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Review of Anchorage Systems for Externally Bonded FRP Laminates

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Abstract: The most recent report by ACI Committee 440 on externally bonded fiber reinforced polymer (FRP) strengthening systems states that systems designed to mechanically anchor FRP should be studied in detail and substantiated by physical testing. To select and design an appropriate anchorage system for use in an FRP strengthening system, it is important that findings from previous research studies be known. This paper presents a comprehensive literature review of the performance of different mechanical anchorage systems used in FRP strengthening applications. Each anchorage system is discussed in terms of its purpose and performance. Advantages and disadvantages of each system are discussed, and areas in need of future research are explored.

Keywords: anchorage, concrete, fiber reinforced polymer, retrofit, repair, strengthening.

1. Introduction

Despite promising developments in the implementation of fiber reinforced polymers (FRP) for the repair and retrofit of reinforced concrete (RC) structures, many challenges exist that have prevented additional growth of this market. Such challenges include: potential brittle behavior of FRP-strengthened RC structures due to sudden failure modes such as FRP rupture or debonding; deterioration of the FRP mechanical properties due to harsh environmental conditions such as wet-dry cycles and freeze–thaw conditions; a reduction in strength due to the effects of improper installation procedures; and lack of agreement among debonding behavior and bond strength models. This paper focuses on another of these challenges: the stated need for mechanical anchorage systems to improve FRP strength in situations where debonding or lack of development length is a problem (ACI Committee 440 2008), and the lack of anchorage-related research data to support widespread implementation of FRP anchorage systems (Ceroni et al. 2008).

In general, the primary role of FRP anchorage systems is to prevent or delay the process of debonding, which occurs when externally bonded FRP detaches from the RC substrate because of the low tensile strength of concrete (Ceroni et al. 2008). Anchorage systems are also 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. The performance of anchorage systems becomes critical in the design of FRP strengthening systems because they may limit the strength of the FRP system. Associated failure modes including global anchorage failure or FRP rupture due to local stress concentrations imposed by the anchorage are sudden and brittle in many situations; thus a thorough understanding of the behavior of anchorage systems is essential for a safe and reliable design.

Because of the large number and wide variety of experimental studies conducted on FRP debonding, recent efforts have been made to compile information in the literature to enable the development of design provisions and guide future research efforts. A recent review by Kalfat et al. (2011) compiles the published literature on several FRP anchorage devices used for flexure and shear strengthening and quantifies the efficiency of each anchorage type discussed. The present paper compliments this effort by characterizing different FRP anchorage devices based on anchorage purpose and behavior. Based on evaluation of the literature, three distinct purposes are identified and defined. The presentation of this paper is largely qualitative by explaining the stress transfer mechanisms for each anchorage type, and then discussing the type of application(s) for which it can be used. Select studies from the literature are elaborated in this context, and a database is presented that summarizes anchorage system application (purpose) and test types used. Independent FRP anchorage system testing is also summarized and discussed. Finally, it should be noted that this paper focuses on anchorage of externally bonded FRP sheets and does not include anchorage of thick prefabricated plates.

2. Background

In nearly every application of externally bonded FRP used to strengthen RC members, the failure mode that results in

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the most efficient utilization of FRP, although not necessarily the most ideal, is rupture of the FRP laminate. Achieving failure by FRP rupture, however, is often difficult due to the common debonding failure modes shown in Fig. 1. The debonding modes depicted in this figure are: (a) concrete cover separation; (b) intermediate flexural crack-induced interfacial debonding; (c) "plate-end" interfacial debonding; (d) intermediate flexural shear crack-induced interfacial debonding; and (e) FRP debonding in a shear strengthening application (Teng et al. 2002, 2003). While these debonding failure modes are specifically related to FRP-strengthened RC beams, FRP for other bond-critical strengthening applications exhibits similar debonding failure modes. "Plate-end" debonding and concrete cover separation are due to the same cause: high interfacial shear and normal stresses near the laminate end due to the termination of the laminate (Smith and Teng 2002; Holloway and Teng 2008). While the interfacial shear and normal stresses can be reduced to an extent by extending the bonded length of FRP, there exists a certain length, frequently referred to as the effective bond length, over which the majority of the bond stress is transferred to the concrete substrate. Studies have shown that an increase in the bonded length beyond the effective bond length does not increase the maximum transferrable load of the externally bonded FRP system or prevent against debonding failure (Chen and Teng 2001; Teng et al. 2002, 2003). Therefore, other methods are needed to increase the effectiveness of the FRP and strength of the member. It should be noted that a thorough understanding of the debonding process and other FRP failure modes is required to evaluate the necessity for anchorage in each situation. However, comprehensive discussion of these processes is beyond the scope of this paper. The reader is referred to Teng et al. (2002), Oehlers (2006), and Holloway and Teng (2008) for additional discussion on debonding and other FRP failure modes.

The debonding failure modes shown in Fig. 1, especially concrete cover separation, have been frequently documented. The current approach to preclude debonding failure is to limit the design strain in the FRP to levels much less than the rupture strain (ACI Committee 440 2008), which as a result, limits the efficiency of the strengthening system. It must also be noted that increasing the number of layers of FRP can reduce the ductility of the strengthened member. Such issues have led to the creation of FRP anchorage systems. In general, FRP anchorage systems serve the purpose of preventing or delaying the debonding process so that greater loads can be transferred to the FRP resulting in higher design strengths. This improves the overall efficiency of the strengthening system. In some cases, as dictated by the geometry of the member to which the FRP is bonded and the location of the critical design section, anchorage systems provide a force transfer mechanism that is critical to the strength of the FRP system. In fact, in certain cases such as flexural strengthening of a cantilever slab, the strength of the anchorage system controls the strength of the overall FRP system.

