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Testing methods and design specifications for FRP-prestressed concrete members: A review of current practices and case studies

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ABSTRACT

Fiber-reinforced polymers (FRP) have been developed as replacement materials for steel bars and tendons in concrete structural members for decades. These materials offer corrosion resistance, perfect durability, and high strength capacity, and therefore can be utilized as the main reinforcements to strengthen reinforced concrete (RC) members. Recently, several studies have focused on investigating the properties of pre-stressed FRP and steel-reinforced concrete structural members. Considering the rapid growth of the use of FRP in the construction industry and the development of various types of tendons, it is necessary to have a comprehensive review article that systematically addresses this development. This review focuses on the engineering properties and durability performance of concrete structures prestressed with FRP. It also discusses the regular FRP composite materials, their features, properties, and applications. Despite some disadvantages and negative effects of utilizing FRP tendons as effective alternatives for steel tendons, such as additional cost, lack of composite materials, and complicated production process, there are still advantages and benefits of utilizing FRP tendons in the construction industry.

1. Introduction

Many modifications have been made to improve the weaknesses of Reinforced Concrete (RC), especially in terms of degradation, corrosion, and spalling. To eliminate these weaknesses, various types of materials, such as Fiber Reinforced Polymer (FRP) composites, have been utilized as a replacement for steel bars, tendons, and reinforcements in the production of RC [1]. In addition, Prestressed Concrete (PSC) has been developed to reduce the dimensions of concrete members and further increase tensile strength [2]. Tendons are special components added to RC to achieve higher tensile strength. There are different types of tendons, the most important of which are FRP and steel tendons. FRP tendons are composed of different materials, such as carbon, basalt, aramid, and glass. These materials are respectively called CFRP, BFRP, AFRP, and GFRP. [3–7].

Due to the development of PRC in the construction industry, many studies have been conducted to evaluate the influence of utilizing various types of tendons on the engineering performance and durability properties of PRC. Since the early 1990s, several researchers have begun studying the properties of different types of tendons and their effects on concrete. [8–11]. Studies, at first, focused on the steel tendons [12,13]. As the use of polymer fibers expanded in construction projects, the number of studies focusing on

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FRP tendons increased. [14–21]. Based on the previous studies, beams [3,22–25], columns [7,14,26–28], bridges [12,29–31], slabs [23,32–34], and nuclear containment [35–39] were the most common structural members were reinforced with various types of tendons. There have been few studies about the use of tendons in other structural members, such as walls [40], towers [41], tunnels [42], and frames [43]. Since the steel tendons were more available, common, and cheaper than FRP tendons, most of the previous research on different structure members was conducted on RC prestressed with steel tendons [44,45]. In contrast, studies on FRP tendons have mainly focused on the properties and performance of tendons in beams and girders [46,47].

A study was conducted by Mertol et al. [48] to compare the durability behavior of PRC using CFRP and steel tendons. The results showed that the concrete girders prestressed with steel tendons did not withstand environmental conditions for 12 months. In contrast, the prestressed concrete girders with CFRP bars endured more than 18 months of intense environmental conditions, demonstrating the extraordinary durability of CFRP in marine environments. In another study, Wang et al. [49] found that strand corrosion reduces the cable's section area, degrades the bond performance, and deteriorates the material characteristics. The degradation of the bond would result in the slipping of the corroded cables from the surrounding concrete, causing incompatible strain and reducing the flexural capacity of concrete members. Wang et al. [50] conducted a study to evaluate the effects of elevated temperatures on the tensile strength of CFRP and GFRP bars and compared the results with conventional steel reinforcement bars. The results showed that temperatures around 250°C and 325°C were critical for the tensile strength of CFRP and GFRP reinforcing bars, respectively. Additionally, Wang et al. [51]. analyzed the change in the tensile performance of hybrid FRP and BFRP tendons in an extreme environment. The authors reported that concrete members prestressed by BFRP tendons had outstanding durability in terms of salt corrosion and that the reduction in the pace of their tensile performance was nonlinearly related to the prestressing ratio. The results of this study indicated that hybridization can reduce the degradation pace of BFRP and CFRP tendons without prestressing.

By considering the rapid growth of PRC use in the construction industry and the development of various types of tendons, it is necessary to have a comprehensive review article that systematically addresses this development. Therefore, this study focuses on the properties of various types of tendons and provides a comprehensive discussion of their effect on the properties of RC. In the second section, the paper explains the history of the PRC with various types of tendons. Section three discusses the engineering performance of RC prestressed tendons in terms of flexural and tensile strength, creep and shrinkage behavior, failure mechanism and fatigue life, shear resistance, crack development, and physical performance, including transfer length and load transfer, and effect of FRP tendons on the anchorage system of PSC. In section four, the durability performance of prestressed RC against harsh conditions, including sulfate and acid attack, deterioration, and corrosion, is elucidated. Section five describes the heat resistance performance of PSC prestressed with FRP tendons. Finally, section six describes the existing challenges and future research on FRP tendons.

2. Categories of PSC

Prestressed concrete is typically produced in one of two ways: 1) pre-tensioning and 2) post-tensioning. Initially, PSC was produced through the pre-tensioning process, which occurred before the concrete was cast. Later, the post-tensioning process was developed, which takes place after the concrete is cast [2]. Two common tensioning processes are mono-strand tensioning and multi-strand tensioning. In mono-strand tensioning, each tendon is stressed separately whereas in multi-strand tensioning all strands in a tendon are stressed simultaneously [5]. In addition, two types of tendons can be distinguished based on their location within the concrete: internal and external prestressing. Internal tendons are completely located within the concrete volume, while external tendons are located wholly outside of it. The main difference between pre-tensioning and post-tensioning processes can be summarized as follows:

i. The pre-tensioning process is applicable in the factories and is not possible to be done on the site, on the other hand, post-tensioning can be done in both sites and factories. Therefore, pre-tensioning is suitable for precast construction works.
ii. Strands are tensioned and placed in their location before the casting of the concrete in the pre-tensioning process, yet in the post-tensioning process, the strands were enclosed in the concrete, and after the concrete attains its sufficient strength, the strands are tensioned.
iii. Usually, in the pre-tensioning process, the size of the structure is limited but there is no limitation on the size of structural members in the post-tensioning process.
iv. The loss of prestressing in pre-tensioned concrete is up to 18% (elastic deformation 3%, relaxation of steel 2%, creep of concrete 6%, and shrinkage of concrete 7%) while it is not higher than 15% (elastic deformation 1%, relaxation of steel 3%, creep of concrete 5%, and shrinkage of concrete 6%) in post-tensioned concrete.
v. Similar prestressed members can be produced in the pre-tensioning process, whereas in post-tensioned concrete members can change according to a structure.
vi. Pre-tensioned concrete is because of the bonding among the steel tendons and concrete is developed while post-tensioned concrete is developed due to bearing capacity.
vii. When the structure members are small, the pre-tensioning process is preferred whereas the post-tensioning process is preferred when the structure members are heavy.
viii. Pre-tensioned concrete is cheaper than post-tensioned concrete due to not involving the cost of sheathing.
ix. The pre-tensioning process is more durable and reliable than the post-tensioning process since the durability of post-tensioned concrete depends on the mechanism of two anchorages.

2.1. Typs of FRP tendons

One of the best alternatives for steel reinforcement in structural members is FRP composites, which are widely used in the construction industry. Using FRP composites as an alternative to steel bars offers many advantages. For example, FRP composites are non-corrosive, have a promising strength-to-weight ratio, exhibit excellent chemical resistance behavior, and are easy and fast to install. Additionally, they do not possess magnetic properties, and their use can help to reduce long-term maintenance costs [52–55]. FRP composites can typically be categorized based on the different elements used to create the reinforcement, such as CFRP, GFRP, AFRP, and BFRP [56].

Due to creep under sustained loads and weak resistance to the alkaline environment, GFRP materials are not recommended for bonded tendons [57]. CFRP and AFRP reinforcement are appropriate for prestressed tendons and have been extensively utilized for prestressing applications [58]. BFRP tendons have a high performance-to-cost ratio and noticeable advantages in engineering and chemical properties, resulting in the development and increasing use of BFRP tendons [51]. This section provides a discussion on the characteristics, applications, advantages, and disadvantages of all types of FRP tendons.

2.1.1. CFRP

Carbon fiber (CF) and polymer are the primary materials used in the production of CFRP composites. The polymer serves as a cohesive matrix that holds and protects the fibers together, while the CF provides the stiffness and strength of the CFRP tendon [59]. Various manufacturing techniques, such as hand lay-up, pultrusion, and filament winding are utilized to produce CFRP in different shapes like sheets, bars, tendons, and strips as presented in Fig. 1. Using CFRP materials can lead to many benefits, including high-strength, corrosion resistance, low density, and high fatigue resistance [60].

The main properties of CFRP composites are listed below:

i. CFRP composites have excellent resistance to alkali environments.
ii. Because of their corrosion resistance characteristic, they are utilized for the rehabilitation of existing RC structures.
iii. They have low thermal conductivity.
iv. Since CFRP composites have a high strength-to-weight ratio, requirements for heavy supporting structures and construction equipment can be eliminated.
v. Due to the short curing period of the CFRP composites, their applications take a lower time and resulted in a reduction in the project duration.
vi. The requirement for frequent maintenance is reduced because of the high fatigue resistance of the CFRP composites.
vii. Their electrical conductivity is very low, and they don't have magnetic properties.
viii. CFRP composites are lighter than steel materials, but they are more expensive than steel tendons.

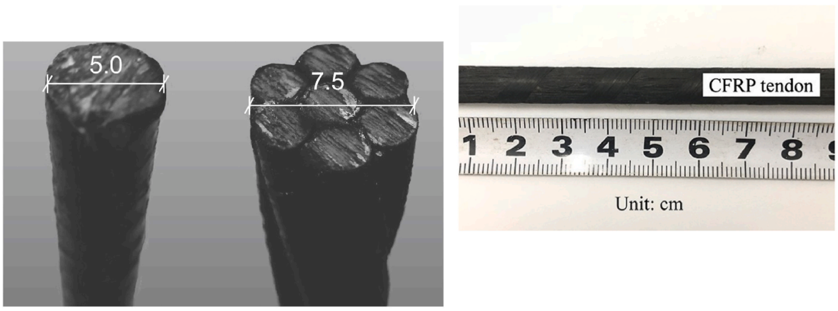
2.1.2. GFRP

GFRP also known as GFR plastic, is another type of FRP composite produced by combining polyester and E-glass materials. The compressive and tensile strength of GFRP composites ranges from 140 to 350 MPa and from 44 to 3040 MPa, respectively [7]. Additionally, GFRP tendons weigh a quarter of steel tendons of the same size. Thermosetting polymers such as thermoplastics, epoxy, or resin can be used to harden woven materials [62]. When using GFRP composites across large areas, a supportive structure such as a wire frame or concrete is required. Fig. 2 presents the GFRP tendons.

There are several advantages to using GFRP rebars in construction projects. For instance, they are resistant to corrosion and do not contain any metal, so they are not magnetic and do not rust. Additionally, GFRP rebars are lighter than steel rebars, and using them can result in a longer lifespan for buildings, particularly in areas where water resistance is critical [55]. Due to their non-corrosive properties, GFRP composites have been used for boat building for many years. Recently, some architectural projects have started to use GFRP as a construction material. Moreover, GFRP can be used as a cladding material and bent into wireframe structures [64].

2.1.3. AFRP

Aramid fiber-reinforced polymer (AFRP) is a group of synthetic fibers with exceptional characteristics that make them highly useful in a variety of applications, such as clothing, armor, and construction. AFRP has evolved from research on polyester and nylon fibers. Nomex, one of the earliest aramid polymers, was developed in the early 1960s and is known for its notable properties, such as insulation, being a replacement for asbestos, and its use in protective clothing [3]. After that, research showed that due to aramid's high tensile strength, it can be considered an alternative for steel rebars in the construction industry. According to the statistics, more



(a) (b)

Fig. 1. (a) CFRP strand (*cm*) [60], (b) CFRP tendons with a spiral-wrapped surface state [61].

