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Performance Of Concrete Beams Strengthened With FRP Using Different Anchorage Systems: State Of The Art

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ملخص البحث:

إن الإنفصال المبكر لمركبات البوليمرات المسلحة بالألياف المستخدمة في التدعيم الخارجي للهياكل الخرسانية المسلحة، جعل البحث عن أنظمة تثبيت فعالة أمرا لا مفر منه. أثبتت العديد من الدراسات من خلال الاختبارات التجريبية والنمذجة العددية أن أدوات التثبيت المطبقة على أنظمة البوليمرات المسلحة بالألياف لا تعمل فقط على تعزيز المرونة والصلابة للهياكل الخرسانية ولكن أيضا تمنع فك الترابط النموذجي للألياف من سطح الخرسانة عند مستوى إجهاد منخفض مقارنة بإجهاد التمزق. لذلك، يجب أن تكون نتائج الدراسات البحثية السابقة معروفة جيدا من أجل اختيار نظام تثبيت مناسب وموثوق للاستخدام مع نظام التدعيم. يلخص هذا البحث أداء العديد من أنظمة التثبيت مع فوائدها وعيوبها. وأخيرا، يتم استكشاف أوجه القصور في الحالة الراهنة للمعرفة والاقتراحات لإجراء مزيد من الأبحاث.

Abstract

Premature debonding of externally bonded fiber-reinforced polymer (FRP) composites, when applied to reinforced concrete (RC) structures, has made searching for efficient anchorage systems an inevitable and challenging issue. Many studies through experimental testing and numerical modelling verified that anchorages applied to FRP systems not only enhance the member's ductility and strength but also prevent the typical debonding of the FRP at low strain level compared to the rupture strain. Therefore, findings from prior research studies must be well known in order to select a suitable and reliable anchorage system for usage with the FRP strengthening system. This paper summarizes the performance of several anchorage systems with their benefits and drawbacks. Finally, shortcomings in the existing state of knowledge and suggestions for further research are explored.

Keywords: Fiber reinforced polymer (FRP), Anchorage, flexure, strengthening, reinforced concrete, beams, debonding.

1. Introduction

- The use of externally bonded (EB) fiber-reinforced polymer (FRP) composites for strengthening of reinforced concrete (RC) structures is commonly deployed to increase the strength and ductility of the structural members. The excellent properties of FRP such as low weight, excellent durability in hostile environments, and high tensile strength encourage the market to utilize FRP for strengthening of deteriorated structures in case of degradation due to environment, or required higher capacity for concrete elements [1]. Numerous experimental and parametric studies have shown that carbon fiber-reinforced polymer (CFRP), glass fiber-reinforced polymer (GFRP), basalt fiber-reinforced polymer (BFRP), and aramid fiber-reinforced polymer (AFRP) are extremely effective at boosting the ultimate strength of reinforced concrete (RC) structures [2].

- During the analysis and design phases, full composite action is typically assumed between the bonding surface of the beams and FRP materials. However, factors including the materials' properties, size, climatic conditions, and shear stiffness of epoxy resins can cause bond slip between FRP and concrete substrate. Due to the frequent premature debonding of the FRP from the concrete substrate, which is a sudden and brittle failure, the allowable stresses are low percentage of the material rupture strain to reach acceptable levels of concrete–FRP contact bond stress [3]. Therefore, one way to enhance the effectiveness of FRP strengthening systems, change the mode of failure and overcome their drawbacks is by implementing an efficient and suitable FRP anchorage system.

- FRP anchorage systems' main function is typically to prevent or postpone the premature debonding, which occurs when externally bonded FRP separates from the concrete substrate affected by the low tensile strength of concrete. In addition, the anchorage systems are used to provide a load transfer mechanism at critical locations of structural members, or in some cases provide a ductile failure mode for the structural member instead of the typical sudden, brittle failure modes of FRP debonding and rupture. A detailed understanding of the behavior of anchorage systems is necessary for a safe and reliable design because anchorages' associated failure modes such as global anchorage failure or FRP rupture due to local stress concentrations imposed by the anchorage are often sudden and brittle [4]. Reviewing the current anchorage techniques for the FRP composites can help to pinpoint the main problems and set the groundwork for implementing the necessary guidelines and regulations.