3. FRP Anchorage System Purposes

Anchorage systems for externally bonded FRP typically serve one or more of the following purposes: (I) to prevent

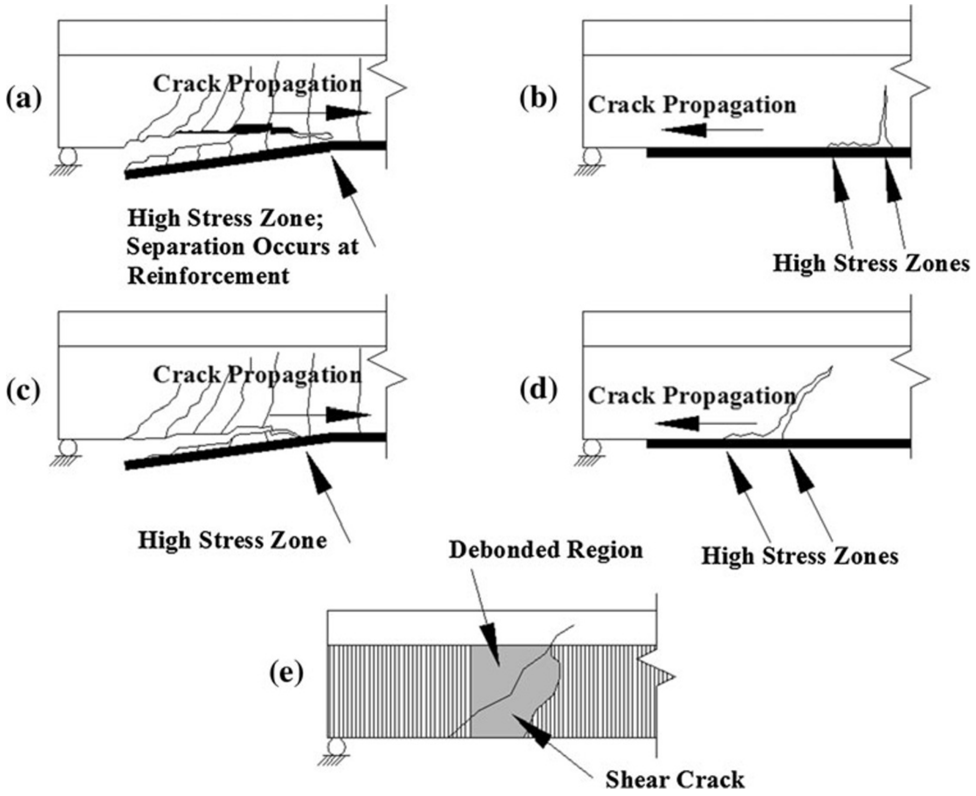


Fig. 1 FRP debonding failure modes (adapted from Teng et al. 2002).

or delay interfacial crack opening; (II) to increase the total 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 to in this paper as Type I, Type II, and Type III anchorage behaviors as described below.

3.1 Type I Anchorage

Anchorage systems with Type I characteristics can be used to prevent or delay crack opening at the onset of debonding or failure of the concrete substrate due to tensile normal forces associated with certain debonding failure modes such as "plate-end" interfacial debonding or concrete cover separation. Type I anchorage is most commonly used at the termination of FRP laminates, and sometimes throughout their entire length. An example application of Type I anchorage is shown in Fig. 2, in which the FRP on a RC beam soffit used for flexural strengthening is anchored at the laminate end in order to prevent concrete cover separation and "plate-end" interfacial debonding.

3.2 Type II Anchorage

Anchorage systems with Type II characteristics can be used to improve the interfacial shear stress transfer. This is usually achieved by increasing the area over which the shear stress is transferred. Type II anchorage is often used when the transfer length is less than the effective bond length, usually due to the geometric conditions of the structural member, or simply to reduce the length of FRP used by increasing the interfacial stress transfer.

3.3 Type III Anchorage

Type III anchorage is used to provide an alternative stress transfer mechanism where no bond length is available beyond the critical section. This condition applies when the critical design section is located at a sheet or plate end, or near an abrupt change in fiber direction, such as at the location of an interface between two orthogonal structural members. Type III anchorages present a very special and difficult challenge because the FRP strengthening system can be considered to have no contribution to the strength without their inclusion. While some Type III anchorages may have Type I and Type II characteristics, it should be noted that anchorage forces in a Type III application are transferred beyond the bonded length. In Fig. 3, the example of a U-Anchor is used to illustrate the difference in behavior of the same anchorage system being used in Type II (Fig. 3a) and Type III (Fig. 3b) applications.

4. Existing FRP Anchorage Systems

Research on systems to mechanically anchor externally bonded FRP strengthening systems has included

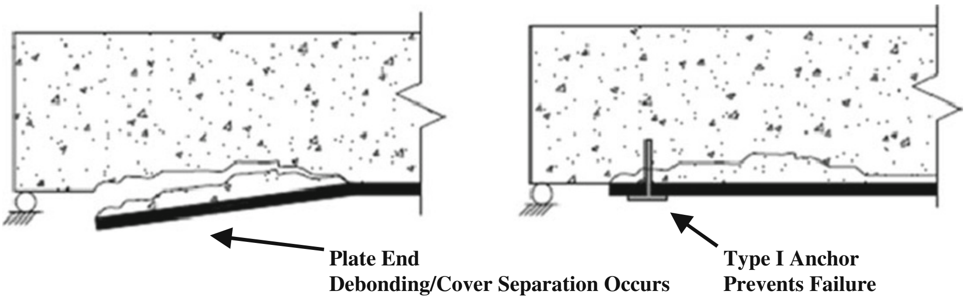


Fig. 2 Example of Type I anchorage device.

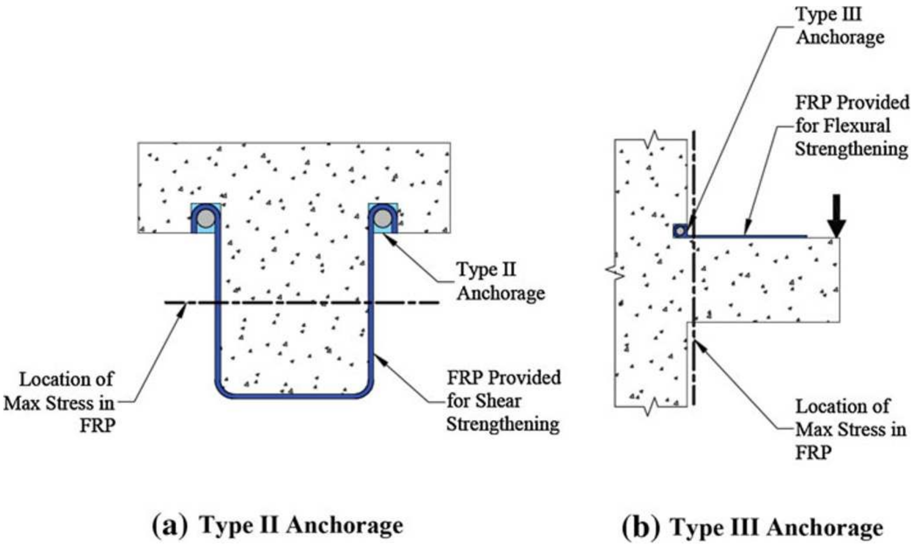


Fig. 3 Comparison of Type II and Type III anchorage (U-Anchor example).