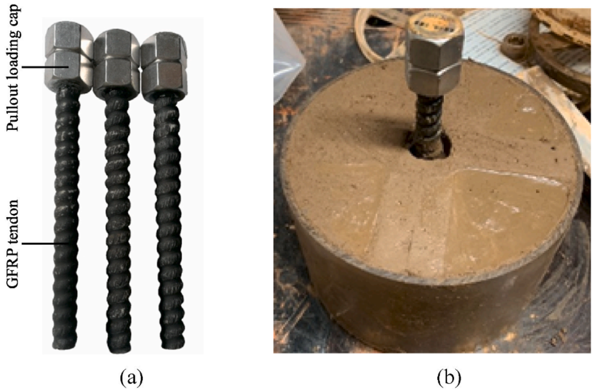


Fig. 2. (a) GFRP tendon and (b) located in the sample [63].

than 60 million kg of AFRP is produced annually, and considering the production growth, its demand is increasing and its cost is reducing [65]. The appearance of AFRP laminate is presented in Fig. 3.

The chemical composition of the chain molecules of AFRP materials, mostly are aligned along the fiber axis, giving them remarkable spectacular strength, abrasion tolerance, and flexibility [67]. AFRP materials are also characterized by low flammability and excellent heat resistance, as they start to degrade instead of melting at around 500°C. Additionally, their low electrical conductivity characteristic, makes them ideal for use as electrical insulators [14]. AFRP composites also have high resistance to organic solvents, making them suitable for a wide range of applications [9]. However, they do have some disadvantages, such as being sensitive to salts, acids, and UV, and producing static electricity without pre-treatment.

2.1.4. BFRP

BFRP composites are produced by combining polymer resins such as isophthalic polyester and vinyl ester with basalt fibers (BF) that are unidirectionally bound. The volcanic basalt rocks are crushed and melted at a temperature of above 1400°C to create continuous and unbroken BF filaments that have diameters ranging from 13 to 20 μm [68]. BFRP rebars are typically produced in two different methods: the pultrusion process and the automated wet-layup process. Both methods provide BFRP composites with the same degree of variation in mechanical properties [69]. As the strength of the resin is much smaller than the fibers' strength, the stiffness and tensile strength of BFRP bars vary depending on the overall volume of fibers to the volume of resin [70].

BFRP is a sustainable, non-corrosive, and rust-proof alternative to steel rebars, tendons, and reinforcements. BFRP tendons have a tensile strength that is 2.5 times greater than steel tendons and are 4 times lighter than steel tendons. These excellent properties make BFRP composites an ideal alternative material for concrete production and construction industry [71]. The durability performance of the BFRP (more than 100 years) is another advantage of using them in construction projects. Additionally, BFRP composites have excellent resistance to corrosive elements, chemicals, and UV [72]. The utilization of BFRP in projects reduces the total amount of waste and lowers the cost of handling, transportation, and installation significantly. Furthermore, the use of BFRP bars reduces maintenance and repair costs. Fig. 4 presents the BFRP tendon after anchoring and bar [73].

2.2. Summary and conclusion

The mechanical properties of tendons are crucial in determining their applications, and it is essential to consider the advantages and disadvantages of different types of tendons. Table 1 shows a comparison of the engineering properties of various types of FRP ten-

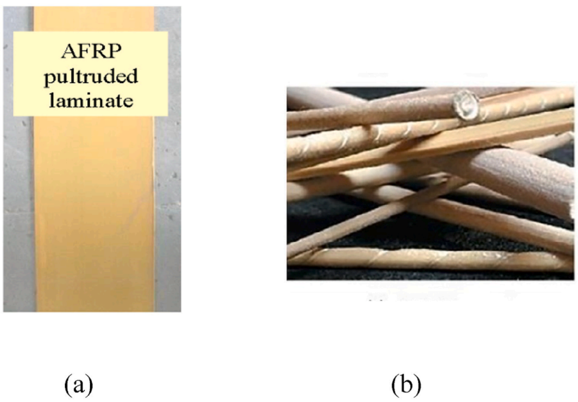


Fig. 3. (a) AFRP laminate [26] and (b) AFRP bars [66].

(a) (b)

Fig. 4. BFRP composites (a) BFRP tendon specimen after anchoring [68] and (b) BFRP bars [73].

Table 1
FRP and steel tendons properties.

Characteristics	CFRP [60,61,74–101]	GFRP [6,33,102–110]	AFRP [8,9,14,15,27,52,67,111]	BFRP [4,68–72,112–116]	Steel Tendons [117–167]
Diameter (*mm*)	4–32	5–20	4–20	4–20	5–40
Density (kg/m^3)	1500 – 1810	1700 – 2100	1200 – 1400	2000 – 2600	6020 – 7850
Yield Strength (Steel)/Tensile Strength (FRP) (MPa)	1336 – 4920	459 – 1770	1200 – 2324	920 – 1738	580 – 1920
Elastic Modulus (GPa)	80–509	30–70	50–121	38–70	180–210
Poisson's Ratio	0.22–0.38	0.22	0.38	0.2	0.2–0.3

dons with conventional steel tendons. While FRP tendons are much lighter than steel tendons due to their lower density, there are still some concerns related to their characteristics. These concerns include their susceptibility to UV radiation and elevated temperature, lack of yielding, and brittle failure, which limit their usage as an alternative to steel tendons.

This section summarized the history of FRP composite materials and their advantages and disadvantages in the construction industry. Considering the availability of the FRP composites, the amount of research conducted, production cost, manufacturing process, and the mechanical, chemical, and physical characteristics of all types of FRP composite, CFRP, GFRP, AFRP, and BFRP composites have been selected for further investigation. In the next three sections, the effects of all types of FRP tendons on the engineering properties and durability behavior of the PRC structures are discussed.

3. Engineering performance of prestressing tendons for PRC

Nowadays, traditional steel cables are extensively used in constructing infrastructures and buildings. Conventional steel tendons are made up of high-strength steel wire strands that are arranged based on a specific shape, offering benefits such as acceptable anchorage, notable tensile strength, and high elastic modulus. Despite these advantages, some disadvantages have emerged for traditional steel tendons, including serious corrosion damage, sag effect, poor fatigue performance, low carrying efficiency, and self-weight [168]. On the other hand, FRP tendons have high fatigue resistance, anti-corrosion, and high strength-to-weight ratio properties, hence, making them suitable not only for reinforcing new structures but also for strengthening and retrofitting existing structures.

Thus far, although the application of steel and FRP cables in building constructions has been extensively investigated, a significant gap still exists between the available research findings and the actual practical use of prestressed FRP tendons in infrastructures and structures. This gap can be attributed to the mechanical specificity of FRP tendons, limitations in research applications, and the structural complexity of FRP tendons. Therefore, it is essential to provide a comprehensive summary of the research status and achievements of FRP tendons for structures and infrastructure to improve both theoretical and methodological studies of FRP tendons [168]. Consequently, the following section discusses the fundamental mechanical characteristics of PSC prestressed with FRP tendons.

3.1. Mechanical performance

The flexural and tensile properties of FRP cables vary significantly depending on the number of tendons, anchorage methods, and material types. Wang et al. [169] found that the ultimate strain of BF/CFRP increased with the hybridization process in proportion to the amount of basalt fiber, which improved the development of the material compared to CFRP. Other researchers have also investigated this topic. For instance, Han et al. [87] reported that the tensile strength and flexural strength of CFRP tendons were 2161 MPa and 1206 MPa, respectively. They noted that after the flexural test, some parts of the tendon consisting of fibers and resin were not fractured, and the damaged tendon still had some tensile strength, which accounted for the higher tensile strength than flexural strength. Yuan et al. [151] found that the tendons attained their yield strength before the concrete achieved its maximum capability. Xu et al. [96] conducted research on the damage development investigation and damage pattern detection of unidirectional CFRP cables under tensile forces. They found that using acoustic emission technology, the median tensile strength of the evolution of unidirectional CFRP cables was 2697.74 MPa, as shown in Fig. 5. The authors suggested that their results could be used to guide the creation of a health monitoring procedure for prestressed CFRP members based on acoustic emission technology.

Ngo et al. [43] proposed a new ductile and dry exterior joint type of moment resistance frame using carbon CFRP bolts and plates. The results showed that these new dry joints can be reasonably utilized for preconstructed structures in non-seismic and earthquake-prone areas, and the CFRP bolts had a tensile strength of 850 MPa or more. Cai et al. [76] conducted analytical and experimental research on the stress behavior of composite anchors on CFRP tensile force. They found that the tensile stress of the steel pipe surface and its change reflected the internal stress distribution of the composite anchor. The authors believed that the radial clamping of wedges can successfully improve the anchoring influence. Mei et al. [99] researched the mechanical performance of bond-type anchors for CFRP tendons. The experiment outcomes showed that the composite anchor represents the most reliable force transfer type, and the notch influence generated from the internal cone anchor can be eliminated. The tensile strength of the CFRP tendon was 2250 MPa, and the end of a scattered tendon is presented in Fig. 6.

Han et al. [87] conducted a study on the mechanical characteristics of prestressed structural lateral reinforcement and high-temperature CFRP tendons. The authors analyzed the lateral and longitudinal engineering performance of a CFRP tendon with three different diameters and reported that the median tensile strength of the CFRP tendon was 2161 MPa. The outcomes revealed that the new CFRP tendon has superior lateral engineering behavior than the conventional CFRP tendon and provides excellent longitudinal engineering behavior. Fracture mode and failure analysis of damaged CFRP tendons were investigated by Han et al. [98]. They found that when the tensile force reaches nearly 47.2 kN, the CFRP cables suffer splitting failure as presented in Fig. 7. Based on the outcomes of this paper, longitudinal cracking might happen in the damaged CFRP cables below the longitudinal tension, ultimately resulting in the splitting failure.

Lou et al. [170] conducted a study to investigate the influence of the utilizing of unbound CFRP and AFRP composite tendons on the short-term performance of FRP PRC girders. This paper analyzed the coupling state of the composite tendons (CFRP and AFRP) and reported that CFRP tendons had a significant effect on the bending reaction of the FRP PRC beam, including crack pattern, failure mode, deformation, tendon stress growth, and neutral axis movement. According to the result of this study, the tensile strength of the unbonded CFRP was between 1750 and 1880 MPa and the modulus of elasticity was between 135 and 144 GPa, which is comparable to the steel tendons. Fig. 8 (a) and (b) illustrate the longitudinal compressive and tensile stress-strain curves, where the red dotted line is an artificial polishing line [87]. From these figures, the authors found that the proposed CFRP tendon had superior lateral engineering performance due to better transverse engineering properties in actual applications of large wedge mechanical fixtures.

Wang et al. [51] evaluated the performance of prestressed BFRP and CFRP tendons in the marine environment. The results showed that the modulus of elasticity of both types of tendons remains constant regardless of the prestressing ratio and aging period. Moreover, both tendons demonstrated excellent resistance to salt corrosion, and the reduction rate of their tensile strength was non-linearly proportional to the prestressing ratios. Au et al. [171] conducted a comparative study of five deformability indices for un-

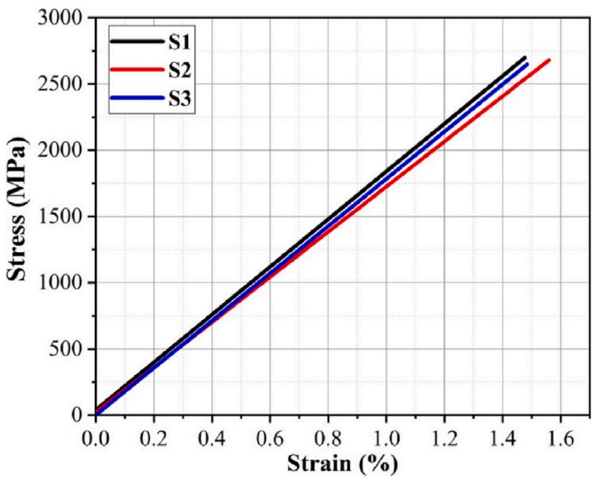


Fig. 5. Stress vs strain curve of CFRP cables [96].

Fig. 6. The scattered end of the CFRP cable [99].

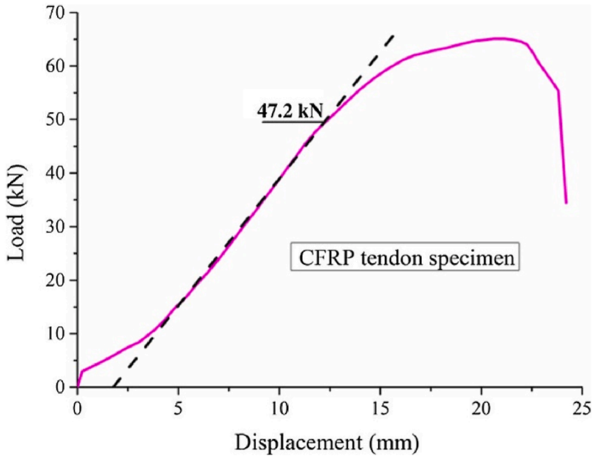


Fig. 7. Normal load-displacement curve for CFRP cable samples [98].