- The most used EB anchorage systems are FRP U wraps, FRP spike anchors, π-anchors, and steel clamps [5]. Some of these systems have been proven to be effective, while others have been found to be less efficient. Additionally, the impact of parameters that have a significant influence may negate the benefits of anchorage procedures [6]. Consequently, many studies are needed to fill the gap of knowledge between design codes and applications of anchorage systems to enable the widespread use of FRP anchorage systems [5]. Presently, the lack of reasonable and reliable design guidelines is the main barrier obstructing the broad implementation of FRP anchorage systems [7]. Consequently, ACI design guideline (440.2R 2017) states that the practical application of anchorage systems must be supported by representative experimental testing.

- It is acknowledged that anchorages can be beneficial for a variety of FRP-strengthened elements like connections, walls, and beam members [7]. However, emphasis in this paper has been placed on flexural members strengthened.

2. Background

- Experimental studies have currently discovered several failure modes for RC beams strengthened in flexure with FRP composites. The modes are summarized as (i) concrete crushing, (ii) FRP rupture, (iii) shear failure, and (iv) debonding failure modes. In addition, the debonding failure modes can be divided into (a) concrete cover separation failure (Yao and Teng 2007); (b) plate end interfacial debonding (Leung and Yang 2006); (c) intermediate flexural crack-induced interfacial debonding (Otherwise known as IC debonding) (Teng et al. 2003; Ombres 2010); and (d) intermediate flexural shear crack-induced interfacial debonding [4,7]. Rupture of the FRP laminate is the failure mode that leads to the most effective usage of FRP, although not always being the most desirable because it is a sudden and brittle failure. The typical debonding failure modes indicated in **Fig. 1** make achieving failure through FRP rupture difficult.

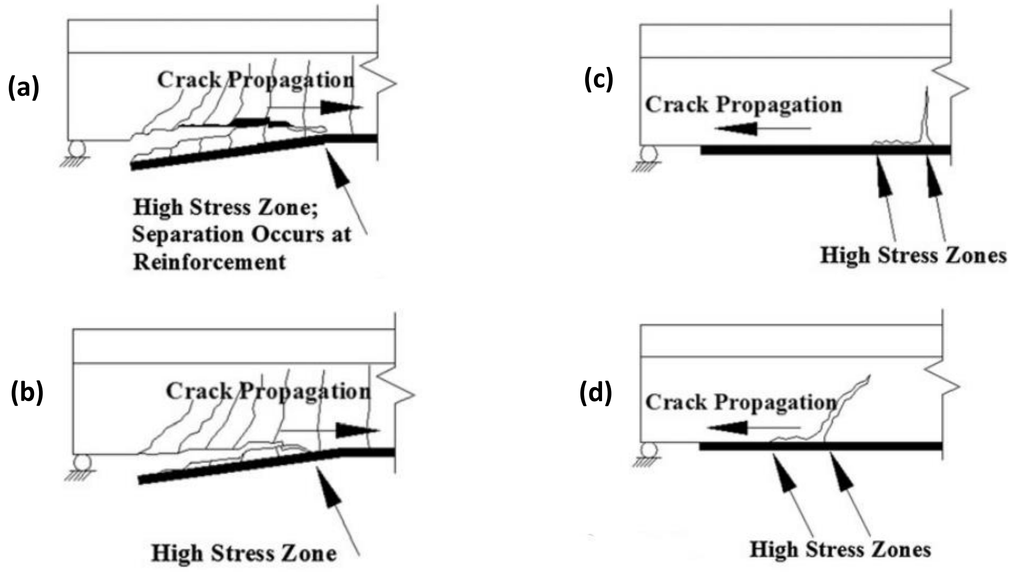

Fig. 1: Debonding modes of failure [4]

- A number of variables affecting on debonding failure mode such as (1) the level of internal steel reinforcement; (2) the distance between the plate end and the adjacent beam support (plate end distance); (3) the length, width, thickness, and elastic modulus of FRP plates; (4) shear-to-moment interaction; (5) concrete tensile strength; and (6) section geometry (Teng and Yao 2007) [7]. According to observations, when the distance between the plate end and support is relatively small, the controlling mode is IC debonding. As the plate end advances further away from the support, the debonding mode shifts to concrete cover separation failure (Yao and Teng 2007). In addition, it has been discovered that the possibility of debonding initiation close to the plate end is highest when the maximum shear force to bending moment ratio is high. Therefore, slender beams with high shear span/depth ratios do not require plate end anchorage because failures start in zones of high bending moment far from the plate ends (e.g. Garden and Hollaway 1998) [7].

