, converting the I-section to a rectangular form at the (CFRP) locations. In the specimen with infill blocks, failure was initiated by the rupture of the middle (CFRP) strip, leading to brittle failure due to load redistribution failure after primary tie rupture as shown in Figure 10.



a) Control (PSC) I-girders (un-strengthened)

b) (PSC) I-girders strengthened with (CFRP) using epoxy bonded (I-SA)

c) (PSC) I-girders strengthened with (CFRP) using epoxy bonded in-fill blocks (U-SA)

Figure 10: Crack pattern, failure aspect of specimens reported by Yaqub et al. (2023) [79].

B. Glass Fiber Reinforced Polymer (GFRP) Laminates

The application of GFRP laminates serves as a cost-effective alternative to (CFRP) materials, offering advantages such as good corrosion resistance despite lower stiffness and strength, can still be utilized effectively in strengthening applications, particularly where the additional stiffness provided by (CFRP) is unnecessary. Among the limited studies, Vijayan and Revathy (2016) [81] investigate the performance of GFRP strengthened (PSC) beams by using Uni-Directional Cloth (UDC) Glass Fibre Reinforced Polymer plates across various concrete grades. The typical failure mode and crack patterns of the (PSC) in the control beam and strengthened PSC beam depicted in Figure 11, resulted from FRP debonding due to interface crack propagation. GFRP strengthened (PSC) beams displayed smaller crack widths compared to control beams.

a) control (PSC) beam.

b) strengthened (PSC) beam specimen.

Figure 11: typical crack pattern of samples tested by Vijayan and Revathy (2016) [81].

Further, Hurukadli et al. (2023) [82] evaluated the behavior of (PSC) beams strengthened with three types of GFRP laminates including (Chopped Strand Mat (CSM), Woven Roving (WR), and Uni-Directional Cloth (UDC)), each available in thicknesses of 3 mm and 5 mm were used, results in enhanced ductility, promoting a ductile failure mode.

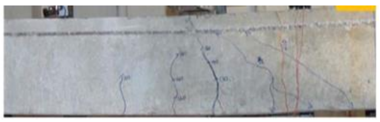
C. Near-Surface Mounted (NSM) (CFRP) Bars and Strips

The NSM technique involves embedding (CFRP) bars or strips placed within grooves along the concrete surface, subsequently filled with adhesive, leading to enhanced bond performance and increased protection for the (CFRP) materials when contrasted to externally bonded systems [83]. This technique utilizing (CFRP) is extensively researched for flexural and shear strengthening [84].

Kuntal et al. (2020) [85] conducted an experimental investigation to assess the efficacy of inorganic bonding materials for enhancing the shear capacity of (PSC) beams through the application of NSM (CFRP) laminates at a 45-degree angle, and focusing on several types of bonding materials. Among tested materials, (EP) was superior to (HSCG) and (GP), which were less efficient overall. NSM shear strengthening led to a significant reduction in the width of diagonal cracks and decreased concrete surface strains post-cracking. Epoxy-bonded specimens experienced cube splitting before the failure of debonding in the FRP. Specimens utilizing HSCG as bonding materials failed as a result of interfacial slip friction, that caused the (CFRP) laminates to pull out. While GP bonded (CFRP) specimens, the failure mechanism was identified as friction of laminates.

The performance of bonding materials in the context of NSM shear strengthening is assessed by their ability to: enhance shear capacity, minimize stirrup strains, control the width of shear cracks, and convert the failure mode from brittle shear mechanism to ductile flexural by altering strength hierarchy. The bond strength between FRP and concrete significantly influences debonding failure modes in NSM FRP strengthening. Epoxy resin is widely utilized as a bonding substance substance because of its superior mechanical attributes and bonding characteristics [85].

Further, Kuntal et al. (2017) [86] conducted tests that examine the effectiveness of various near-surface mounted (NSM) strengthening configurations utilizing (CFRP) laminates at a 45-degree and 90-degree angle on the shear performance of (PSC) beams. The failure patterns observed in (PSC) beams with NSM configurations are illustrated in Figure 12. Failure mode changed from brittle shear to ductile flexure.



a) control (PSC) beam

b) (PSC) beam strengthened using (CFRP) Lamnates at 90o orientation

c) (PSC) beam strengthened using (CFRP) Lamnates at 45o orientation

Figure12: Failure pattern of PSC beams with shear reinforcement tested by Kuntal et al. (2017) [86].