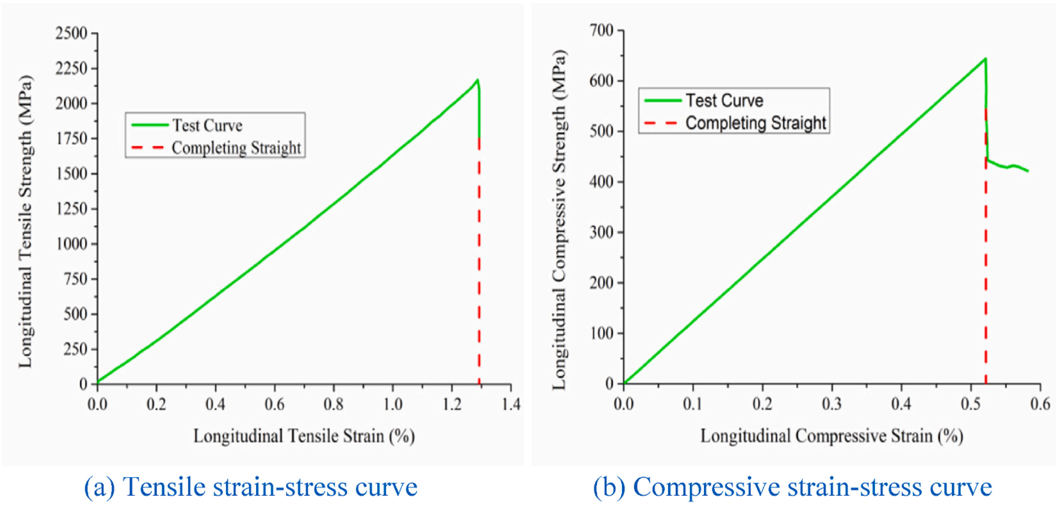


Fig. 8. The results of longitudinal tests [87].

bonded partially PC girders with FRP cables. The authors developed numerical methods to calculate the full range reaction of PC girders with coupled unbound FRP cables under load and reported that their findings were consistent with the test outcomes reported in the technical literature. The strain index, defined as the ratio of the extreme value to the product of the moment at the crack, continuously decreased as the composite reinforcement ratio increased. The ultimate tensile strength of the 7-wire strands of Grade 270 used in this study was 1863 MPa. In the research developed by Le et al. [83], the stress of CFRP tendons at the final force was 1748 MPa, equivalent to 93.9% of the supposed prestressing steel cables' tensile strength (1860 MPa). Lou et al. [58] presented a numerical analysis of the behavior of continuous PC girders with bonded FRP and steel tendons. They developed a Finite Element Method (FEM) and verified the available experimental data. The tensile strength values of CFRP, AFRP, and steel tendons used in the test were 1840 MPa, 1500 MPa, and 1860 MPa, respectively. In addition, the elastic modulus of AFRP and CFRP were 35% and 75% of the steel tendon's elastic modulus.

YouaKim et al. [20] presented a method for evaluating the long-term performance of concrete elements prestressed with different FRP tendons. They introduced a simple method for calculating the long-term prestressed loss of continuous PC members and the long-term changes in concrete stress using CFRP tendons. The CFRP, AFRP, and steel tendons' tensile strengths were 2000 MPa, 1200 MPa, and 1860 MPa, respectively. The results of this study revealed that the long-term variation in concrete deflection and stresses might be either greater or smaller than those when compared to the steel tendons prestressed girders, depending on the type of FRP tendons and the initial stress profile of the cross-section under consideration. Wu et al. [2] conducted a comparative study on the flexural behavior of RC girders with lightweight aggregate prestressed with CFRP tendons. They developed a geometric-based approach to analyze tendon stress growth in terms of deflection. Additionally, the authors created an algorithm for evaluating the deflection of prestressed girders with unbound CFRP tendons by decomposing the analysis procedure into unbounded girder analysis and unbounded member analysis. In this study, a CFRP bar with a helical groove with a diameter of 8.65 mm was used as a non-adhesive prestress and auxiliary junction reinforcement. The authors reported that the addition of steel fibers and the application of prestressing force reduced the crack width and deflection of the beams. Furthermore, the proposed algorithm in this study yielded acceptable deflection predictions and stress raises at the service load level.

Zhang et al. [172] developed a new type of prefabricated beam (Fig. 9) called a hybrid beam (HB), which combines FRP composites and concrete. The goal of this innovation was to lower initial material costs and expedite the construction process. The suggested HB in this study included a precast concrete slab and in-situ cast ultra-high performance concrete (UHPC) pockets around bolted connections. To compare the effectiveness of this new design, one FRP-concrete HB with a regular concrete slab was tested alongside four FRP-concrete HBs with UHPC pockets through flexural testing. The results indicated that the suggested bolted shear connection in UHPC pockets considerably decreased interfacial slip and raised the flexural rigidity of the HBs when compared to the normal FRP-concrete HB.

Another study [174] aimed to evaluate the flexural performance of beams made of BFRP PSC with varying levels of reinforcement, as well as non-prestressed concrete beams, through both experimental and analytical methods. The outcomes of this study indicated that while the non-prestressed beams had good deformability and flexural strength, they did not meet the requirements of serviceability such as crack width and deflection. Considerably under-reinforced PSC beams met both strength requirements and serviceability but had decreased cracking and poor deformability. Over and under-reinforced PSC beams worked well in terms of serviceability and strength. Partial prestressing with multiple layers of tendons improved ductility and reduced the risk of sudden or catastrophic failure compared to single-layered fully prestressed concrete beams. Therefore, the under-reinforced design proposed in this study has the potential to be used alongside the over-reinforced design suggested in international codes/standards to improve the safety and durability of PSC beams.

3.2. Creep and shrinkage behavior

This subsection presents a brief exposition of the creep and shrinkage of concrete prestressed with various types of tendons. The creep effects are particularly important for PSC structures due to their high flexibility. Although the theory of creep and shrinkage of concrete has not been considered as a constituting part of damage mechanics, remarkable damage to structures is caused by such inelastic phenomena. These damages consist of excessive deflection that results in out-of-service structures and distributed cracking as classical damage [175]. Therefore, a lot of research has been conducted on the effect of creep and shrinkage in PC structures. Yuen et al. [165] reported that unaccounted prestress variations would increase with other long-term losses because steel relaxation, concrete shrinkage, and creep can change the predicted structural performance. Another study has shown that as the loading time increased, the viscoelasticity of the FRP tendons more clearly resulted in creep and stress relaxation [168]. In addition, for BFRP tendons, it can be said that, according to the reliability-based assessment, the creep rupture stress constraint can be adopted for up to 52% of its tensile strength [176]. The authors believed that the creep strain-to-time relationship of BFRP tendons depends greatly on the applied stress level. The relationship between creep rate and stress level of BFRP tendons is presented in Fig. 10.

When it comes to the resistance to creep and tensile strength of FRP tendons in concrete members, most studies and research have chosen AFRP or CFRP, rather than GFRP, due to the latter's poor resistance to creep and lower tensile strength. Both AFRP and CFRP tendons have negligible creep, which can be disregarded for most practical purposes [20]. Moreover, both AFRP and CFRP tendons have significant tensile strength comparable to that of prestressing steel tendons. The modulus of elasticity of AFRP tendons is much lower than that of steel tendons, while the CFRP tendons have a comparable elastic modulus ranging from 0.4 to 2.5 times that of steel [177]. However, due to the high elastic modulus of CFRP tendons, they experience a considerable long-term prestress loss caused by the shrinkage and creep of concrete. In contrast, AFRP tendons experience considerably greater prestress loss due to tendon relaxation. But, owing to their lower modulus of elasticity, AFRP tendons have lower prestress loss associated with concrete shrinkage and creep when compared to CFRP and prestressed steel tendons.

3.3. Failure mechanism & fatigue life

The failure mechanism of prestressed concrete depends on several factors, including the type and severity of the loading, the age and quality of PSC, the type and properties of tendons, and the environmental conditions. The failure mechanism of PSC can be divided into compressive failure, tensile failure, shear failure, flexural failure, fatigue failure, and environmental degradation. PSC can experience fatigue failure over time due to repeated loading and unloading. The fatigue life of PSC structures can be estimated using

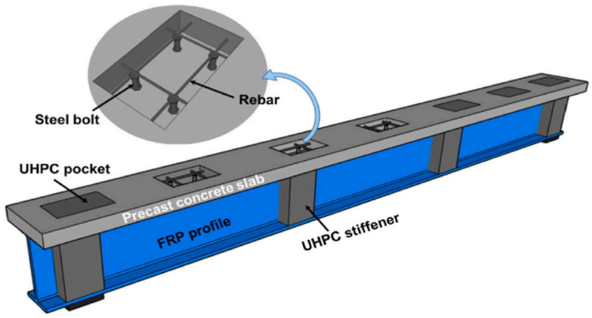


Fig. 9. FRP-precast concrete HB with UHPC pockets [173].

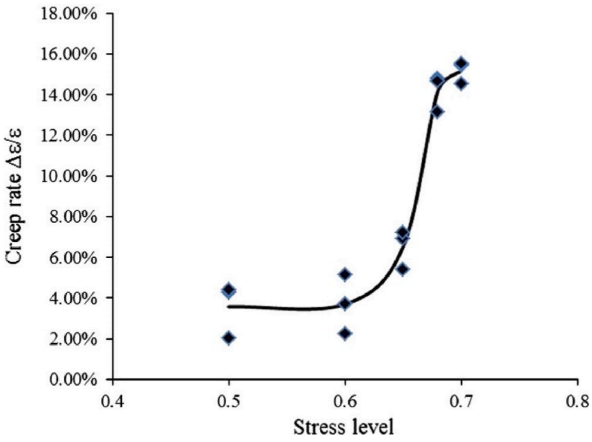


Fig. 10. Relationship between the stress level and creep rate [176].

fatigue analysis techniques, which consider the stress range, stress amplitude, and number of load cycles. The fatigue life of PSC members can be extended by using high-quality materials, proper design and construction techniques, and regular maintenance and inspection. In addition, the use of post-tensioning systems and other techniques can help redistribute the stresses in the structure, reducing the risk of fatigue failure.

In their study, Han et al. [100] analyzed the influence of chamfering the tendon clamp plate utilized in the linked joint among struts and prestressed tendons for girder string members on the shear behavior of CFRP cables. They investigated the shear fracture mechanism and fatigue life of CFRP cables based on the results of the flat double shear test (FDST). Fig. 11(a) shows that in the initial shear region, the shaded part represents the high-stress area, while the empty part represents the low-stress area. Fig. 11(b) demonstrates that as the diameter increases, the primary shear section for the cross-sectional area decreases. This is why the shear strength decreases as the diameter of the CFRP tendon increases. Fig. 11(c) shows that the cross-section is divided into various successive shear regions, and the load-displacement curve experiences a distinct period of variation. In conclusion, as the diameter of the CFRP tendon

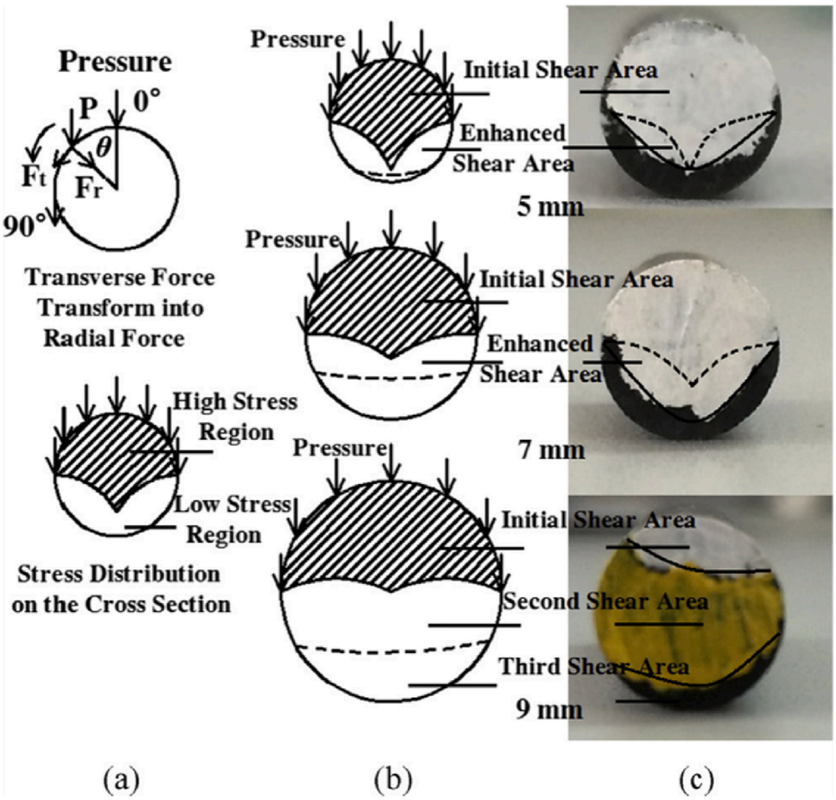


Fig. 11. Failure procedure of shear forces, (a) crosswise bearing properties, (b) stress spreading for various sizes of CFRP cables, and (c) actual failure image [100].

increases, the ratio of the primary shear section to the cross-sectional area decreases, resulting in a decrease in the shear strength of the tendon. In addition, chamfering has a greater impact on the failure mode of CFRP tendons than FDST. The chamfered double shear test did not completely sever all of the specimens, which allowed some transverse bearing capacity to remain even after failure. This change in shear failure mode is advantageous for CFRP tendons with brittle failure characteristics and poor transverse performance. It can enhance the safety and dependability of CFRP tendons in structure systems, and encourage their broad use in practical engineering applications.