- Debonding modes (a) and (b) mentioned in **Fig. 1** begin at or very close to the plate end due to high interfacial shear and normal stresses because of the laminate's termination as shown in **Fig. 2** (Fig. 14.1 ACI) (Smith and Teng 2002; Holloway and Teng 2008) [4], whereas modes (c) and (d) begin away from the plate end [7]. Increasing the FRP's bonded length may partially reduce the interfacial shear and normal stresses. However, there is a specific distance, commonly referred as the effective bond length, over which the majority of the bond stress is transmitted to the concrete substrate. According to studies (Chen and Teng 2001; Teng et al. 2002, 2003), an increase in the bonded length beyond the effective bond length has no influence on the maximum transferable load of the externally bonded FRP system. It should be highlighted that determining whether anchorage is necessary in any circumstance requires a detailed grasp of the debonding process and other FRP failure causes. Such information is required by the research community to create strength models that can precisely forecast the FRP flexure contribution in the presence of anchorages.

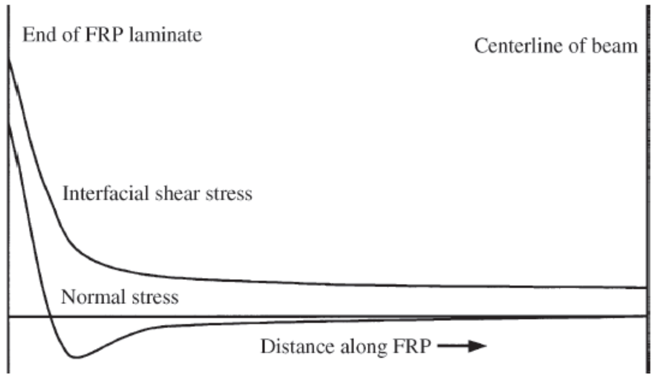

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Fig. 2: Conceptual interfacial shear and normal stress distributions along the length of a bonded FRP laminate [8]

- Three categories can be used to categorize the anchorage methods that have been suggested in the literature: (a) FRP anchors, which utilize FRP products; (b) metallic anchors, which use steel or aluminium for anchorage; and (c) mixed anchors, which employ both FRP products and metals for anchorage.

3. FRP Anchorage System Purposes

- Externally bonded FRP anchorage systems often serve at least one of the following objectives: (I) to prevent or postpone the beginning of an interfacial crack; (II) to enhance the total amount of available interfacial shear stress transfer; or (III) to provide a stress transfer mechanism, where no bond length is available beyond the critical section. These anchorage behaviors will be referred in this paper as Type I, Type II, and Type III anchorage behaviors, respectively, as described below [4].

3.1 Anchorage Type (I)

- Anchorage systems type (I) can be suitable when the tensile normal forces at the concrete substrate are higher than the tensile strength of the concrete. These stresses initiates cracks at the plate end, which cause ‘‘plate-end’’ interfacial debonding or concrete cover separation. Therefore, this type of anchorage is usually used at the termination of FRP laminates (an example shown in **Fig. 3**) or sometimes throughout the full length of the member to postpone the initiation of crack opening.

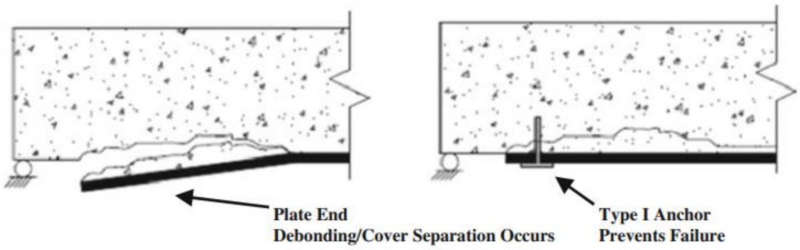
3.2 Anchorage Type (II)

- Anchorage systems type (II) can be used to increase the interfacial shear stress transfer, which is typically accomplished by increasing the area over which the shear stress is transferred. This is needed when the transfer length is shorter than the effective bond length, which is typically caused by the geometric properties of the structural member, or when curtailment of the length of FRP is required.