D. Prestressed (CFRP)

Prestressing FRP enhances the performance of (PSC) beams and girders. In EBR systems prestressed FRP laminates (strips) or sheets bonded to concrete tension surfaces with strength adhesives. This method can restore or enhance the prestress level in concrete beams, leading to increased load-carrying capacity and improved serviceability, resulting in restored structural integrity and extended service life [87-89]. One of the initial studies on the strengthening of reinforced concrete beams utilizing prestressed fiber-reinforced composites was conducted by [90]. Additionally, El-Hacha (2003) [91] examined the post-strengthening of concrete beams using prestressed FRP strips through experimental and analytical methods.

Aram et al. (2008) [92] investigated prestressed (CFRP) strips on (PSC) beams at varying levels. Three (PSC) beams strengthened using (CFRP) strips, which (Pb2) strengthened with unstressed (CFRP), (Pb3) strengthened with prestressed (CFRP), 36% of tensile strength, (Pb4) strengthened with prestressed (CFRP), 18% of tensile strength. The gradient anchorage method was used for the prestressed (CFRP) strips. Findings indicate that this method did not significantly decrease beam deflection or crack width, there was no increase in the failure load, and deformation ductility was reduced.

E. Prestressed NSM (CFRP) Laminates and Strips

Prestressing NSM ((CFRP) bars, or steel strands) with (CFRP) laminates and strips before embedding within the concrete beams can significantly improve the structural performance. Obaydullah et al (2021) [93] examine the flexural performance of strengthening of (PSC) beams using the NSM technique with a prestress level of (CFRP) bars. The study involved five beams that were strengthened with NSM (CFRP) bars, each prestressed to 30%, 40%, 50%, 60%, and 70% of the maximum tensile strength of the (CFRP) material. The failure modes of the control beam and prestressed beam are illustrated in Figure 13.

a) control specimen (PSC) beam

b) strengthened (PSC) beam with NSM-C-70%F

Figure 13. Failure pattern of the tested beams [93].

Further, Obaydullah et al (2016) [94] experimental analysis of prestressed near surface mounted (NSM) steel strands enhances the flexural performance of concrete beams significantly. In this investigation, five specimens were strengthened with near-surface mounted (NSM) steel strands, which were prestressed to varying degrees of 30%, 40%, 50%, 60%, and 70% of the strands' tensile capacity. The failure modes for both the control beam and the beam enhanced with a 70% prestress force are represented in Figures 13-a and 14 respectively. The application of prestressing to the strengthening strands did not negatively impact the failure mode.

Figure 14. Failure mode of strengthened (PSC) beam with NSM reported by Obaydullah et al (2016) [94].

F. Combining Externally Bonded (CFRP) Sheets with Prestressed NSM Steel Strands

A hybrid strengthening methodology involves the application of externally bonded (CFRP) sheets in conjunction with prestressed NSM steel strands. This method takes advantage of both materials, where the (CFRP) sheets provide additional tensile capacity, and the prestressed steel strands improve stiffness and crack control. Obaydullah et al. (2021) [95] investigate a combined strengthening method aimed at improving the flexural performance of (PSC) beams using (CFRP) sheets and prestressed steel strands with varying prestress levels. The failure modes for the control beam and the beam enhanced by combining a 70% prestress force and (CFRP) Sheets are illustrated in figures 13-a and 15, respectively

Figure 15: Typical failure mode of strengthened (PSC) beam (NSM-S-70%F-Sh) tested by Obaydullah et al. (2021) [95].

Table 3: provides a comprehensive overview of experimental studies focused on the strengthening of restressed concrete beams through the application of different varieties of FRP.

No	**Author**	**PSC Beam Section**	**Concrete Strength (MPa)**	**Strengthening Type**	**Strengthening Schemes**	**Ultimate Load / Shear Capacity Increase (%)**	**Failure Modes**
1	Xuân Vinh et al. (2023) [76]	Rectangular	60	Flexural	EBR (CFRP) Sheets: Full-length (CFRP) sheets bonded to soffit	24	Flexural failure
2	Nguyen-Minh et al. (2018) [77]	Rectangular	47	Flexural	EBR (CFRP) + Anchors: Longitudinal (CFRP) with/without U-wrap spike anchors	37	(CFRP) debonding, anchor failure
3	Kang and Ary (2012) [78]	Rectangular	60	Shear	EBR (CFRP) Sheets: U-shaped (CFRP) strips with spacing	38	(CFRP) debonding, fracture