In the study conducted by Wu et al.'s study [164], the capability of PSC beams to endure numerous impacts was investigated. The findings of the study showed that if the tendon remains elastic, the PSC beam exhibited significant residual load capacity after four repeated impacts. However, if the tendon yields, irreversible deformation induces complete prestress losses. This leads to the progressive expansion of concrete cracks and initiates failure behavior in the target structure. Hung et al. [120] investigated the ductility behavior of concrete columns under cyclic loading. All seven specimens exhibited stable ductility behavior at a drift of up to 6%. Flexural failure was observed as the failure mode for all specimens, and the fracturing of the vertical reinforcing bars resulted in strength degradation. In the case of the conventional cast-in-place monolithic column sample, strength loss occurred instantly following the fracture of two vertical reinforcing bars over the second cycle at a drift of 6%. Notably, the maximum fracture in the vertical reinforcing bars occurred during the first cycle at a drift of 7%.

A test was carried out by Larson et al. [178] on five pre-tensioned, prestressed concrete T beams that were designed to withstand specific levels of stress from prestressing strands when under live loads. The experiment involved creating pre-existing cracks in the beams, reinforcing them using CFRP, and then applying mechanical loads to investigate how the increasing live load affects the fatigue of the strands. In all cases where the beams were reinforced, the mode of failure observed was the rupture of the FRP. The outcome of this study showed that strengthening with FRP can be effectively utilized to increase the live load of concrete beams that are prestressed with straight strands. Another study [179] investigated the low cycle fatigue behavior of GFRP PSC beams by using analytical and experimental methods. Based on the results of this study, a trend of three stages (unstable crack propagation, stable crack propagation, and crack initiation) was identified through the fatigue crack analysis. Once the crack had grown through the entire section, it caused damage to the beam. In addition, the experimental data were used to fit the fatigue crack propagation model. This helped to determine the damage evolution patterns, dynamic stiffness, and deflection of GFRP PSC beams. Based on the crack propagation and damage evolution found in this work, models were developed to predict the fatigue life.

In order to assess how much relaxation occurs in large-diameter CFRP tendons, a model test was carried out by Ref. [180] to study the variation in relaxation of CFTP tendons over time under different initial prestress levels. The results indicated that the relaxation loss rate of CFRP tendons increased as the initial prestress level increased. Furthermore, most of the relaxation loss occurred within the first 100 h after the prestress was applied, with values typically ranging between 1% and 4%. When concrete members were reinforced with FRP tendons, they tend to have higher deflections than those reinforced with steel tendons due to the lower modulus of elasticity of the FRP reinforcement. According to Hiesch et al. [181], one solution to counteract this issue was to prestress the FRP reinforcement, which can considerably decrease deflections. However, over time, the prestress may be lost due to concrete shrinkage and creep as well as the relaxation of the prestressing tendons. To address this, relaxation rates for the specimens were derived based on test data and a mathematical method. Additionally, using a logarithmic extrapolation approach, the relaxation rates at 1 million hours (end of service life) were calculated, and the residual tensile properties determined from the experiment were evaluated.

3.4. Shear resistance

FRP tendons can be considered anisotropic materials, with their transverse shear performance significantly lower than their longitudinal tensile strength. BFRP and CFRP cables exhibit transverse shear strength of approximately 15% and 10%, respectively, compared to their longitudinal tensile strengths. Hybrid CFRP tendons have a shear strength of around 16% of their tensile strength [91]. Based on the available evidence presented in the literature, deboning failures in FRP bolts between resin matrix and fibers [88,182] and interfacial shear fractures [47,90] are the main shear failure modes for FRP members. However, it should be noted that FRP cables have different failure modes. As shown in Fig. 12, the fracture appearance is a completely or partly sheared area that does not involve interfacial delamination or debonding [183].

Table 2 presents the deformation rate and shear strength of various FRP tendons. As per the table, different FRP tendons have a relatively narrow range of discrepancy in terms of the deformation and shear strength ratio. The study results indicated that the shear strength of FRP tendons mainly depends on the internal fibers, with a minimal correlation with fiber types or diameters. It should be noted that only a few studies have examined the shear behavior of FRP tendons with multiple tendons. Therefore, further studies are required to investigate the possible impact of anchorage methods and quantity on the shear performance of FRP tendons [168].

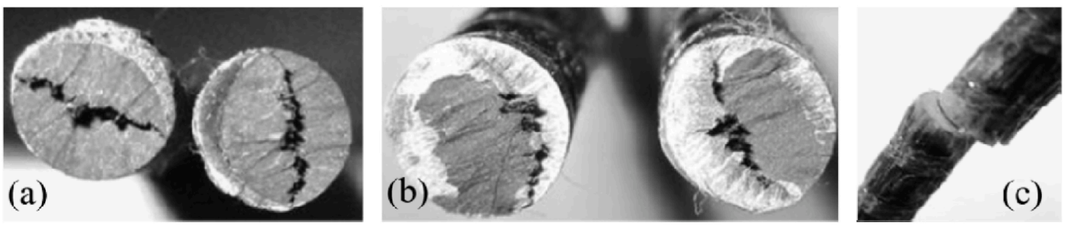


Fig. 12. Fracture appearance area of shear failure of FRP tendons: (a) Entire shear of BFRP, (b) Entire shear of B/CFRP; (c) Fractional shear of BFRP [183].

Table 2
Shear deformation and strength of various types of FRP tendons [183].

Tendon Types	D (*mm*)	Strength (MPa)	Deformation (*mm*)
BFRP	4.0	198	0.768
BFRP	6.0	131	0.876
BFRP	8.0	191	1.518
CFRP	6.0	242	1.00
B/CFRP	6.0	211–242	0.92–1.07

Concrete beams reinforced with FRP bars experience failure modes similar to those reinforced with steel bars, which are categorized into diagonal compression failure, shear compression failure, and shear tension failure [184]. The shear test results of concrete members reinforced with FRP tendons of varying stirrup ratios and sizes were analyzed by Jumaa and Yousif [185]. From the results of this study, it was observed that an increase in stirrup ratios resulted in a decrease in the inclination angle between the diagonal crack and the axial direction of the beam. However, the experimental results were found to be highly variable and did not match the predicted values. Similar findings were reported by Razaqpur and Spadea [186], where the inclination of the shear crack varied widely and deviated significantly from the predicted values. These discrepancies may be due to several factors, including the complex shear resistance mechanism, the significant variation in the mechanical performance of the longitudinal and transverse FRP tendons, the bonding properties' inhomogeneity, and the mechanical performance of the concrete material.

Hung et al. [120] conducted a numerical simulation and experimental research on the behavior of prestressed segmented bridge columns with semi-rigid connections. They used shear keys as the main factor in shear resistance to avoid the large axial prestress force required for post-tension precast segment columns. The authors developed six post-tensioned and precast segment bridge columns with two different methods of connections and analyzed them under lateral cyclic loads to investigate the column's seismic behavior. The suggested connection methods between sections included unbounded prestressed tendons, shear keys, and bonded bar reinforcements joined by bar couplers. Since a shear key can provide the shear resistance between neighboring sections, high prestress energy was not required in the tendon. In conclusion, the research showed that the columns with shear keys as the main factor in shear resistance had a stable cyclic behavior and a good energy dissipation capacity. An original anchor approach for multi-tendon FRP tendons was studied by Wang et al. [187]. They proposed a new style of conical anchor with a new constant FR load transfer component (LTC) to overcome the shortcomings of existing anchors. The distribution of shear stress along the interface among the FRP tendon is presented in Fig. 13. Additionally, Fig. 14 shows the LTC for three different cases. At the loading end of the LTC, a high shear stress concentration with a constant coefficient was detected, significantly influencing the binding behavior at the loading end. Conversely, other styles of LTCs with a different modulus showed a more consistent shear stress distribution and considerably reduced peak shear stress for the original half.

3.5. Transfer load/length

In PSC, transfer load/length refers to the load/length that is transferred from the prestressing tendon to the concrete when the tensioned tendon is released. Sha et al. [56] introduced a new approach to determining the transmission length of multi-FRP tendons (CFRP and AFRP) in PSC. Comparisons with experimental data deformation outcomes showed that the achieved closed-form solution predicted the delivery length of the pre-stressed FRP tendon with notable efficiency and accuracy. Furthermore, based on the pro-

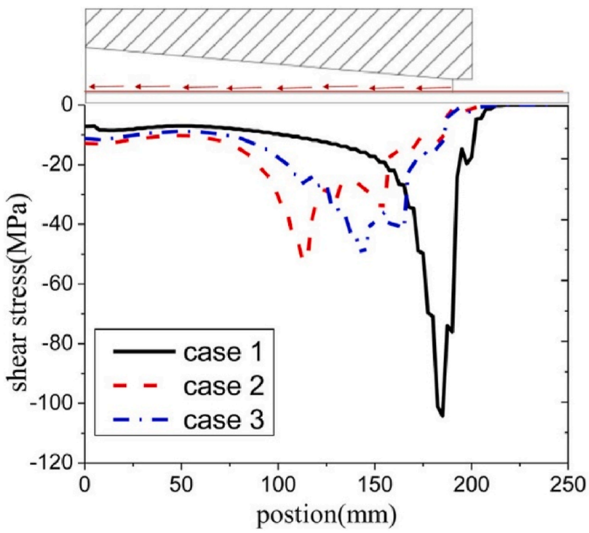


Fig. 13. Shear stress spreading of FRP tendons with various LTC [187].

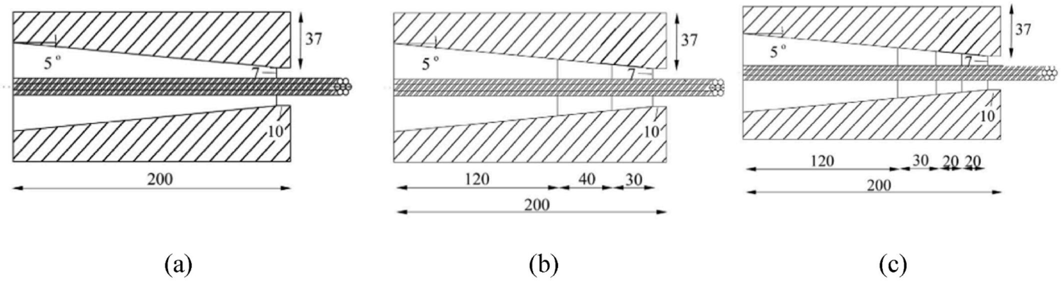


Fig. 14. Three models of LTC different modulus (a) model 1 (25 GPa), (b) model 2 (from loading 1, 5, and 25 GPa), (c) model 3 (from loading 1, 5, 15, and 25 GPa) [187].

posed theory, the major mechanical issues affecting the delivery length of the FRP tendon were investigated. The transfer length results from the comparison of previous works are indicated in Table 3. As shown in Fig. 15 parameters were normalized and factors affecting the delivery length of the FRP tendon were clearly quantified through experimental data studies. The authors considered that FRP tendons showed higher bond strength than steel cables and that there was little tendon slip in the experiment. The solid lines in Fig. 22 present that the transfer length was increasing as the binding stress coefficient increased. If the adhesive force is strong, the distance of the transfer force is shortened within a slip range of less than 1 mm. This was because the amount of initial strain is higher.