Table 1 Summary of FRP anchorage applications and test types.

System/device	Application	Study	Test type	FRP strengthening application
90° Anchor spike	Type I	Kim et al. (2011)	–	Confinement of RC columns
		Zhang and Smith (2012)	*SS*	Representative testing only
		Zhang et al. (2010)	*SS*	Representative testing only
		Niemitz et al. (2010)	*SS*	Representative testing only
		Kim and Smith (2010)	–	Analytical anchor model only
		Sami et al. (2010)	*BT, PO, DS*	Representative testing only
		Pham (2009)	*DS, BT*	Representative testing only
		Ozbakkaloglu and Saatcioglu (2009)	*PO*	Representative testing only
		Li and Grace Chua (2009)	–	Flexure of RC beam-column and beam-wall joints
		Orton (2007)	*BT*	Flexure of RC beams with height transition
		Eshwar et al. (2005)	*PO*	Flexure of RC beams with curved soffits
		Karantzikis et al. (2005)	–	Confinement of RC columns
		Piyong et al. (2003)	*PO*	Flexure of RC slab with prestressed flexural FRP
		Lam and Teng (2001)	–	Flexure of RC cantilever slabs
180° Anchor spike	Type II	Kim and Smith (2010)	–	Analytical anchor model only
	Type III	Sadone et al. (2010)	*SS*	Representative testing only
		Prota et al. (2005)	–	Flexure/shear and axial loads of RC columns
Transverse wrapping	Type I	Aiello and Ombres (2011)	–	Flexure of continuous RC beams
		Khan and Ayub (2010)	–	Flexure of rectangular RC beams
		Pan et al. (2010)	–	Flexure of rectangular RC beams
		Sadeghian et al. (2010)	–	Flexure of eccentrically loaded RC columns
		Zhuo et al. (2009)	–	Prestressed FRP strap
		Yalim et al. (2008)	–	Flexure of RC T-beams
		Orton (2007)	*BT*	Flexure of RC beams with height transition
		Al-Amery and Al-Mahaidi (2006)	–	Flexure of RC beams
		Pham and Al-Mahaidi (2006)	–	Prestressed FRP strap
		Kotynia (2005)	–	Flexure of RC beams
		Antonopoulos and Triantafillou (2003)	–	Flexure and shear of RC beam-column joints
		Sawada et al. (2003)	–	Flexure of RC beams
		Shahrooz et al. (2002)	–	Flexure of RC T-beams
		Spadea et al. (2001)	–	Flexure of RC beams (steel plates used as anchorage)
		Grace et al. (2000)	–	Flexure and shear of RC beams
	Types I/II	Sagawa et al. (2001)	–	Flexure of RC beams with inclined straps

Table 1 continued

System/device	Application	Study	Test type	FRP strengthening application
U-Anchor	Type II	Petty et al. 2011	–	Shear of PC girders
		Beigay et al. (2010)	–	In- and out-of-plane flexure in masonry shear wall
		Ceroni et al. (2008)	*DS*	Representative testing only
		Micelli et al. (2002)	–	Shear of RC T-beams
		Khalifa et al. (1999)	–	Shear of RC T-beams
	Type III	Beigay et al. (2010)	–	Flexure of masonry shear wall
		Teng et al. (2001)	–	Flexure of RC cantilever slab
Longitudinal chase	Type II	Kalfat and Al-Mahaidi (2010)	*DS*	Representative testing only
FRP strips	Types I/II	Petty et al. (2011)	–	Shear of PC girders
		Donchev and Nabi (2010)	–	Flexure of RC slabs
		Ortega (2009)	–	Shear of RC and PC girders
		Antonopoulos and Triantafillou (2003)	–	Flexure and shear of RC beam-column joints
		Lamothe et al. (1998)	–	Shear of RC T-beams
Steel/FRP plates	Types I/II	Jin and Leung (2011)	*SS*	Representative testing only
		Ortega (2009)	–	Shear of RC and PC girders
		Wu and Huang (2008)	–	Flexure of RC beams
		Ceroni et al. (2008)	*DS*	Representative testing only
FRP sandwich plate	Types I/II	Ortega (2009)	–	Shear of RC and PC girders
Bolted U-Anchor/angle	Types I/II	Nagy-György et al. (2005)	–	Flexure and axial loads of RC shear walls
After-joint plate	Types I/II	Ceroni et al. (2008)	*DS*	Representative testing only
Steel angle	Types I/II	Antonopoulos and Triantafillou (2003)	–	Flexure and shear of RC beam-column joints
Bolted angle	Types I/II	Tanarslan and Altin (2010)	–	Shear of RC T-beams
	Type III	Deifalla and Ghobarah (2010)	–	Shear and torsion of RC T-beams
		Hiotakis (2004)	–	Flexure of RC shear wall
		Hwang et al. (2004)	–	Flexure of RC shear wall
		Hall et al. (2002)	*DS*	Flexure of masonry shear wall
		Foo et al. (2001)	–	Flexure of RC shear wall
CHS anchor	Type III	Hiotakis (2004)	–	Flexure of RC shear wall
Plate & angle/pipe	Type III	Hall et al. (2002)	*DS*	Flexure of masonry shear wall
Plate & pipe	Type III	Grelle (2011)	–	Flexure of RC column

BT bending test, *DS* double-shear test, *PO* pull-out test, *SS* single-shear test.

anchor spikes, transverse wrapping, U-Anchors, longitudinal chases, FRP strips, plate anchors, bolted angles, cylindrical hollow sections, ductile anchorage systems, and other miscellaneous systems. Each of these anchorage systems has unique geometrical constraints, installation limitations, and force (stress) transfer characteristics. Although published research focusing specifically on FRP anchorage system behavior has been limited, studies have shown promising results regarding the functionality of various systems. In this section, the different anchorage systems presented in existing literature are described, and their application types are discussed in terms of their purpose and behavior. Representative studies involving FRP anchorage systems are summarized in Table 1, and studies in which anchorage performance and behavior are reported are reviewed in the following sections. Advantages and disadvantages of each system are also discussed. The reader is referred to Kalfat et al. (2011) for discussion on efficiency of selected anchorage types. The main objective of this work is to synthesize the current information on FRP anchorage systems and characterize them in terms of purpose so that practitioners and researchers can develop improved anchorage design guidelines.