4	Yaqub et al. (2023) [79]	I-shaped	110	shear	EBR (CFRP) Sheets + Anchors: Longitudinal (CFRP) with epoxy blocks and mechanical anchors	40	(CFRP) rupture
5	Vijayan & Revathy (2016) [81]	Rectangular (Post-Tensioned)	42	Flexural	EBR GFRP Plates: UDC GFRP plates bonded at soffit	54.4	FRP debonding
6	Hurukadli et al. (2023) [82]	I-shaped	35	Flexural	EBR GFRP Sheets: GFRP in CSM, WR, and UDC forms	93.15	Flexural failure, no early FRP failure
7	Kuntal et al. (2020) [85]	Rectangular	60	shear	NSM (CFRP) Laminates: NSM grooves with epoxy, HSCG, and GP pastes	56.2	Pullout, debonding
8	Kuntal et al. (2017) [86]	Rectangular	60	shear	NSM (CFRP) Strips: 45° orientation in NSM configuration	54	Flexure-shear failure
					NSM (CFRP) Strips: 90° orientation in NSM configuration	50	Flexure-shear failure
9	Aram et al. (2008) [92]	Rectangular	48	Flexural	Prestressed (CFRP) Strips: EBR prestressed (CFRP) strips	17.5	(CFRP) delamination, concrete crushing
10	Obaydullah et al. (2021) [93]	Rectangular	50	Flexural	NSM Prestressed (CFRP) Bars: Bars prestressed and grouted in NSM grooves	47	(CFRP) rupture
11	Obaydullah et al. (2016) [94]	Rectangular	50	Flexural	NSM Prestressed Steel: Steel strands prestressed and embedded	40	Concrete crushing
12	Obaydullah et al. (2021) [95]	Rectangular	50	Flexural	Combined EBR + NSM: EBR (CFRP) sheets + NSM prestressed steel strands	70	(CFRP) rupture and concrete crushing

3. 4 Shape Memory Alloys (SMAs)

3. 4. 1 Overview:

Shape memory alloys (SMAs) possess significant potential in civil engineering [96, 97], yet it is still in the initial stages of exploration. Laboratory and field applications have successfully utilized iron-based shape memory alloy rods to enhance a strengthened concrete (RC) beam as well as a real bridge in the US [98]. Various forms of shape memory alloys (SMAs) such as nickel titanium (Ni-Ti), nickel titanium niobium (Ni-Ti-NB), copper aluminum manganese (Cu-Al-Mn), and iron-based SMAs have been studied for civil engineering applications [99]. In addition, (Fe-SMA) materials can be designed in multiple forms and dimensions, such as rods, bars, and strips. Prestress in the material is achieved by heating and cooling, eliminating friction-induced losses. (Fe-SMA)is an elastoplastic material lacking a yield platform, with mechanical characteristics varying due to elemental composition and processing technology. Its elastic modulus ranges from 125–200 GPa, ultimate strength from 676–1140 MPa, yield strength from 260–600 MPa, and ultimate strain can exceed 50%, indicating significant ductility and deformability [100].

3. 4. 2 Advantages, Challenges and Limitations:

These methods of strengthening offer a variety of benefits. They allow for quick application in situ without the necessity for extensive preparations and offer high strength. The latest innovations in alloy composition and manufacturing propose new applications, particularly for the repair of structures and new construction engineering (Zhao and Andrawes , 2020; Cladera et al., 2014), and both flexural and shear strengthening are efficiently achievable. Environmentally, the use of recyclable materials is essential [101]. Despite the promising advantages of Shape Memory Alloys (SMAs), several challenges and limitations prevent the extensive implementation of these methods, including high material cost, particularly for iron-based (Fe-SMA) and nickel-titanium (Ni-Ti) alloys. Furthermore, the complex activation process depends on specific heating or mechanical loading for effective shape recovery. Inadequate bonding performance may cause premature debonding and inefficiency in strengthening. Environmental factors, such as corrosion, particularly in Fe-SMA. Moreover, The absence of design guidelines and standardization [100].