3.3 Anchorage Type (III)

- Anchorage system type (III) is mandatory if the critical design section is situated at the end of the strengthening sheet or close to a sudden change in the fiber direction, such as the intersection of two orthogonal structural members. These types pose a particularly unique and challenging problem because, without them, the FRP strengthening system can be said to make no improvement to the strength.

- The different behaviors of the same anchorage system used in Type II and Type III applications are shown in **Fig. 4** using the example of a U-Anchor anchorage system.



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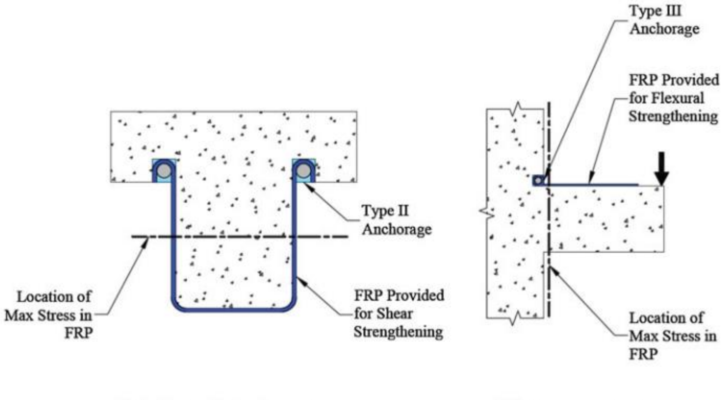
3.3 **Fig. 3**: Example of type I anchorage device [4]



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(a) Type II Anchorage **(b)** Type III Anchorage

Fig. 4: Comparison of Type (II) and Type (III) anchorage (U-anchor example) [4]

4. Anchorage systems for EB FRP laminates

- There are currently three main anchorage mechanisms for non-prestressed EB FRP laminates in RC-strengthened structures, namely: (1) FRP U-jackets anchorage system; (2) π-anchor anchorage system; (3) FRP anchors anchorage system. Each of these anchorage systems has specific installation restrictions, geometrical constraints, and force (stress) transfer properties. In the following sections, the miscellaneous anchorage systems that have been utilized in previous experiments are discussed and the various applications in terms of their function and behavior are explored. The major aim of this research is to compile the most recent data on FRP anchorage systems and to characterize them according to their intended use so that practitioners and researchers may formulate guidelines for anchorage systems design.

4.1 FRP U-Jacket Anchorage System

- FRP U-jacket anchors are implemented by wrapping FRP sheets around the cross-section of the beam with the adhesive material at the FRP laminate’s end or along its whole length. The fibers’ direction could be inclined or perpendicular to the member's longitudinal axis. **Fig. 5** depicts the layouts of the U-jacket anchors systems that are most typically utilized. The primary purpose of the U-jacket anchors is to offer the virtue of confinement which is delaying longitudinal crack propagation at fiber end points or intermediate cracks. Moreover, they provide the clamping force to withstand tensile peeling stresses. As a result of using the same material for both the transverse wrap and the strengthening material, possible corrosion problems that may arise from using different materials in other systems are avoided.

- Research on U-jacket anchors is substantial and has received a lot of attention due to their ease of construction and their improvement to the bond strength at the concrete-FRP laminate interface [4]. Chen et al. used Basalt FRP laminates to study the effects of different wrapping schemes and concluded that: the inclined U-jacket anchors at 45^{o} was more effective and had higher peak loads than the vertical one with the same amount of FRP materials (Sagawa et al. (2001)); covering the full span by U-jacket anchors provides slight enhancement compared to partial coverage of U-jackets [1].