3.6. Effect of FRP on the anchorage system of PSC

Cai et al. [75] conducted a numerical investigation on the composite anchoring behavior of CFRP tendons. They established a numerical approach of composite anchor for CFRP tendon utilizing ANSYS software. The author optimized the design parameters and performed numerical investigations to obtain better anchor performance. The final tensile strength of the CFRP tendon in their work was 2200 MPa. Wang et al. [187] performed optimization of key factors affecting anchor efficiency using a novel anchor and FEM for large FRP cables with various types of tendons including steel and BFRP tendons. The outcomes showed that the suggested anchor not only preserved a fundamental benefit in bonding by incorporating the transfer load component and FRP tendon but also recognized the different modulus of the transfer load component by altering the winding angle of fiber roving.

Wang et al. [187] conducted a study to analyze the limitations of existing anchorage systems for FRP tendons/cables and overcome the shortcomings of existing anchors by proposing a new method of a conical anchor with a unique continuous multiple FRP

Table 3
Comparison of the transfer length for CFRP tendons [56].

Ref.	Type	Measured (*mm*)	Predicted (*mm*)	ACI 440.4R-04 (*mm*)	AASHTO (*mm*)
Soudki et al. [188]	R1(25% release)	545–695	265	168	400–480
	R2(50% release)	545–695	374	336	400–480
	R3(75% release)	545–695	457	504	400–480
	R4(100% release)	545–695	527	672	400–480
Nanni et al. [189]	B1-S8(50% release)	400	296	230	600–720
	B1-S8(100% release)	450	417	461	600–720

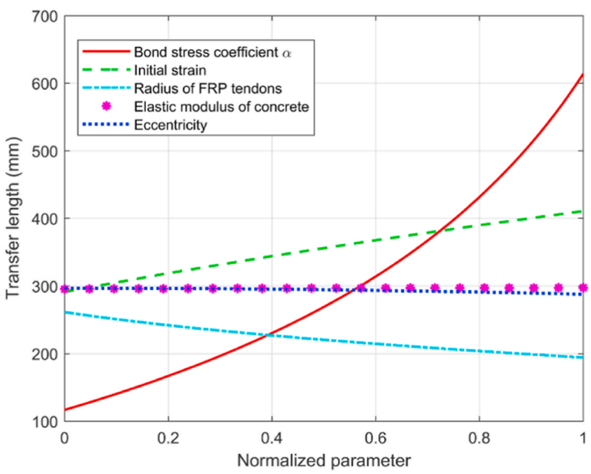


Fig. 15. Effect of parameters on multi-FRP tendon transfer length [56].

load transfer component (LTC). Four key factors, such as modulus fluctuation, LTC thickness, anchor length, and conical degree, which affected anchor efficiency, were analyzed, respectively. Generally, the effect of the conical shape on the shear stress propagation is mainly in a part in which the peak stress was comparatively lower than that of the third part of the load transfer component. Fig. 16 shows the shear stress propagation of anchors with various degrees of cones. The adoption of soft materials at the loading end of the load-carrying part greatly relieved that the concentration of stress occurred at the loading end and because of that, the ultimate stress also moved to the center of the anchor. In conclusion, it can be said that the degree of the cone had little effect on the shear stress distribution.

Mihara et al. [190] conducted a study to evaluate the feasibility of using CFRP tendons in internal strengthening systems under corrosive conditions by studying their load capacity. The main issue with this new technique was securing the CFRP tendon in the internal wedge. Typically, external fasteners are used to grip both ends of the CFRP tendon and apply a tensile force using a hydraulic jack. However, in an internal prestressing system, one end of the CFRP tendon should be anchored without any external fastener. Therefore, the authors focused on developing a method for anchoring CFRP in a wedge-shaped hole and examined its tensile load capacity. To increase the cable diameter and improve the pullout resistance, the end of the CFRP tendon was reversely twisted. The results of this study showed that the CFRP tendon, with a reverse-twisted tip embedded in the anchorage, had sufficient load-bearing capacity. Therefore, this research approved that post-tensioned prestressing systems using CFRP tendons are suitable for strengthening RC structures with a thickness of at least 200 mm, such as bridge deck slabs.

To account for the effect of environmental conditions on the interface between FRP and concrete with anchorage, it is necessary to explore the use of additional anchorage in hygrothermal environments. To this end, Wang and Guo [191] conducted a study to improve the existing mechanical end anchorage and prevent damage to the CFRP tendon and concrete substrate. The study found that as temperature and relative humidity increased, the load increment of the ultimate strength of the CFRP-concrete interface decreased. Consequently, the friction surfaces resulting from compression provided by end anchorage changed from a concrete-concrete interface to a concrete-adhesive or adhesive-CFRP interface. In another study [192], the pullout behaviors of BFRP bars with mechanical anchorages in concrete subjected to seawater were investigated. The study utilized three types of mechanical anchorages that can be flexibly assembled on BFRP bars: additional straight bar, composite head, and additional hook (presented in Fig. 17). The findings showed that the use of mechanical anchorages resulted in significant increases in the plateau length at the peak and decreases in the descending branch. Moreover, after exposure to seawater, the samples with composite heads displayed no considerable deterioration in their pullout performance, indicating the efficiency of the composite head in protecting against corrosive media. These outcomes suggested that composite-head mechanical anchorage holds promise for BFRP reinforcement in concrete members built-in marine environments.

Another work [194] evaluated the effectiveness of new composite anchorages made from CFRP tendons. The study examined the impact of factors such as over-tensioning, load level, and the number of tendons on the long-term performance of the anchorages. The residual anchoring capacity of the anchorages after a long-term test was also investigated, and the slippage of the CFRP tendons was analyzed using the time-strengthening theory. The results of this research revealed that the composite anchorages had an excellent long-term performance. Over-tensioning was found to significantly improve the long-term behavior of the samples by decreasing load loss caused by slippage of each measuring point and tendon slippage. The residual anchoring effectiveness of the remaining samples was higher than 0.95, except for one group due to incomplete axial tension. Theoretical analysis revealed that over-tensioning can successfully decrease load loss caused by the creep influence of the free section tendon.

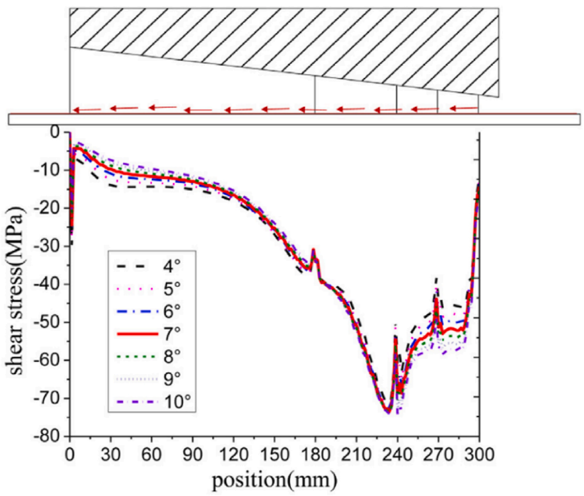


Fig. 16. Interfacial shear stress propagation of multi-FRP tendon with various conical degrees of LTC [187].

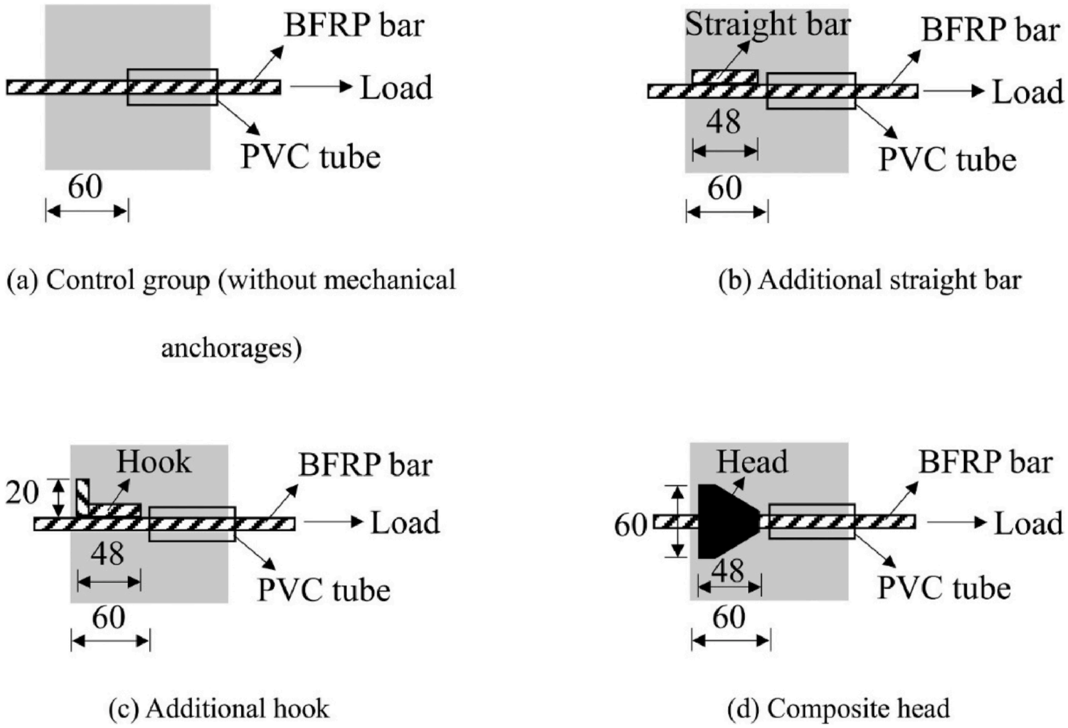


Fig. 17. Anchorage details (unit in *mm*) [193].

4. Durability

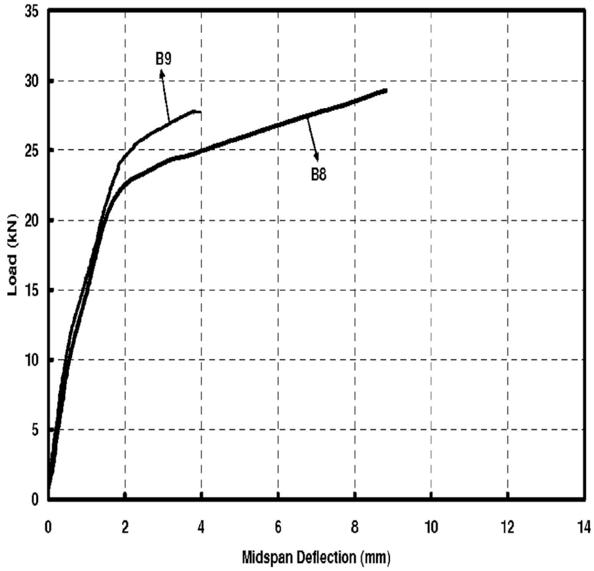
4.1. Durability of concrete structures prestressed with FRP tendons

FRP composites are known for their superior durability when compared to steel tendons. However, there are fundamental differences among various types of composite materials with respect to their ability to sustain prestressing and exposure to different environmental conditions [47]. The limited availability of data and information on the long-term performance and durability of FRP prestressed concrete is a major challenge that hinders the wider use of these materials as an alternative to steel bars and tendons in the construction industry. To address this issue, Mertol et al. [48] conducted a study to compare the durability performance of RC prestressed with CFRP and steel tendons, using different loading processes and environmental exposures including 15% salt water spray at 54 °C and normal air curing.