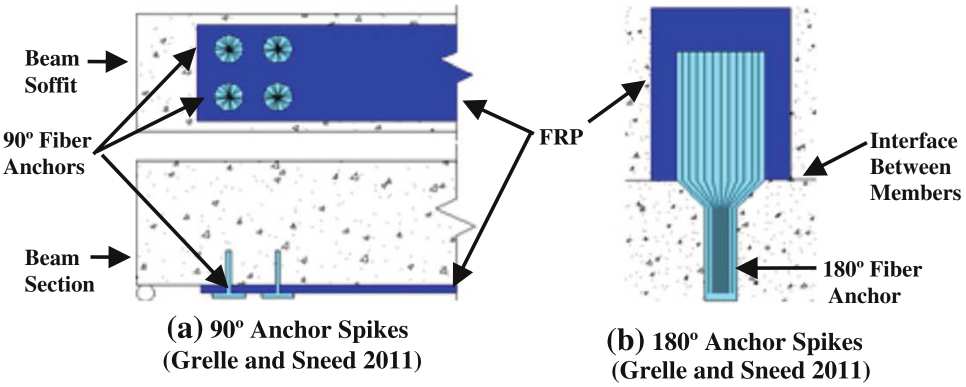
4.1 Anchor Spikes

Anchor spikes, also referred to as FRP anchors, FRP dowels, or fiber anchors, are strands of bundled fibers with one end embedded in the composite matrix and the other end embedded in the concrete substrate. Because they can be seamlessly integrated with the matrix of the FRP being anchored, they can be fabricated to overcome various geometric complexities. Another advantage to anchor spikes is that the spikes can be fabricated from the same FRP materials as the externally bonded fabric, which facilitates construction and eliminates potential corrosion hazards from dissimilar materials. Anchor spikes can be manufactured by hand, which can result in variations between individual anchors, although Zhang et al. (2010) found that variations among individual anchors did not significantly affect the anchorage system performance. Anchor spikes have been widely used as anchorage systems, and their physical geometry is dictated by their role in the strengthening application. Anchor spikes are commonly installed orthogonal to or in-plane with the FRP, termed 90° and 180° anchor spikes respectively, although other orientations can exist (e.g. Ozbakkaloglu and Saatcioglu 2009). Differences in the installed geometry between 90° and 180° anchor spikes can be seen in Fig. 4 and are discussed in the sections that follow. It is worth noting that 180° anchor spikes are typically used to anchor FRP strengthening systems where geometric complexities in concrete members require that the FRP sheet or plate must be discontinued (Type II or III anchorage), whereas 90° anchor spikes are typically used for anchorage throughout the length of the FRP laminate, or near its termination (Type I anchorage).

4.1.1 90° Anchor Spikes

90° Anchor spikes are installed with the fiber bundle embedded into the concrete substrate, and the remaining fibers are fanned out on the FRP surface and incorporated into the matrix. The axis of the embedded portion of the anchor spike is orthogonal to the plane of the FRP. 90° anchor spikes are typically provided for Type I applications and have been studied by Lam and Teng (2001), Eshwar et al. (2005), Piyong et al. (2003), Orton (2007), Li and Grace Chua (2009), Ozbakkaloglu and Saatcioglu (2009), Kim and Smith (2010), Zhang et al. (2010), Sami et al. (2010), Niemitz et al. (2010), Zhang and Smith (2012), and Kim et al. (2011). 90° anchor spikes are commonly assumed to resist axial forces (pullout), although some studies (Orton 2007) have relied on a complex force transfer that includes axial, shear, and bending resistance.

Lam and Teng (2001) used 90° GFRP anchor spikes to anchor GFRP strips provided for flexural strengthening of cantilever RC slabs. The anchor spikes were used along the length of the cantilever to arrest the propagation of debonding towards the free end of the member resulting from the formation of a major crack. Eshwar et al. (2005) used 90° GFRP anchor spikes to anchor FRP provided for flexural strengthening of RC beams with curved soffits; while the beams containing anchor spikes failed by anchor spike pullout and FRP debonding, the beams achieved a higher peak load than similar strengthened beams without anchorage. Piyong et al. (2003) used GFRP anchor spikes and noted their effectiveness in preventing debonding by observing reduced stress concentrations at the ends of the anchored FRP strips. Orton (2007) observed that negative effects of poor concrete surface preparation were reduced when 90° anchor spikes were used to anchor FRP for flexural strengthening. Li and Grace Chua (2009) did not observe 90° anchor spike failure during tests of FRP strengthened RC beam-column and beam-wall joints and noted that the anchor spikes were effective in enhancing the capacity of the FRP. Kim and Smith (2010) compiled a database of tests on FRP anchor spikes to develop models to predict the pullout strength. Their models, while useful for determining the standalone anchorage strength, are difficult to apply to the design of an FRP strengthening system since the interaction between anchorage and anchored FRP was not studied. Zhang et al. (2010) performed independent testing (tests that evaluate the strength of an anchorage system in the absence of a global FRP strengthening system) of 90° anchor spikes made from GFRP or CFRP with different fiber content and anchor construction. They observed that anchored specimens first exhibited complete FRP debonding followed by significant slippage compared to



(a) 90° Anchor Spikes (Grelle and Sneed 2011)

(b) 180° Anchor Spikes (Grelle and Sneed 2011)

Fig. 4 Comparison of 90° and 180° anchor spikes.

unanchored specimens, as well as higher joint capacity. The increased slippage and joint capacity were attributed to the tensile resistance of the anchor spike, the clamping effect provided by the anchor, and friction between the debonded FRP strip and concrete. A study by Zhang and Smith (2012) found that slip could be increased by omitting the epoxy impregnation within the bend region of the anchor spike. An unusual application of 90° anchor spikes was studied by Karantzikis et al. (2005), whereby GFRP anchor spikes were used to anchor GFRP jackets to the sides of L-shaped RC columns, resulting in an increase in confinement provided by the jacket. Similarly, Kim et al. (2011) used CFRP anchor spikes to anchor CFRP jackets provided confine square and rectangular columns with inadequate lap splices. Columns with anchor spikes and CFRP jackets were found to have increased strength and deformation capacity than those with CFRP jackets alone.