3. 4. 3 General Behavior for flexural and shear strengthening, and failure modes in Recent studies:

The application of Shape Memory Alloys (SMAs) in civil engineering is gaining traction, particularly for their effectiveness in strengthening (PSC) beams. This process improves the flexural strength capacity and serviceability of the beams, thereby effectively addressing problems like excessive deflection and cracking. The study by Yaqub et al. (2024) [99] investigates the use of iron-based shape memory alloys (Fe-SMA) for effective shear strengthening of prestressed concrete beams. The first system involved externally applied as strengthening (EAR) and secured at the upper section utilizing chemical anchors. The second strategy utilized (Fe-SMA) rebars as near surface mounted (NSM) reinforcement within closed rectangular formations, the upper section of these rebars was welded, and set into a groove for secure embedding with the application of mortar, as summarized in Table 4.

Table 4: Summary of Shear Strengthening of (PSC) Beams utilizing (Fe-SMA)

No.	Author	Beam Type	Concrete Strength (MPa)	Strengthening Type	Strengthening Schemes	Ultimate Load / Shear Capacity Increase (%)	Failure Modes
1	Yaqub et al. (2024) [99]	I-Girder	100	Shear	(Fe-SMA) Externally Applied Reinforcement (EAR) using chemical anchors	40	Initial web shear crack formation progressing toward load and support; final failure through steep shear cracks between stirrups (except NSM system)
					Near Surface Mounted (NSM) (Fe-SMA) rebars with closed rectangular loops embedded in mortar	47	

The failure mechanisms with crack patterns under ultimate loads are illustrated in Figure 16. It is observed that shear cracks first appeared along the web and propagated toward the loading points and supports, ultimately forming steep shear cracks between stirrups, except for the NSM system.

a) control specimen (PSC) girder

b) Shear strengthening system with (Fe-SMA) strips

b) Shear strengthening system with (Fe-SMA) rebars

Figure 16: Typical crack pattern and ultimate failure mode of (PSC) beams tested by Yaqub et al. (2024) [99]

4 Comparative Results and Discussion

Various techniques in application and effectiveness have been developed to strengthen prestressed concrete beams, each offering unique benefits and limitations. Engineers and researchers can choose the most appropriate method based on comparisons of these techniques. These techniques aim to improve flexural and shear capacity, and ductility, and extend service life. Selecting a suitable strengthening method depends on multiple considerations, such as structural requirements, material compatibility, application ease, and cost. Table 5 is a comparative table illustrating various strengthening techniques, for prestressed concrete beams.

Table 5: Comparison of enhancing techniques for prestressed concrete beams

No.	Technique	Flexural Capacity Increase (%)	Shear Capacity Increase (%)	Stiffness Enhancement (%)	Ductility Effect	Typical Failure Mode	Installation Complexity	Durability	Relative Cost
1	Steel Plates Bonding	13–48	13–60	20–50	Moderate increase	Plate debonding, steel yielding	Low–Moderate	Moderate (corrosion risk)	Moderate
2	External Post-Tensioning								
2.1	External Post-Tensioning (Steel Tendons)	40–118.1	N/A	50–80	High	Anchorage failure, tendon rupture	High	Moderate	High
2.2	External Post-Tensioning (CFRP Tendons)	31–54	N/A	40–70	Moderate–High	Tendon rupture, anchorage failure	High	Excellent	Very High
3	FRP Systems (General)								
3.1	Externally Bonded (CFRP) Sheets & Laminates	24–40	10–38	15–40	Slight increase or brittle failure	Debonding, fiber rupture	Low	Excellent	Moderate
3.2	GFRP Laminates	54.4-93.2	10–56	10–35	Moderate	Fiber rupture, adhesion loss	Low	Good	Moderate
3.3	Near-Surface Mounted (NSM) (CFRP) Bars	40–75	Up to 56	30–55	Moderate–High	Concrete crushing, bar slippage	Moderate	Excellent	High
3.4	Prestressed CFRP (EB)	50–90	N/A	40–75	Moderate	FRP rupture,	High	Excellent	Very High

					(better service ability)	anchorage failure			
3.5	Prestressed NSM (CFRP) Laminates & Strips	Up to 47	N/A	50–80	High	Anchorage failure, concrete crushing	High	Excellent	Very High
3.6	Combining Externally Bonded (CFRP) Sheets with Prestressed NSM Steel Strands	Up to 40	N/A	50–90	High	Concrete crushing, steel slippage	Very High	High	Very High
4	Shape Memory Alloys (SMAs)	N/A	40–47	50–90	Very High (self-centering)	Concrete crushing, SMA slippage	Very High	Excellent	Very High

According to the data collected and reviewed in this research, presents results and assessments of strengthening techniques for prestressed concrete beams. The most commonly prestressed concrete beam geometries in this article include rectangular and I-shaped sections, represent the most widely used in bridges, and industrial structures. The cross-sectional shape directly affects flexural stiffness, shear resistance, and crack propagation patterns. Experimental data supports a systematic review of flexural performance, shear enhancement, stiffness improvement, failure behavior, and practical considerations among the different strengthening approaches.