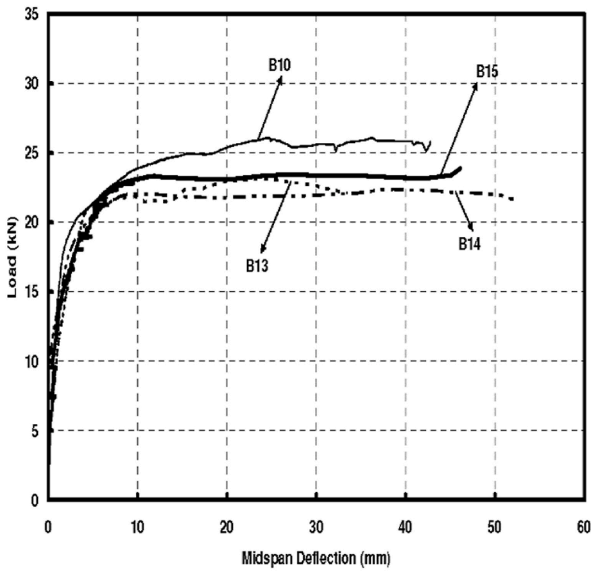
The results showed that the concrete girders prestressed with steel wires did not withstand extreme environmental conditions for more than 12 months. In contrast, the concrete girders prestressed with CFRP tendons endured up to the end of the 18-month-long testing period, demonstrating the excellent durability of CFRP in severe environments. Fig. 18(a) and (b) present the results of the midspan deflection vs load, which indicate that the midspan deflection for beams prestressed with steel tendons was larger than for beams prestressed with CFRP tendons. This result suggests that in harsh environmental curing conditions, the performance of CFRP tendons is superior to that of steel tendons, and beams prestressed with CFRP tendons are more durable than those prestressed with conventional steel tendons.

Another study [195] developed theory-based methods for investigating the service life-retention of stressed CFRP tendons for concrete bridge applications. In this regard, 120 CFRP PSC samples were exposed to stress levels of 65% and 40% of their final strength, and around 50 samples were tested without continued load under tension. According to the prediction results of this research, and following 100 years of service life with high temperature and constant load, for relative humidity $<90\%$ and a moisture-saturated condition, the tensile strength retention for CFRP tendons is expected to preserve over 0.95 and 0.84 of final tensile strength, respectively. Fig. 19 displays the normal relationship between the expected strength-property retention level and the expected service life at the two mean annual temperatures for CFRP tendons under constant load, correspondingly. This figure presents that the expected strength-performance retention level for the CFRP tendon samples subjected to a temperature of 10°C might be marginally affected over 150 or 200 years.

The degradation of FRP materials can lead to a reduction in their mechanical properties, such as stiffness, strength, and ductility. This can, in turn, affect the structural behavior of the concrete prestressed with FRP tendons. The degradation of FRP tendons can lead to a reduction in the bond strength between the FRP and concrete, which can result in the failure of the structure under load. Furthermore, the degradation of FRP tendons can also lead to changes in their dimensions and shape, which can result in the development of internal stresses and strains that can affect the behavior of the structure. For instance, if the cross-section of an FRP tendon reduces due to the degradation process, it can lead to an increase in the stress concentration, which can result in premature failure. Therefore,



(a)



(b)

Fig. 18. Load vs midspan deflection of prestressed beams with (a) CFRP and (b) Steel [48].

it is important to consider the degradation of FRP tendons when designing structures and to monitor their condition during the service life of the structure to ensure that they continue to provide the intended structural performance.

4.2. Acid/alkali attack

As mentioned previously, due to the wide range of applications of FRP materials, the long-term behavior of FRP composite materials has become a significant area of study. The service life of an FRP PC member may be remarkably affected by extreme environmental issues such as elevated temperature, acid or sulfate attack, and UV radiation [196]. Nowadays, much research has been conducted to evaluate the effects of environmental conditions, exposure duration, and reinforcement type on the durability and long-term behavior of FRP RC members. For instance, Zhang and Deng [197] designed an accelerated aging test to study the compressive performance of GFRP tendons under a constant loading system in two different environmental conditions, including a concrete environment subjected to an alkaline solution and a marine environment subjected to a salt solution. The results of this research showed that the

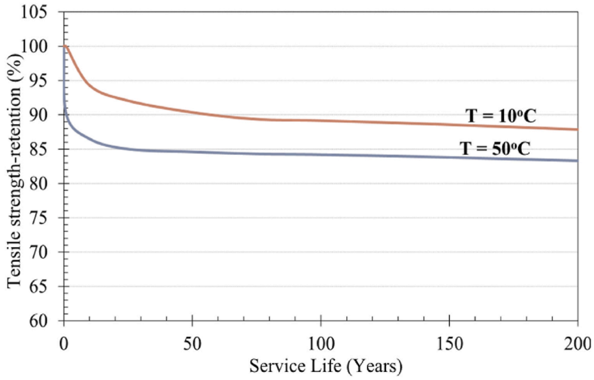


Fig. 19. Relationship between the strength property retention and the expected service life for CFRP tendons under constant load (65% of loading) [195].

compressive strength retention of GFRP bars over time in a salt solution decreased at a higher rate than in an alkaline solution, as presented in Fig. 20.

Cui et al. [198] investigated the bond performance of CFRP PC bonding interfaces while considering the reduction of the quality of the epoxy primer quality under wet-dry cycles. The authors stated that due to the exposure of the epoxy primer to wet-dry cycles, the moisture absorption process is significantly affected, leading to a noticeable decrease in the mechanical properties of the CFRP PC interface. Additionally, as the aging period increases, the failure types of the CFRP PC interface transform from the interaction of concrete and epoxy to the epoxy initial layer. They also reported that a time-dependent bond-slip approach is necessary to evaluate the time-dependent mechanical characteristics of PC members subjected to extreme environments. Korminejad et al. [199] conducted an experimental study to evaluate the strength behavior of steel plates damaged by corrosion and strengthened with one-sided CFRP patches under concentrated sulfuric acid and distilled water environments. They reported a significant increase in strength, with at least 50% and 40% increases in displacement and load-carrying capacity, respectively, compared to non-patched dry samples. The load-carrying capacity of all sample formats was compared and the results are presented in Fig. 21.

The lack of natural resources such as river sand, freshwater, and coarse aggregate has led to the utilization of other alternatives, such as kernel shells, sea shells, coal bottom ash, sea sand, and seawater [200–207]. The results of previous experimental research have shown that the engineering and durability characteristics of concrete made with the aforementioned alternative materials are not significantly different from those of conventional concrete [208,209]. Therefore, the utilization of alternative materials could solve the shortage of natural resources but also create new problems. For instance, the existence of chloride ions in coal bottom ash and sea sand can significantly increase the corrosion of steel tendons. The alkaline environment in the conventional RC provides a shielding effect for steel reinforcements to prevent further corrosion. However, as mentioned, the presence of cl^{-} can cause serious damage to the protection film leading to the acceleration of the corrosion process of steel bars in RC. Thus, due to the better corrosion resistance property of FRP materials, these composite materials can be utilized as a replacement for steel bars in sea sand or coal bottom ash RC.

However, it needs to be considered that over time and especially in alkaline and humid environments, FRP bars may exhibit a degradation trend. In this regard, Dong et al. [210] conducted experimental research to investigate the bond durability of steel tendons, BFRP tendons, and steel-FRP composite bars (SFCBs) in sea sand seawater concrete, exposed to a simulated seawater environ-

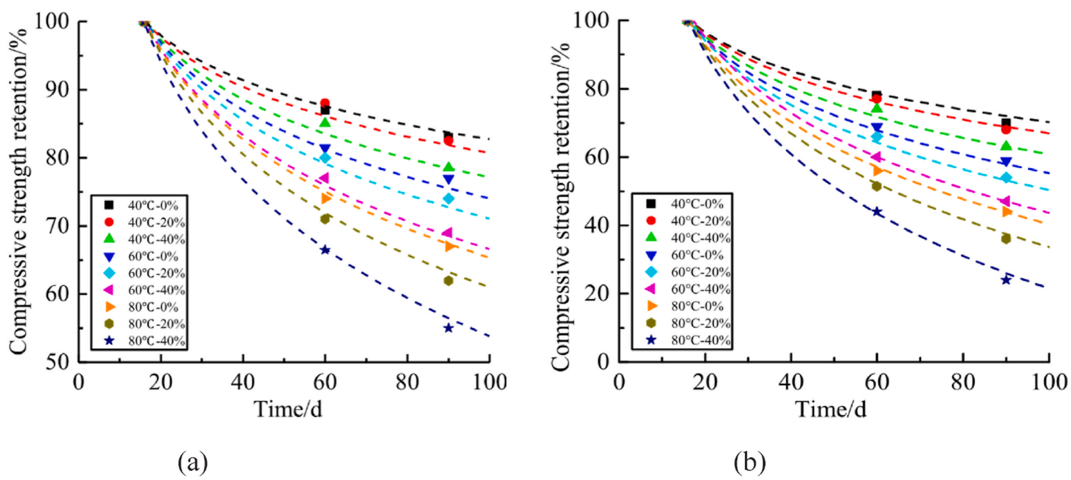
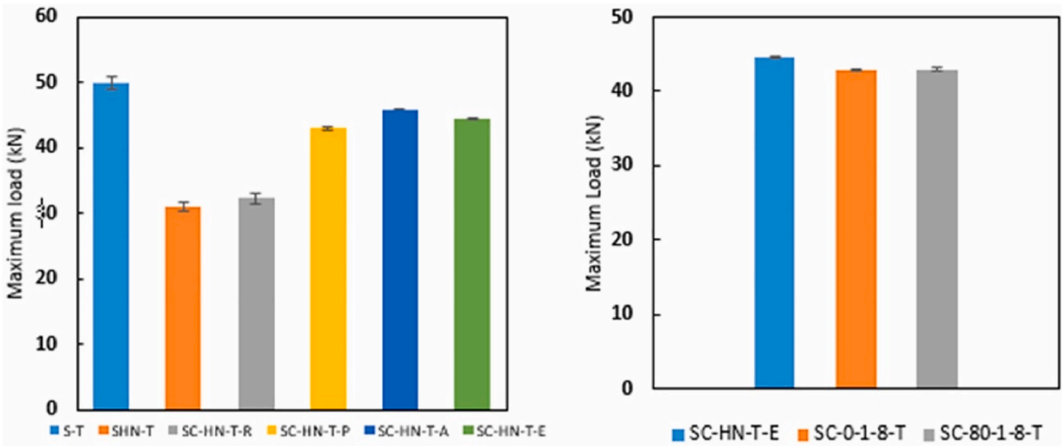


Fig. 20. Results of compressive strength retentions for the GFRP tendons in the (a) salt solution and (b) alkaline solution [197].



(a) (b)

Fig. 21. Load-carrying capability of all formats of steel samples, (a) comparison between dry specimens, (b) comparison between patched samples subjected to acidic solution and distilled water and dry ones [199].

ment. The authors reported that for steel tendons, the failure type was governed by the shearing of the concrete, whereas for the unconditioned BFRP tendons and SFCBs, bond failure modes were controlled by the shearing of the BFRP-concrete interface. They also found that the bond degradation of SFCBs and BFRP bars, when subjected to an aggressive condition, was more severe than that of a wet-dry cycling condition, as presented in Fig. 22. As seen in this figure, the bond durability of SFCBs was marginally superior to that of BFRP tendons.

In another study, Dong et al. [211] investigated the flexural performance of FRP tendons in RC beams after exposure to simulated seawater wet-dry cycling conditions. They examined BFRP tendons and SFCBs for 12 months and found that the RC beams prestressed with steel tendons appeared to have better macro-mechanical properties than SFCBs and BFRP tendons in the long term during the 12 months. However, the outcomes of this work do not imply that the durability performance of any type of RC members (BFRP tendons, SFCBs, and steel tendons) was acceptable. For instance, the microscopic analysis revealed that along the length of the beam, the inner steel tendons were entirely rusted during the 12 months. This indicates that the process of corrosion for steel tendons encased in the concrete cover was rapid, and this corrosion caused an expansion in the rusted area of the bars, creating cracks in the concrete cover. Due to the creation of new cracks in the concrete cover, the inner steel tendons were subjected to more corrosive and harsh conditions. As a result, the degradation of the macro-mechanical characteristics of sea sand concrete with steel bars over time became nonconvergent, as presented in Fig. 23. On the other hand, seawater flushing and carbonation resulted in a reduction in the value of the alkalinity of the concrete pore solution. As a result, the degradation of the macro-mechanical characteristics of sea sand concrete with SFCBs over time became convergent.