4.1.2 180° Anchor Spikes

180° Anchor spikes are typically installed in-plane with the anchored FRP so that the fibers in the anchors can transfer the tensile force in the anchored FRP to the anchor. 180° anchor spikes are typically used in Type II (Kim and Smith 2010) or Type III (Prota et al. 2005; Sadone et al. 2010) applications. It should be noted that in some cases, practical installation procedures may prevent the anchor spike from being installed at 180°, such as at a reentrant corner, leading to a slightly larger installation angle.

Sadone et al. (2010) performed independent testing of 180° anchor spikes made from pultruded carbon fiber plates. Spikes featuring notches into the embedded portion of the anchor performed better than smooth, un-notched plates. While the steel fiber spikes used for ductility enhancement of RC columns in Prota et al. (2005) were not used to anchor FRP, their effectiveness in providing additional flexural strength for the columns suggests that similar Type III FRP anchorage applications may also be effective.

4.2 Transverse Wrapping

In some situations, wrapping bonded FRP transversely with another FRP sheet will provide a clamping effect evidenced by strains measured in the wrapped FRP (e.g. Sawada et al. 2003), thus providing a form of anchorage. Transverse wrapping can be in the form of discrete strips located at the laminate end or along its length, or as continuous along the length. Fiber orientation may be perpendicular to the longitudinal axis of the member or may be inclined. An example of transverse wrapping anchorage is shown in Fig. 5. It is important to note that transverse wrapping anchorage is not effective until a certain level of tensile stress is reached in the wrap. Thus, it may be desirable to prestress the transverse wraps in order to generate a higher clamping force. While prestressing of surface-bonded FRP has been rather unsuccessful in practice, alternate concepts have been investigated (Pham and Al-Mahaidi 2006; Zhuo et al. 2009). Similar to anchor spikes, the material used in a transverse wrap can be the same as the strengthening material, which eliminates potential corrosion hazards that can result from dissimilar materials. Installation of the wrap, however, may be challenging due to member geometry and access to its adjacent sides. Because of the clamping effect provided to the FRP and concrete beneath it, transverse wrapping anchorage can be considered to exhibit Type I behavior. In the case of inclined wrapping, combined Type I and Type II behavior is likely because of the fiber direction.

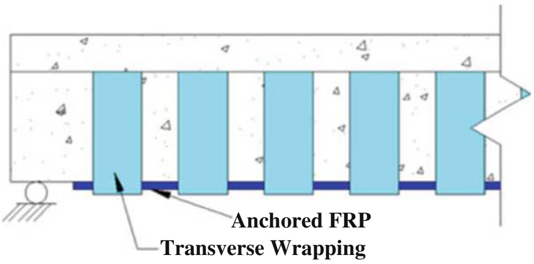
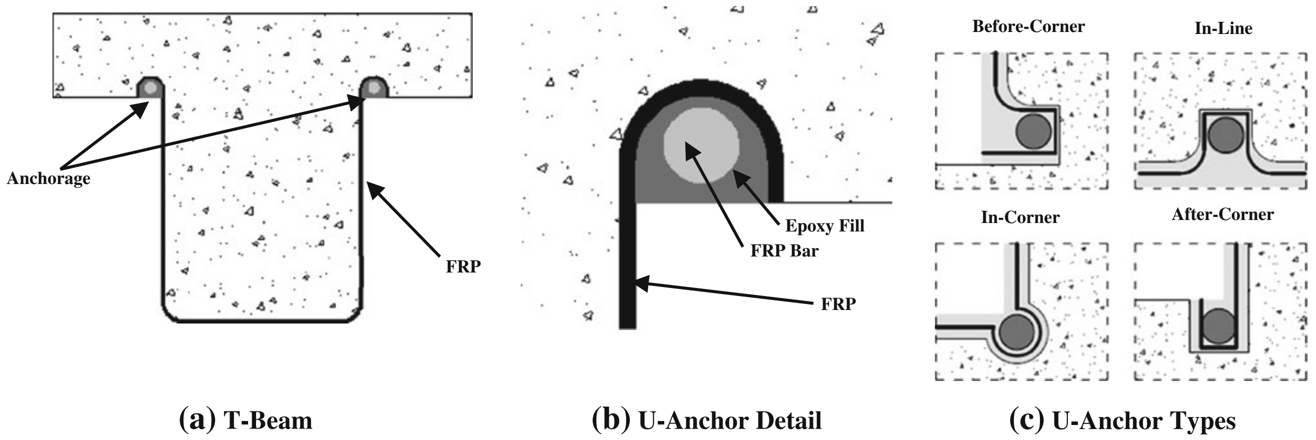


Fig. 5 Example of transverse wrapping anchorage on T-beam.

Transverse wrapping anchorage has been researched extensively, including in studies by Grace et al. (2000), Spadea et al. (2001), Sagawa et al. (2001), Shahrooz et al. (2002), Antonopoulos and Triantafillou (2003), Sawada et al. (2003), Kotynia (2005), Pham and Al-Mahaidi (2006), Al-Amery and Al-Mahaidi (2006), Orton (2007), Yalim et al. (2008), Zhuo et al. (2009), Khan and Ayub (2010), Pan et al. (2010), Sadeghian et al. (2010), and Aiello and Ombres (2011). Antonopoulos and Triantafillou (2003) utilized transverse wrapping of FRP used to reinforce RC beam-column joints in flexure and shear; this anchorage was noted to have substantially increased the effectiveness of the anchored FRP. Additionally, the transverse wrapping anchorage used in this study performed significantly better than a steel angle system, which was installed over the column corners. Kotynia (2005) used U- and L-shaped transverse wrapping to strengthen RC beams and noted their effectiveness in developing a greater percentage of the underlying flexural FRP's rupture strain. U-shaped anchors reportedly allowed the flexural FRP to develop higher strains than L-anchor strips. Sadeghian et al. (2010) used transverse wrapping to anchor flexural FRP on eccentrically loaded columns. It was observed in this study that transverse wrapping anchorage could not provide confinement to the FRP on the compression face of the column where the FRP tended to debond at strain levels approaching the crushing strain of concrete. Spadea et al. (2001) used U-shaped steel plates to anchor flexural FRP reinforcement to RC beams in a manner similar to traditional transverse FRP wrapping. Bond slip failure was noted between the steel anchorage plates and the anchored FRP, but the U-shaped steel plates still provided a more ductile failure compared with a similar FRP strengthened beam without anchorage. Sagawa et al. (2001) compared the effect of wrapping fiber orientation on the response of RC beams strengthened with flexural FRP. Beams with wrapping oriented 45° relative to the beam longitudinal axis failed due to fiber rupture of the strengthening system resulting in a