1) **Flexural Performance**: Flexural strengthening methods, including externally bonded (CFRP), Near-Surface Mounted (NSM) reinforcements, and prestressed (CFRP) tendons, significantly enhance bending capacity and serviceability by enhancing load resistance and decreasing deflections. Prestressing methods such as external post-tensioning and prestressed FRP systems, achieve the highest flexural improvement (80–100%) by postponing tensile failure, while externally bonded steel plates, FRP (EB-FRP) sheets provide moderate increases (30–60%) often constrained by early debonding, whereas near-surface mounted (NSM) CFRP bars increase flexural capacity (40–75%) through superior bond and stress transfer in highly prestressed beams. Shape memory alloys (SMAs) demonstrate potential for improved ductility and self-centering, necessitating further examination.

2) **Shear Performance:** Enhancing shear capacity is essential to avoid brittle diagonal cracks at supports. shear strengthening techniques, like (CFRP) U-wraps, steel plates, and (Fe-SMA) stirrups in-fill concrete blocks, effectively reduce shear-related failures by increasing resistance to diagonal cracking and enhancing ductility. EB-FRP sheets and laminates typically offer modest shear improvements (10–25%) due to dependence on adhesive bonding, whereas NSM bars and prestressed systems perform better shear resistance (20–45%) due to improved anchorage and load distribution. Failure modes observed across studies indicate that EB-FRP typically experiences debonding, while NSM and prestressed systems fail through fiber rupture or tendon/anchorage failure.

3) **Stiffness and Serviceability:** Prestressed and hybrid techniques significantly enhance beam stiffness (ranging from 50-80%) similar to flexural gains, leading to reduced midspan deflections and enhancing serviceability. EB-FRP systems provide moderate stiffness improvements by (15 - 40%), which are often constrained by debonding and delayed cracking. NSM techniques offer superior performance compared to EB techniques due to better bond and a reduction in crack propagation.

4) **Failure Mechanisms:** The behavior of failure mode is significantly influenced by the type of strengthening techniques and material behavior. EB-FRP application tend to suffer early debonding due to stress

concentrations and limited bond capacity at the adhesive-concrete interface. Conversely, NSM systems enhance bond efficiency and stress distribution, often lead to concrete crushing or bar rupture. In most cases, shear failure occurs when flexural capacity increases without corresponding shear reinforcement, causing brittle behavior at support locations. As flexural failure offers enhanced ductility and safety, whereas shear and sudden debonding failures compromise structural integrity. It is important to develop a design that considers both flexural and shear performance.

5) **Practical Aspects:** Laboratory studies indicate the effectiveness of various strengthening methods; their practical application involves additional challenges. The process of installing steel plate is relatively simple, however, plates add considerable weight, may require the use of anchors, and require corrosion protection. The installation of EB-FRP technique on site is generally easily but prone to early debonding if not properly anchored, requires careful surface preparation and apply protective coatings for enhance durability. The application of NSM techniques offers better bond, long-term durability and higher strength, though groove cutting which can be difficult in established structures. Prestressed and hybrid systems (EB + NSM or SMA) results in high performing, they require complex installation, specific equipment, and accurate prestress application. Although SMAs offer self-centering capabilities, further study is needed. In addition, EB-FRP and GFRP are moderately priced, whereas prestressed systems, NSM methods, and SMA techniques incur higher costs due to due to materials and labor requirements.

5 Future Research Directions

The field concerning the enhancement of prestressed concrete beams has seen significant advancements, but there are still multiple fields that necessitate further study to enhance their durability, load-bearing capacity, resilience, and address existing challenges and unlock new possibilities. Based on the identified research gaps in the reviewed studies, several key areas for future research are recommended:

1) NSM-CFRP performance in high-prestress beams, NSM techniques offer superior bond and flexural performance, but there is limited data for beams with high prestress levels. While limited data exist for beams with their behavior in fully prestressed beams.

2) SMAs under Real Conditions, Shape memory alloys offer notable self-centering and ductility advantages, but their long-term behavior under real environmental conditions are largely untested. highlighting the necessity for full-scale field studies.