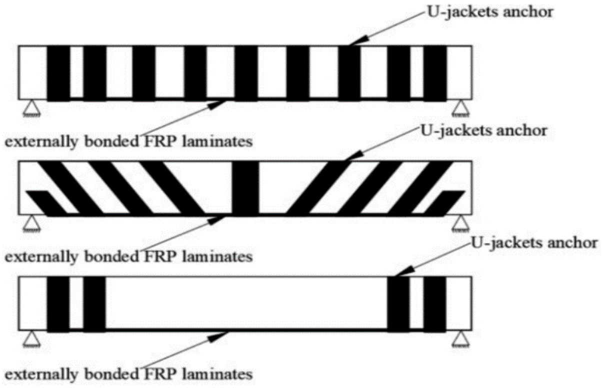

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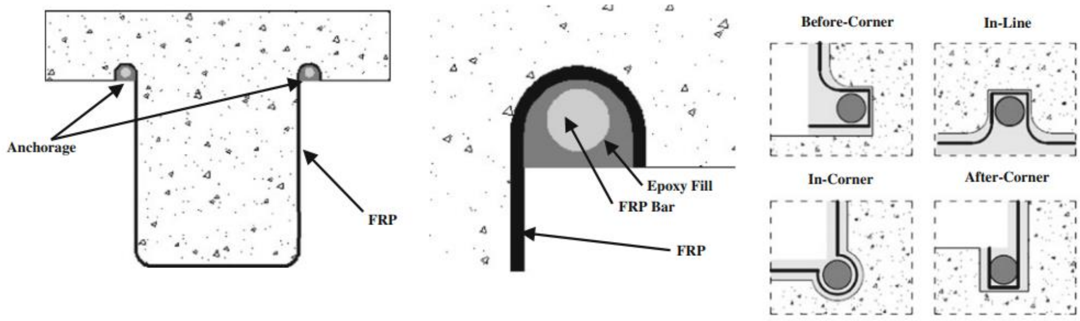
Fig. 5: Schematic view of typical layouts of U-jackets anchor [2]

- Numerous studies have shown that the debonding failure mode is changed from concrete cover separation to IC debonding or even FRP rupture when FRP U-jacket anchors are added at the plate end [Smith and Teng (2003); Pham and Al-Mahaidi (2006); Kalfat et al. (2011)]. Yalim et al. (2008) tested 26 beams in a three-point loading flexure test using 4, 7, 11, and continuous U-jacket configurations with the same number of layers. The configuration of using four and seven U-jacket anchors at the FRP ends was effective in changing the failure mode from end interfacial debonding failure to IC debonding, while with eleven jackets and full continuous jackets, the failure mode was FRP rupture [9]. Although U-jacket anchors are beneficial in flexural retrofitting applications, providing U-jackets throughout the full span may not be a materially effective way to increase the efficiency of FRP strengthening applications as more material is needed to achieve a given strength (Orton et al. 2008).

- Sawada et al. (2003) studied by using CFRP the vertical strain distribution within the vertical CFRP legs for better understanding to the confining action of FRP U-jacket anchors. The observed strains reached ranges of 3000 με in the concrete's cover zone in the tension side at a load level corresponding to the FRP debonding. At the highest loading point, 6000 με were observed after additional load application. This shows that the CFRP U-jacket was the reason to withstand the stresses that usually cause cover separation failure [10].

- Some innovative researchers constructed a groove in the concrete surface and pressed the ends of the FRP sheets into the grooves. The filler material, which is normally epoxy, is then inserted into the groove to fill it and then FRP or steel bar is inserted to increase the bonded area. **Fig. 6** depicts a schematic of a grooved U-Anchor and different U-Anchor configurations [4].



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(a) T-Beam **(b)** U-Anchor Detail **(c)** U-Anchor Types

Fig. 6: Schematic of U-anchor configurations (Grelle and Sneed 2011)

4.2 π-Anchor Anchorage System

- For the EB strengthening system, a relatively innovative and easy-to-use anchorage mechanism called the π-anchor anchorage system has been presented. The current investigation uses two π-anchor anchorage systems. The first one is entirely constructed of FRP material (also known as FRP π-anchor) and consists of a head plate and two legs that are monolithically built with the head plate (see **Fig. 7(a)**). The other is constructed using two metal screws that are fixed into the metal head plate (also known as the metal π-anchor (see **Fig. 7(b)**). In both systems, the head plate is bonded to the externally bonded FRP and fixed to the adjacent concrete by the legs or screws. Practically, using metal plates with FRP (first type) not only has the limitation of the possibility of usual steel corrosion due to environmental factors, but also has the hazard of potential corrosion due to dissimilar materials in the long term [6,7].