In another work, the same authors examined the bond behavior of SFCBs RSSC beams when subjected to a seawater wet-dry cycling environment [212]. According to the results of this work, after wet-dry cycling with a constant force for a period of 90 days, there were no noticeable changes in the load-carrying capacity properties of the beams prestressed with steel tendons. on the other hand, during the same period of time, the load-carrying capacity properties of the RC beams prestressed with SFCB gradually reduced. The energy ductility and flexural stiffness of both SFCB and steel tendon beams increased, and it can be said that these enhancements were more considerable for the beams with SFCB. As presented in Fig. 24, the spreading of the crack width for the SFCB RC beams in the long term was not clear, whereas the crack widths of the aged RC girders prestressed with steel tendons considerably enhanced. Additionally, no considerable variations were discovered in the crack spreading of both steel and SFCB RC beams. Nevertheless, small branch cracks were discovered in the pure bending regions of the conditioned beams prestressed with SFCB.

The reduction of the tensile characteristics of hybrid FRP and BFRP bars in a seawater condition was investigated by Xin et al. [51]. The authors reported that the BFRP bars had higher resistance to salt corrosion than the hybrid FRP, and the reduction pace of their tensile performance was nonlinearly related to the prestressing ratio. According to the results, hybridization can reduce the degradation pace of BFRP and CFRP tendons without any prestressing. On the other hand, steel-wire FRP showed a much faster degradation ratio than BFRP and CFRP tendons, because of the internal corrosive steel strands which are shown in Fig. 25.

5. Heat resistance

FRP composites have higher fire-resistance capacity than steel reinforcements and maintain structural serviceability at higher temperatures. However, conventional approaches for optimizing the mix design of FRP PRC have various problems such as low efficiency, safety issues, and low accuracy. To address these issues, Chen et al. [213] conducted a convolution-based machine learning algorithm for optimizing purposes. The authors reported that their proposed method provides a flexible and accurate tool that can be

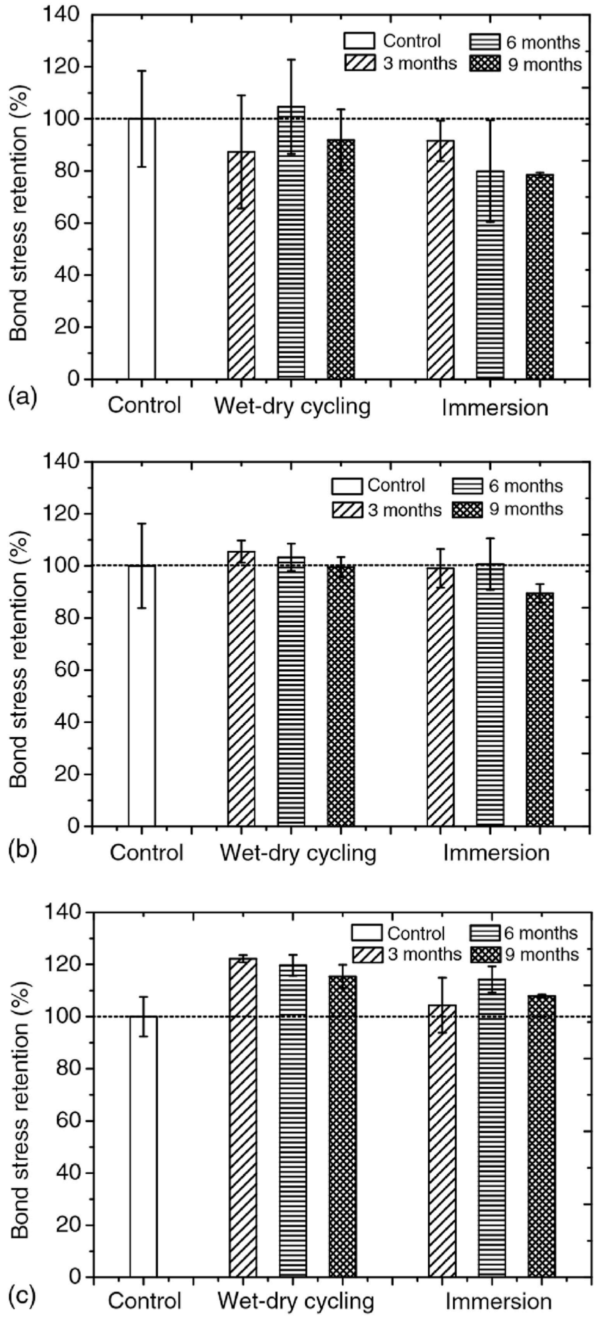


Fig. 22. Bond stress changes with different ages: (a) BFRP tendons; (b) SFCBs; and (c) steel tendons [210].

utilized for strength prediction and mix design optimization of FRP PSC. Another study [35] showed that PRC with steel tendons in nuclear containment did not face any major damage at low elevated temperatures (between 20°C and 140°C). However, the results of pull-out tests indicated that the ultimate bond between concrete and tendons decreased.

Azevedo et al. [214] conducted research to evaluate the influence of using three different techniques on the fire performance of CFRP-reinforced concrete slabs. The results showed that the continuous reinforcement embedded at the ends (CREE) method provided higher fire resistance than the other two alternatives, named near-surface mounted (NSM) and externally bonded reinforcement (EBR). In addition, when fire protection was applied, the CREE and NSM methods showed higher fire resistance than the EBR approach. Yu and Kodur [215] investigated the influence of elevated temperature on the modulus and bond strength of NSM CFRP PSC. The bond modulus can refer to the stiffness or rigidity of the chemical bond between concrete and tendons. The bond modulus is a measure of how much force is required to stretch or compress a chemical bond between two different materials and it directly is related to the strength of the bond. This property is reduced by increasing the temperature. The results of this study revealed that both

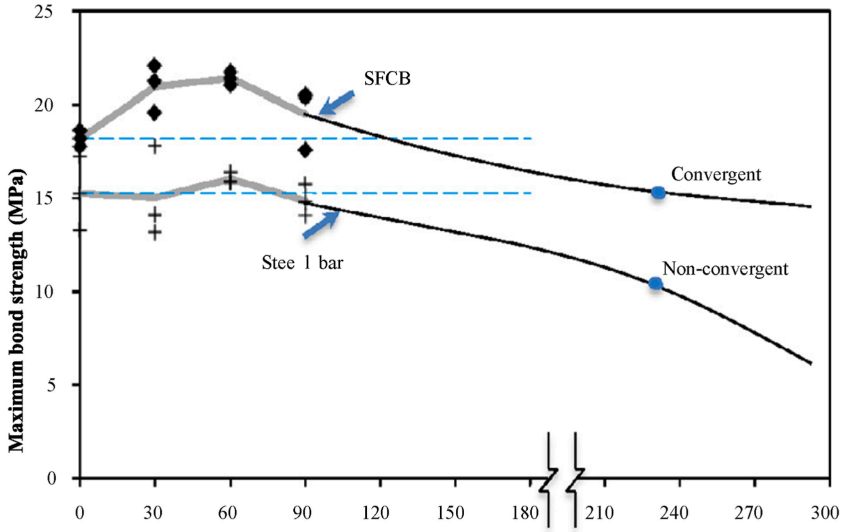


Fig. 23. Bond degradation trend of steel bars and SFCBs embedded in SSC [211].

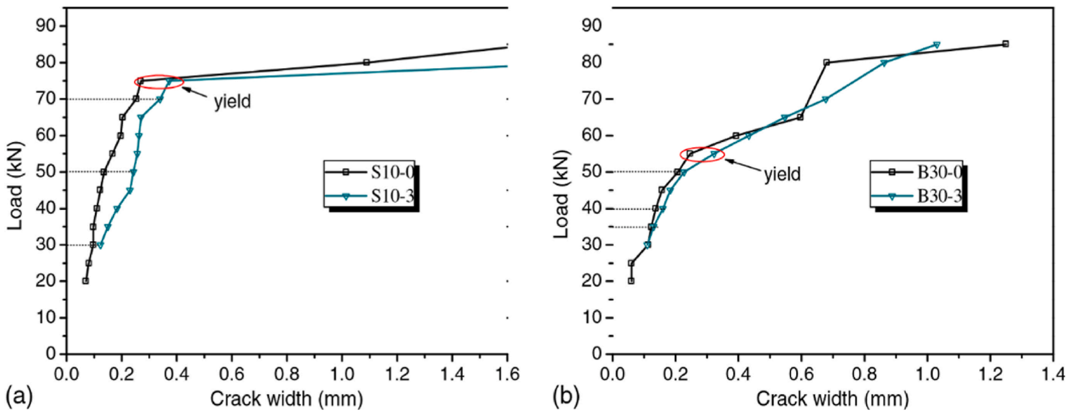


Fig. 24. Load-crack width curves of the girders: (a) RC with steel tendon; (b) SFCB RCb [212].

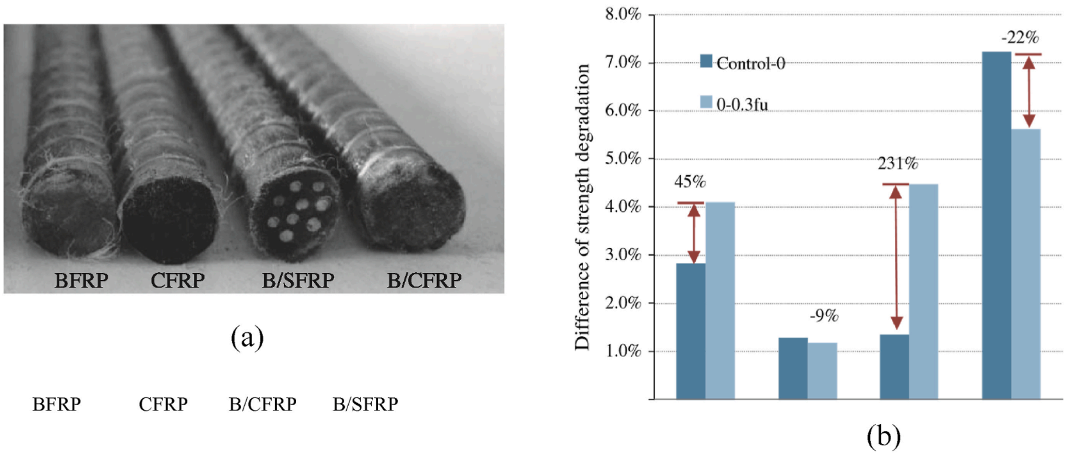


Fig. 25. (a) Surface and cross-section of FRP bars; (b) Comparison of strength degradation [51].

bond modulus and bond strength decreased significantly at temperatures up to 200°C and only keeps 20% of their original values. Additionally, up to 400°C, NSM CFRP PSC possesses negligible bond strength. The comparison between expected bond modulus retention from the empirical formula and evaluated data from the test is presented in Fig. 26.

The authors conducted another research [216] to evaluate the influence of high temperatures up to 600°C on elastic modulus and tensile strength of NSM CFRP rods and strips (the failure modes are presented in Fig. 27). The results revealed that both CFRP rods and strips maintain most of their primary elastic modulus and tensile strength up to 200°C. However, due to the decomposition process of CFRP resin further than 300 °C, the initial tensile strength and modulus of elasticity of NSM CFRP rods and strips significantly decreased.

Wang et al. [50] developed a study to evaluate the influence of elevated temperatures on the tensile strength of CFRP and GFRP bars and compared the results with conventional steel reinforcement bars. According to the findings, temperatures around 250°C and 325 °C are critical for the tensile strength of CFRP and GFRP reinforcing bars, respectively. Fig. 28 illustrates the difference in tensile strength for CFRP, GFRP, and steel reinforcing bars at different temperatures.

Terrasi et al. [217] analyzed the slip performance of CFRP-pretensioned high-strength RC slabs at elevated temperatures. The results of this study showed that the use of high numbers of additive materials, such as polypropylene microfibers in the concrete mixture, can intercept spalling and prevent the thermal splitting-crack-induced bond failure of the CFRP tendons in their prestress transfer zone. Moreover, due to the softening process of the resin at high temperatures (higher than 150 °C), was observed, which played significant roles in the tests discussed in this paper. Fig. 29 shows the spalled area of a slab that was cured for 8 months and has a thickness of 60 mm and a cover thickness of 27.5 mm.

Fig. 30 represents the CFRP tendon's slip process, which started after 21 min when a spall of the high-performance, self-consolidating concrete (HPSCC) occurred near the northern support concrete. It can be seen that the 47 min took for the slab spalling to be completely finished and resulted in the formatting of the tensile splitting crack which is considered a negative property for CFRP tendons [217].