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

Fig. 6 Schematic of typical U-Anchor (Grelle and Sneed 2011).

higher peak load compared with a beam with wrapping oriented perpendicular to the beam axis, which failed due to bond slip of flexural FRP.

Kalfat et al. (2011) noted that the debonding failure mode has been shown to change with the addition of U-shaped wrapping provided to anchor flexural FRP, in particular from concrete cover separation or plate end debonding to intermediate crack-induced interfacial debonding. As observed by Al-Amery and Al-Mahaidi (2006), transverse wrapping used to anchor flexural FRP could also contribute to the shear resistance of the strengthened member, resulting a potential change in member behavior, as well as additional tensile stresses in the transverse wrapping. This complex debonding resistance-strengthening interaction has not been investigated in detail.

4.3 U-Anchors

U-Anchors are created by first constructing a groove in the concrete surface. Ends of FRP sheets are then pressed into the grooves so that they line the groove walls. The groove is then filled with a filler material, usually consisting of epoxy and sometimes in combination with an FRP or steel bar. The U-Anchor system increases the bond of FRP to concrete by increasing the bonded area. A schematic of a typical U-Anchor is shown in Fig. 6a, b, and various arrangements of U-Anchors are shown in Fig. 6c.

Regardless of the orientation of the U-Anchor, the extension of the FRP into the groove allows the epoxy bond in the groove to transfer stress between the FRP and the concrete via interfacial shear (Type II) behavior. U-Anchors for Type II applications have been studied by Khalifa et al. (1999), Micelli et al. (2002), Ceroni et al. (2008), Beigay et al. (2010), and Petty et al. (2011). While U-Anchors can potentially be used in Type III applications, such as in studies by Teng et al. (2001) and Beigay et al. (2010), they are generally not strong enough to resist the large anchoring forces typically required in full-scale applications due to the limited bonded length of FRP within the groove as well as the need to transfer load relatively deeply into the supporting member. Careful consideration should be taken in selecting the U-Anchor arrangement, depth, and location because constructing the required groove may result in stress concentrations in the substrate or a weakened section at the groove location.

After-corner U-Anchors used by Khalifa et al. (1999) to anchor FRP shear reinforcement at T-beam flanges increased the FRP contribution to the strength by 30 % compared to the beams with unanchored FRP shear reinforcement. Ceroni et al. (2008) tested in-corner and in-line U-Anchors in an independent anchorage test; both systems experienced premature failure due to detailing difficulties, specifically when pressing the FRP into and out of the groove. Micelli et al. (2002) studied after-corner U-Anchors used to anchor FRP shear reinforcement to T-beam flanges. FRP debonding was observed, which challenges the statement made by Khalifa et al. (1999) that “the failure mode of FRP debonding is not to be considered” when using U-Anchors. Petty et al. (2011) used a modified U-Anchor system to anchor FRP shear reinforcement at the beam-to-flange connection of prestressed concrete bridge girders, noting that the groove that was cut in the concrete for the U-Anchor initiated cracking and caused premature failure of the girder.

4.4 Longitudinal Chase

A longitudinal chase is created by cutting a groove along the length of the concrete in the direction of the force in the FRP. After the groove is filled in with epoxy and, in some cases, a steel or FRP bar, the FRP sheet is bonded to the concrete and over the top of the groove. The longitudinal chase anchorage system utilizes the exceptional mechanical properties of the bonding epoxy to distribute the interfacial shear stresses to a larger area of concrete. The additional bonded area is equal to the width and twice the depth of the groove times the length of the groove. The concept was developed for use in combined shear and torsional strengthening of box girder bridge webs, but has wide applications for FRP strengthening. Longitudinal chase anchorage behaves in a similar manner to U-Anchors to increase the interfacial shear stress transfer in Type II applications, except that the chase typically extends in the direction of the force in the FRP. Details of the chase systems developed by Kalfat and Al-Mahaidi (2010) are shown

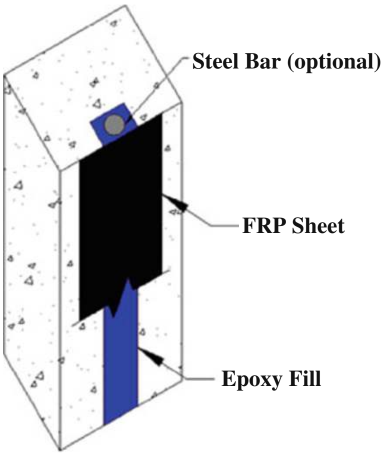


Fig. 7 Longitudinal chase anchorage used by Kalfat and Al-Mahaidi (2010).

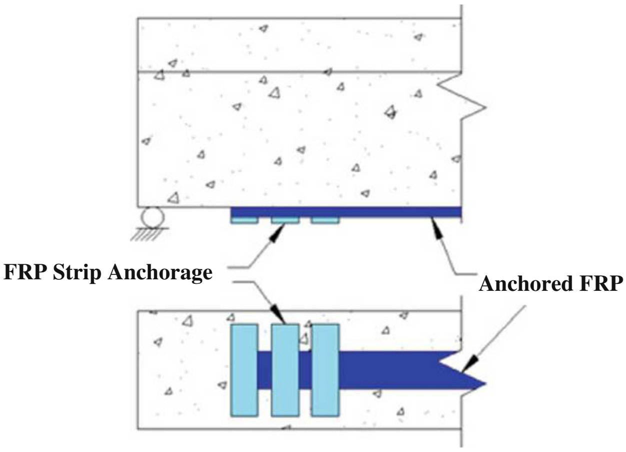


Fig. 8 FRP strip anchorage.

in Fig. 7. Kalfat and Al-Mahaidi found that exclusion of the bar from the chase system should not affect the strength of the anchorage system. Similar to U-Anchors, consideration should be taken constructing the required groove, which may result in stress concentrations in the substrate or a weakened section at the groove location.