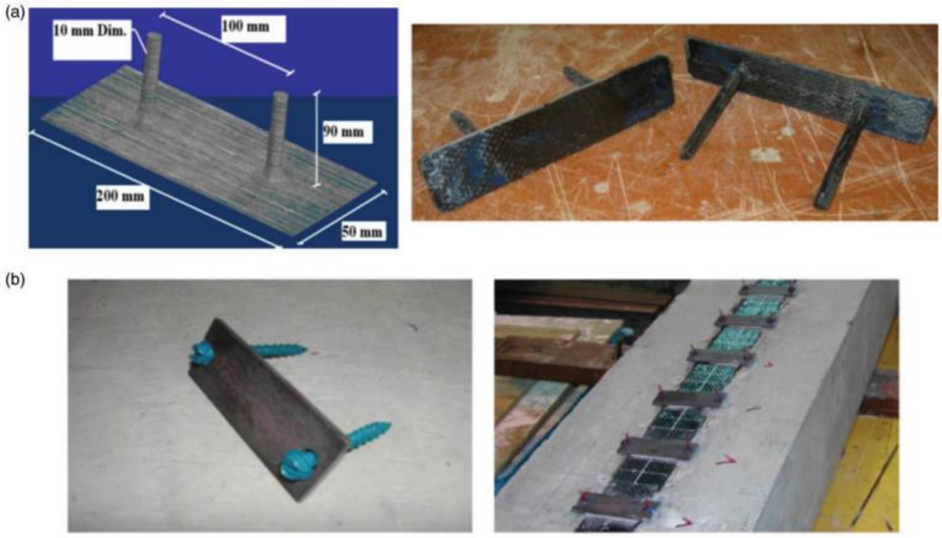

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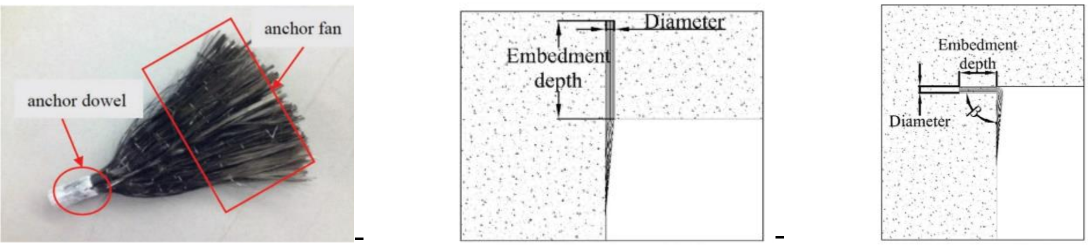
Fig. 7: The structures of π-anchors: (a) Typical dimensions and picture of FRP π-anchor. (b) Typical dimensions and picture of metal π-anchor [2]

- Three different stress mechanisms are implicated in this anchorage system as a result of the installation procedure: adhesion, friction, and dowel action [11]. The adhesion primarily occurs at the FRP-concrete interface, the friction is activated when the FRP laminate moves perpendicularly, and the dowel action is mostly provided by the legs or screws embedded into the concrete. Wu and Huang (2008) focused in their study on the tensile normal forces resistance by using thin steel plate anchors fixed to the concrete substrate with two thin concrete nails. After the failure of the specimens, the inspection of the nailed plate anchors showed very little lateral (shear) deformation of the nails; thus, the increase in the FRP bond strength provided by the anchorage system was due to frictional resistance due to the normal pressure exerted on the FRP by the anchors.