3) Hybrid and Emerging Techniques, combined EB + NSM and SMA-based systems offer potential for improved performance, but limited experimental data exist. Future studies should explore optimal configurations, scaling behavior, and durability. The development of hybrid systems and integrating smart materials such as SMAs can enhance structural adaptability.

4) Future investigations should focus on the development of advanced strengthening materials, such as high-performance fiber-reinforced polymers FRP, shape memory alloys (SMA), and nanocomposites. These advanced materials can enhance mechanical properties, bond behavior, and resistance to environmental deterioration. A vital area for future inquiry is the optimization of existing strengthening techniques to enhance their efficiency while minimizing costs and labor-intensive applications.

5) Research should also focus on refining bonding techniques, investigating new anchorage systems, and improving load transfer mechanisms to prevent premature debonding failures.

6) Future studies should emphasize the durability of systems under cyclic loading, harsh environmental conditions, and aging effects, which are often neglected in existing literature.

7) Sustainability is another significant research direction in strengthening methods. The development of eco-friendly and economical strengthening materials, such as recycled carbon fibers, and geopolymer composites, could reduce the environmental impact of retrofitting processes. Lastly, strengthening techniques must be tested under realistic loading and environmental conditions to validate their effectiveness for large-scale prestressed concrete bridge girders.

6 Conclusion

Strengthening prestressed concrete beams is essential for structural integrity and extending their service life due to factors like aging, fatigue, environmental degradation, and loading demands. Various strengthening techniques have been developed to mitigate the challenges of structural deterioration. Each technique has its unique advantages and limitations that require careful evaluation relevant to the structure's needs. This paper collects and examines extensive research derived from experiments on strengthening prestressed concrete beams through different methods. The review explains the impact of methodologies on the flexural and shear strength of prestressed concrete beams, emphasizing effectiveness, performance, advantages, as well as challenges and opportunities highlighted in prior studies. Additionally, the review elucidates failure mechanisms. The outcomes of the current study lead to the following conclusions:

1) In summary, the investigated strengthening methods significantly enhance the flexural and shear capacities of (PSC) beams. The application of steel plate bonding resulted in an improvement of flexural capacity by up to 70% and shear capacity by 34%. The external post-tensioning technique resulted in improvements of up to 97% in flexural strength and around 57% in shear strength, along with significant enhancements in crack control and deflection. Fiber-Reinforced Polymer (FRP) systems—such as (CFRP) and GFRP in various configurations (U-wrap, side-bonded, NSM), demonstrated significant improvements in flexural strength gains of 30–80% and shear capacity of 19–80%, alongside notable enhancing ductility and energy dissipation. Finally, the use of Shape Memory Alloys (SMAs), particularly (Fe-SMA) stirrups and NSM reinforcement, resulted in 40–47% enhancement in shear strength and improved crack angle and better serviceability.

2) Flexural strengthening methods, including externally bonded (CFRP), Near-Surface Mounted (NSM) reinforcements, and prestressed (CFRP) tendons, significantly enhance bending capacity and serviceability by enhancing load resistance and decreasing deflections.

3) Meanwhile, shear strengthening techniques, like (CFRP) U-wraps, steel plates, and (Fe-SMA) stirrups in-fill concrete blocks, effectively reduce shear-related failures by increasing resistance to diagonal cracking and enhancing ductility.

4) A comparative analysis of these techniques emphasizes the necessity for strategic selection based on specific structural demands, considering factors such as bonding efficiency, stress distribution, durability, and long-term performance.

5) Emerging technologies such as Shape Memory Alloys (Fe-SMA), offer promising alternatives by providing self-stressing capabilities and active prestressing effects.

6) Despite advancements, challenges like debonding failures, stress concentrations at anchorage zones, and cost-effectiveness remain critical issues.

7) While a various studies demonstrate significant enhancements in flexural and shear capacity. A large portion of the available studies use small specimen sizes and focus on short-term monotonic loading, neglecting fatigue, long-term performance, and environmental exposure. Furthermore, smaller-scale models may not accurately represent real structural behavior. These factors should be carefully considered when implementing the reported results in practice.

Future research should aim to optimize material properties, enhance bond performance, and integrate advanced analytical models for more efficient and sustainable strengthening strategies. The application of these innovations enables engineers can ensure the long-term resilience, safety, and durability of prestressed concrete structures within modern infrastructure.

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