4.5 FRP Strips

Fiber reinforced polymer strips are simple forms of anchorage installed on top of an FRP sheet used for strengthening. FRP strip anchorages are typically installed in the plane of the FRP sheet and perpendicular to the direction of force in the FRP, although in some cases, the geometry of the RC members does not allow for a right angle between the strip and strengthening sheet. While anchorage using FRP strips may seem similar to transverse wrapping, the behavior can be distinguished because the strips do not provide a clamping effect to the FRP below. Because of this, the FRP strip anchorages are loaded in directions orthogonal to the strip fibers resulting in combined Type I and Type II attributes, but limited efficiency. Despite this limitation, a major advantage to using an FRP strip anchorage system is that the anchorage and strengthening materials are the same, which facilitates construction and minimizes anchorage fabrication efforts. Additionally, the material used in FRP strips can be the same as the strengthening material. An example of FRP strip anchorages is displayed in Fig. 8.

Fiber reinforced polymer strip anchorage systems are reported to be relatively ineffective compared to other anchorage devices thus limiting the number of studies in which they are used. Because of this, the behavior of FRP strip anchorage has not been widely reported. Studies utilizing this system have been conducted by Lamothe (1998), Antonopoulos and Triantafillou (2003), Nagy-György et al. (2005), Ceroni et al. (2008), Ortega (2009), Donchev and Nabi (2010), and Petty et al. (2011), with inconsistent results. Ortega (2009) used FRP strips to anchor FRP shear reinforcement to RC and prestressed concrete girders. In all specimens tested with FRP strip anchorage, the FRP system failed by debonding of both the anchor strip and the FRP shear reinforcement. On the contrary, Petty et al. (2011) anchored FRP shear reinforcement to I-shaped girders with FRP strips and found that the FRP strip anchorage system was an effective solution considering the ease of application, consistent performance, and simplicity of design.

4.6 Plate Anchors

Metallic or composite plates have been used as a form of anchorage for FRP laminates in several studies (Aridome et al. 1998; Ceroni et al. 2008; Wu and Huang 2008; Ortega 2009; Jin and Leung 2011). It should also be noted that plate anchors have also been used as a form of anchorage for FRP plates many other studies, however, anchorage of FRP plates is beyond the scope of this paper. The reader is referred to Kalfat et al. (2011) for a discussion of studies on anchorage of FRP plates. Detailing varies between studies, but in general, the FRP sheets being anchored are bonded to the plates, which are either bolted or bonded to the concrete substrate. Details of various plated systems used are shown in Fig. 9. As with several other types of FRP anchorage systems, care must be taken to avoid potential corrosion hazards from dissimilar materials. Combined Type I and Type II behavior is likely exhibited by plate anchors depending on their construction. Because the FRP is typically bonded to the surface of the plate, shear stress is transferred at the FRP–plate interface. The plate then transfers the stress to the concrete substrate via its connection, which may consist of bolts through the plate into the concrete, or areas of the plate outside of the FRP that are glued to the concrete. In the case of bolted plate systems, the embedded bolts can provide Type I resistance to forces normal to the concrete surface, similar to that shown in Fig. 2. For instance, Type I behavior was the focus of the study by Wu and Huang (2008), who used thin steel plate anchors attached to the concrete substrate with two thin concrete nails to resist tensile normal forces associated with plate-end debonding and concrete cover separation of flexural FRP sheets. Inspection of the nailed plate anchors after failure of the specimens indicated very little lateral (shear) deformation of the nails; thus the increase in FRP bond strength provided by the anchorage system was attributed to

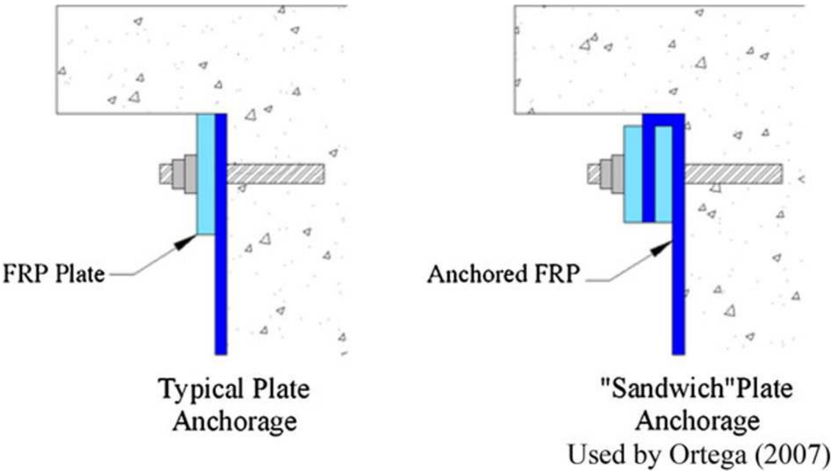


Fig. 9 Plated anchorage types.

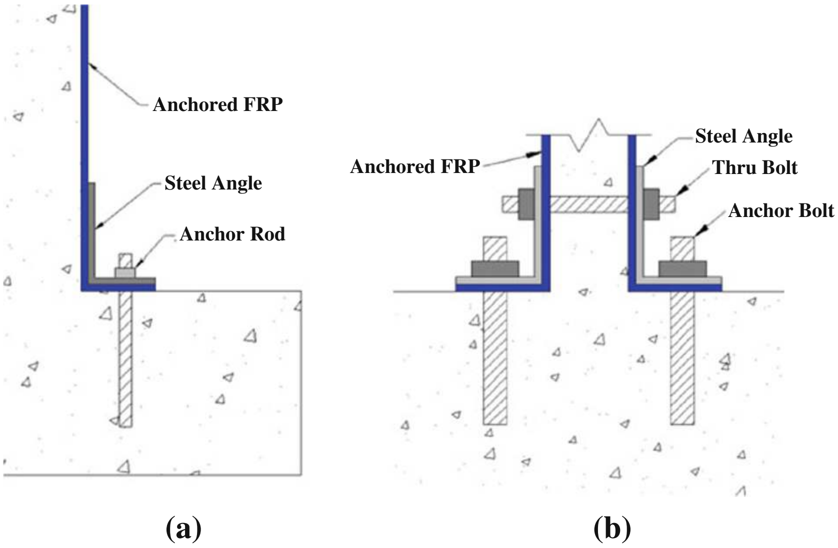


Fig. 10 Bolted angle systems.

frictional resistance from the normal pressure exerted on the FRP by the anchors.