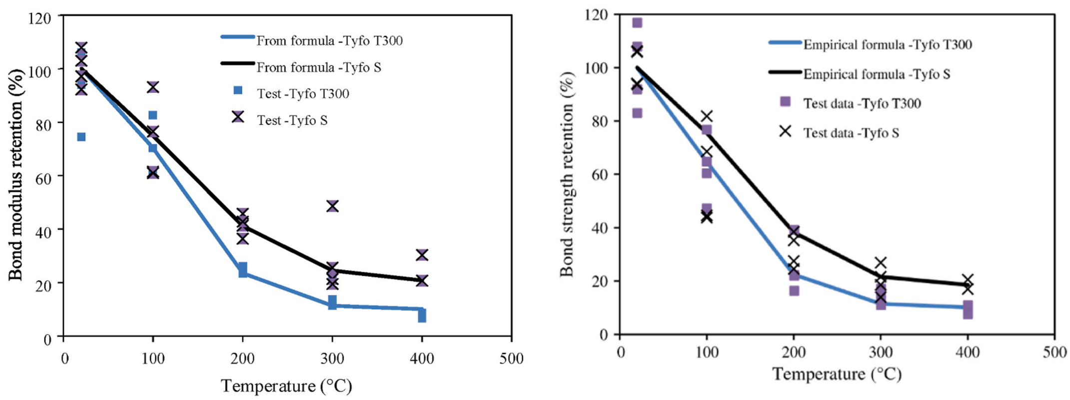


Fig. 26. Comparison between predicted bond modulus from empirical data and test data [215].

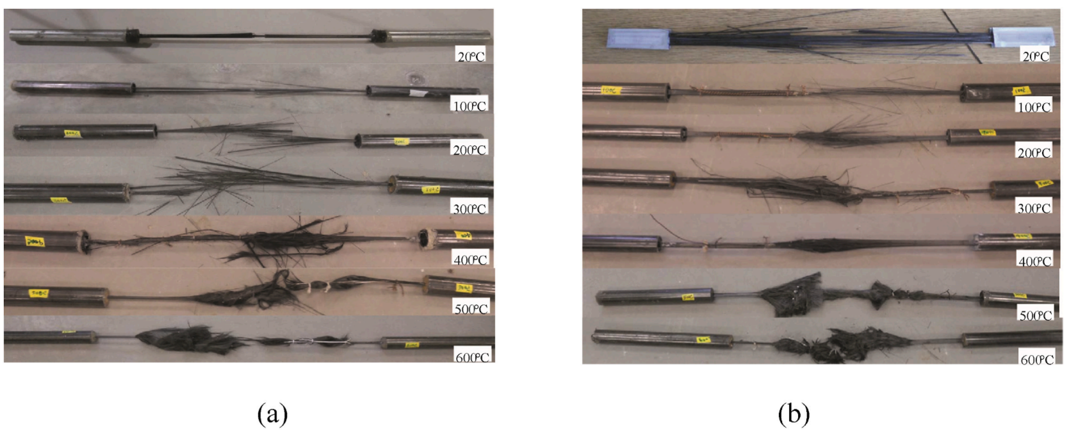


Fig. 27. Failure modes of CFRP a) rods and b) strips at various elevated temperatures [216].

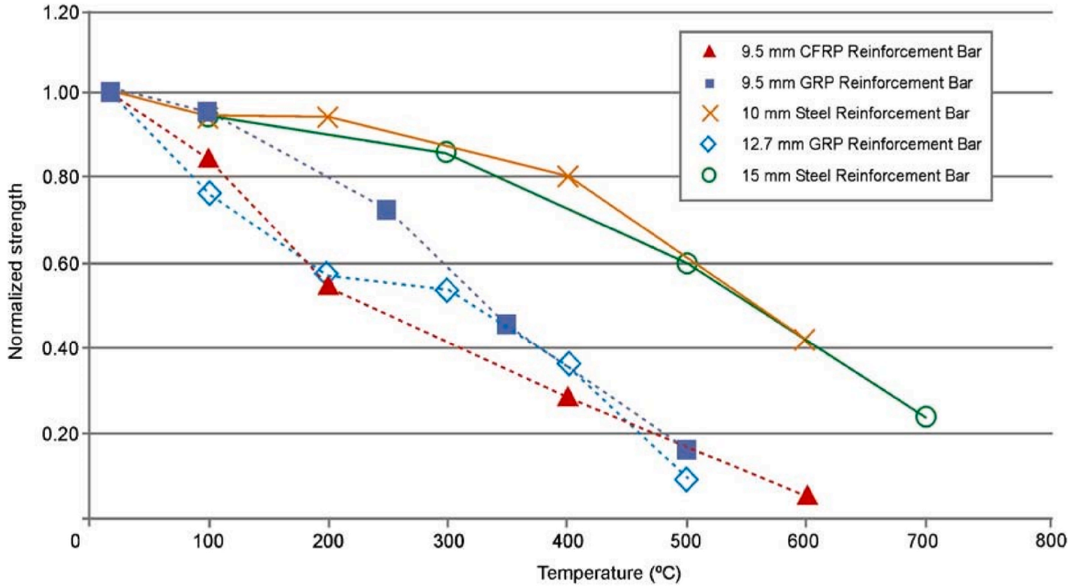


Fig. 28. Variation of tensile strength with different temperatures for CFRP, steel, and GFRP bars [50].

Fig. 29. Spalled area of the Slab after fire resistance testing [217].

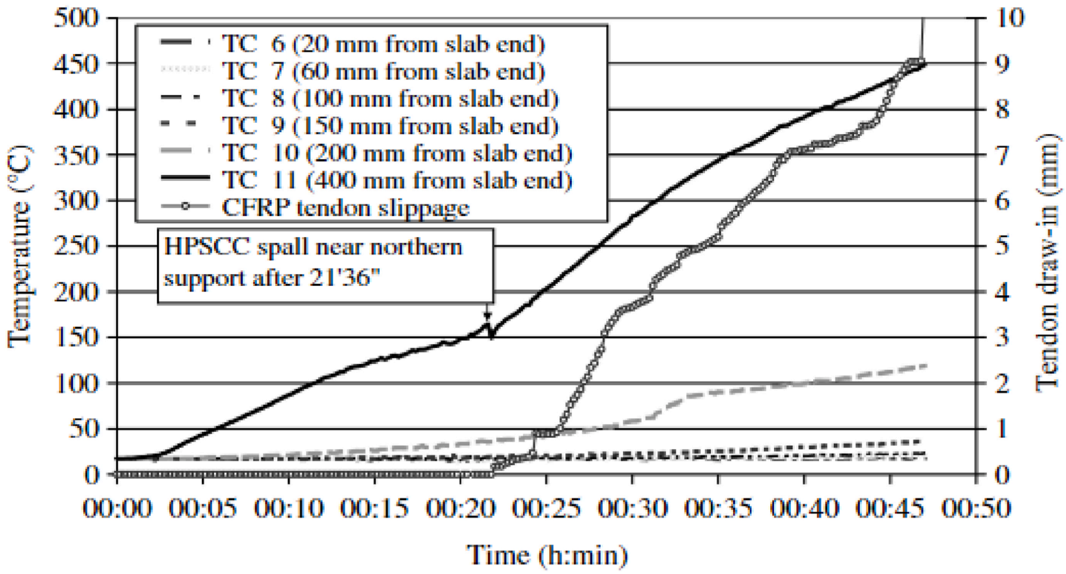


Fig. 30. Tendon slippage and tendon temperature in prestressed transfer zone during fire resistance test of slab [217].

6. Existing challenges of FRP and steel tendons and directions of future research

This section highlights the existing challenges and negative effects of utilizing FRP tendons on the engineering properties and durability performance of reinforced concrete. Additionally, some recommendations for future research are proposed. Despite the successful application of FRP composite materials in the construction industry, several challenges and issues persist. Technical challenges, higher production costs compared to steel tendon production, limited availability of raw materials, and a complicated production process are some of the main challenges and issues identified by previous studies. The following recommendations for future research are based on these existing challenges.

1) The results of previous studies showed that older PC beams with commonly decent FRP composite materials, even though presenting no external sign of deterioration, might have some stage of deterioration enough to produce developing crush under load and a decreased final capability. Considering the potentially critical nature of this mode of failure procedure, it is obvious that additional studies are needed to develop the present knowledge of the mechanisms and modes of failure. These researches can be valuable in the enhancement of more precise predictive tools and evaluation techniques for life-cycle engineering.
2) Since some of the collected test data for estimating the influence of elevated temperature levels on bond strength of near-surface mounted reinforcement with FRP were scattered, in future studies, additional bond experiments are required to achieve more accurate modulus and bond strength at high temperatures.
3) Additional study is required to get load-slip relations that specify more accurately the performance of the FRPs-concrete interface and might consider the significant influence of the bond between concrete and FRP composites. The described method makes up a robust, dependable, and computationally economical alternative for the evaluation of PSC members.
4) The long-term behavior of PSC structures is critical for their durability and sustainability. Future studies can focus on investigating the long-term behavior of FRP-PSC structures, including creep and shrinkage effects, and their impact on the performance of these structures.
5) FRP PSC structures may be exposed to extreme conditions such as fire, earthquakes, etc. Future studies can evaluate the performance of these structures under such extreme conditions to determine their resilience and robustness.
6) The design of FRP PSC structures can be optimized to enhance their performance and reduce their cost. Future studies can focus on developing design guidelines and optimization techniques for FRP PSC structures.
7) The cost of FRP materials can be a limiting factor in their use in PSC structures. Future studies can focus on reducing the cost of FRP materials and optimizing their use in PSC structures to achieve a cost-effective solution.
8) The development of new FRP materials with improved properties can enhance the performance and reliability of PSC structures. Future studies can focus on developing new FRP materials with improved durability, mechanical properties, and reduced cost.

7. Conclusion

This study investigates the effects of FRP tendons on the properties of PSC members, including mechanical properties and long-term durability performance. Despite some disadvantages and negative effects of utilizing FRP tendons as effective alternatives for steel tendons, such as additional cost, lack of composite materials, and a complicated production process, there are still some advantages and benefits of utilizing FRP tendons in the construction industry. Based on an extensive review of research data, the following conclusions can be drawn:

- The tensile performance degradation of BFRP tendons instead of the fibers themselves mostly remains in the interfacial deterioration.
- The performance of PRC beams with steel and CFRP tendons is comparable, while AFRP tendons cause higher deformation capacity and lower ultimate load. Moreover, due to the existence of secondary moments, the effect of prestress level on the moment at the middle support of PRC beams is negligible.
- The failure mechanism of concrete prestressed with steel tendon consisted of the yielding of the bottom part of the steel section under tensile stresses, followed by the collapsing of the concrete slab because of the compression. The concrete slab had a considerable reserve capacity as it collapsed. Because of the considerable loads in the tendons and due to induction by large curvature, the girders buckled after the slab crushed under a huge strain (over 3%).
- The shear strength of CFRP, BFRP, and hybrid FRP was similar to the shear strengths of steel rods and they had continuous shear deformation rates. The fiber and resin types and diameters of CFRP and BFRP tendons did not considerably affect their shear deformation and strength ratios.
- Based on the process of increased stress and the mechanical principles in unbonded tendons, the nonlinear finite element approach can be utilized to evaluate the final stress of prestressed curved concrete slabs with external unbounded tendons and to assess the crack development and ultimate strength of mentioned concrete.
- Experimental outcomes presented that the prestressed steel strands concrete girders subjected to the extreme environmental condition did not survive over 12 months whereas the girders prestressed with CFRP and BFRP tendons survived up to 18 months offshore environmental exposure, showing the excellent durability of CFRP and BFRP tendons in the severe environment.
- The critical temperatures for loss of strength, based on a 50% strength decrease criterion, are 250 °C and 325 °C for CFRP and GFRP bars, correspondingly. On the other hand, this temperature for reinforcing steel is 580 °C. The critical temperature of the reinforcement has a considerable influence on the fire resistance of RC members.

Credit authorship contribution statement

Mahdi Rafieizonooz: Conceptualization, Data curation, Writing - original draft, Writing –review, Resources Methodology.
Jang-Ho Jay Kim: Supervision, Editing, Funding acquisition, Project administration.
Elnaz Khankhaje: Writing - original draft, Writing – review, Resources Methodology, Validation.
Yeonwoo Nam: Writing – review, Data curation, Investigation.
Hesam Varaee: Writing - original draft, Resources Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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