- Numerous improvements have been made recently to π-anchor systems. According to those findings, the metal π-anchor was successful in preventing cracks-induced debonding failure in the EB strengthening system. These encouraging results have led to the establishment of the design equations and guidelines for the metal π-anchor. Mostafa and Razaqpur studied the impact of the number and spacing of the FRP π-anchor on the strengthening effect of the EB strengthened structures. The findings showed that the best configuration for preventing debonding failure was a uniform distribution of anchors along the laminate and the installation of the laminate between the anchor legs. Regardless of the basic construction and surprising viability in improving the strengthening efficiency, the screws or the legs of the π-anchors utilized in the previous literature reached 90 mm long. This means deepest holes to be drilled into the soffit of the strengthened structures. Subsequently, the potential damage of utilizing π-anchors to the tensile steel reinforcement or the stirrups should be avoided [12].

4.3 FRP Spike Anchorage System

- Spike anchors, which is also named as fan anchors or FRP dowels, are made from rolled fiber sheets to form the two main parts of the anchor. The first part is the bundled fibers embedded in the holes predrilled into the concrete element, which is called the anchor dowel, and the second part is the strands of loose fibers spread and glued over the surface of EB FRP sheets to disperse local stress concentrations, which called the anchor fan, as shown in **Fig. 8 (a)** (Smith 2010). Depending on the direction in which the anchors are inserted into the structure, anchors are often classified as straight or bent anchors, as shown in **Fig. 8 (b&c)** [2]. Because they are entirely formed from the same FRP materials as the EB fabrics, anchors have the advantages of being lightweight, easy to construct, and have no potential corrosion hazards from dissimilar materials. Another advantage is that they can be seamlessly integrated with the matrix of the FRP being anchored so they can be fabricated to overcome various geometric complexities. Moreover, FRP anchors are smaller in size and more flexible in their physical configurations than those of the π-anchors and the U-jacket anchors.



(a) (b) (c)

Fig. 8: Attributes of FRP anchors: (a) Construction phase. (b) Side view of straight anchor. (c) Side view of bent anchor. [2]

- In the early times, Lam and Teng described an experimental program with RC cantilever slabs of 700 mm span that had been strengthened in flexure with bonded GFRP strips. It was found that the FRP anchors' presence could delay the premature debonding at the GFRP-concrete interface, which in turn led to FRP rupture or concrete crushing failure but in the presence of curvature [13]. Eshwar et al. (2005) examined RC beams with a span of 5.5 m with both straight and curved beam soffits (curvature 5 mm over 1 m). A single row of 10 mm FRP spike anchors were embedded 76 mm into the concrete beam at 500 mm spacings. The strength of the curved-soffit specimen improved by 35% when the FRP anchors were implemented with the wet lay-up system as compared to the unanchored specimen. Consequently, the curved soffit beam with the FRP anchors had more strength than the flat soffit beam strengthened with wet lay-up fibers [14]. Orton et al. (2008) proved that two rows of three 10 mm diameter anchors were sufficient to increase the tensile strength of the FRP and caused the material to fracture throughout its full width. Furthermore, they reported that larger spacings did not adequately anchor the whole width of the FRPs, leading to partial debonding, whereas a higher number of smaller anchors and smaller spacings were more successful in completely developing the capacity of the FRP fiber.

5. Conclusions and Recommendations

- This paper provides a thorough analysis of the commonly used anchorage systems with promising outcomes for RC structures enhanced with FRP laminates. The research developments, advantages and disadvantages, and various fields of application for each of the aforementioned anchorage systems are covered in this article. The main conclusions of this review article are listed below:

1. Each of FRP U-jacket anchors, FRP π-anchor, and FRP transverse anchors are effective in preventing, or at least delaying the debonding failure in the EB strengthened structures.
2. Anchorage types that are made from FRP material are more applicable than metallic types as they require less labor, installation time and not vulnerable to corrosion. It is advised to utilise the metallic anchorages when a high level of anchoring is required, and this anchoring cannot be obtained with non-metallic anchors.

- Despite the fact that this review includes a substantial number of researches on anchorage systems for FRP laminates, few of these studies focus on anchorage behaviour, and even fewer offer recommendations and equations for design that may be used in actual construction. The following research recommendations are suggested to aid the future work:

1. To assess the mechanical performance and anchoring effectiveness of each anchorage system and to create a single evaluation index system.
2. More work is required to modify and optimize the current anchorage systems in order to improve their anchorage performance and durability based on the benefits and drawbacks of each anchorage system.

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