Tests of steel and FRP plate anchors by Ceroni et al. (2008) indicated that the plates generally offered improved performance over U-Anchors and unanchored FRP on otherwise identical specimens. The study also noted that extending FRP around a reentrant corner with or without anchorage can have an adverse effect on the FRP system strength due to detailing effects, despite the perceived increase in bonded length. Ortega (2009) found that the “sandwich” plate anchorage system shown in Fig. 9 performed better than similar single plate systems.

4.7 Bolted Angles

Steel and aluminum angles have been used as FRP anchorage devices at 90° joints in several studies. Typically, the FRP is laid around the joint, the angle is bonded to the FRP in the joint, and the angle is bolted to the concrete either through or around the FRP sheet. Because steel angle shapes are easy to obtain and require little fabrication for use as an anchorage device, they have been a popular choice in literature. However, bolted angles have several limitations: first, steel angles are subject to corrosion; second, the 90° corner in the angle leads to stress concentrations in the FRP, which can cause premature failure. Bolted angle anchorages are shown in Fig. 10.

Bolted angle systems with anchor bolts through the angle leg that is perpendicular to the plane of the anchored FRP have combined Type I and Type II attributes. This type of bolted angle system was used by Tanarslan and Altin (2010) to anchor U-shaped CFRP strips for shear strengthening to the beam-slab interface on T-beams. The beams were subjected to cyclic loading of increasing magnitude. The anchorage reportedly prevented the CFRP strips from peel off allowing for an increase in shear strength relative to the unanchored condition, as well as rupture of CFRP. Direct comparison of specimens is difficult, however, since the spacing of CFRP strips was different. Bolted angles have also been used as Type III anchorage in studies by Foo et al. (2001), Hall et al. (2002), Hiotakis (2004), and Hwang et al.

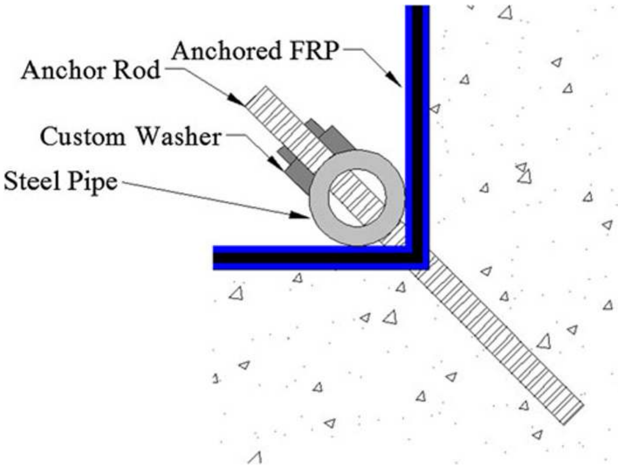


Fig. 11 CHS anchorage (adapted from Hiotakis 2004).

(2004). Hall et al. (2002) tested bolted steel angles in an independent anchorage test. When the angles contained a 90° corner, the FRP failed prematurely due to stress concentrations in the corner of the specimen, which included longitudinal, shear, and through-the-thickness stresses. To reduce the stress concentrations, an angle with a rounded corner was fabricated from steel tube and used as the anchorage, resulting in noticeable improvements in strength and ductility. Hiotakis (2004) reported that prying action caused by debonding of the FRP at the angle limited the amount of anchorage provided by the anchorage. Deifalla and Ghobarah (2010) used bolted angles to anchor CFRP used for shear and torsional strengthening to the beam-slab interface on T-beams. Various strengthening schemes were tested and compared, and anchorage was provided in each case in order to contribute to the shear flow mechanism for torsion. Thus, the influence of the anchorage system could not be isolated.

4.8 Cylindrical Hollow Section (CHS) Anchorage

Hiotakis (2004) initially studied steel angles as an alternative for anchorage devices for FRP on RC shear walls; however, due to the prying action observed, a new form of anchorage was developed. This form of anchorage, termed a CHS anchorage, is currently protected by a United States Patent. The CHS anchorage is designed specifically for Type III applications. At a 90° joint, a steel pipe is bolted through the FRP at a 45° angle in order to eliminate the potential for local stress concentrations at the 90° corner. Additionally, Hiotakis theorized that the reaction of FRP on the CHS anchorage would create a reaction along the line of the 45°-inclined anchor bolts. A schematic of the CHS anchorage is shown in Fig. 11. Although performance of the anchorage system was not described in detail, Hiotakis (2004) reported that the CHS anchorage offered improved performance over traditional bolted L-shaped angle anchorage systems.

4.9 Other Anchorage Systems

Because FRP failure is often sudden and brittle, Hall et al. (2002) found it desirable to design an anchorage system that would promote ductile failure of an FRP strengthening system for masonry shear walls. While ductile failure of the anchorage would lead to underutilization of FRP strength, the design strength of the FRP reinforcement system could be accurately and safely predicted. This ductile anchorage system consists of a structural steel plate and a cold-formed steel angle with a rounded corner. Details of this anchorage system are shown in Fig. 12. Plate thickness and distance from the face of the masonry wall were varied. The capacity of the anchorage was determined by assuming cantilever bending about the centerline of the bolts, with the tip of the rounded steel angle as the free end of a cantilever. Based on the behavior of the ductile anchorage systems, it is apparent that this system was designed specifically for Type III applications. Although the ductile anchorage system used by Hall et al. (2002) provided substantially improved performance compared to bolted angle and unanchored specimens, the ductile anchorage allowed the anchored FRP to reach only 50 % of its tensile capacity.

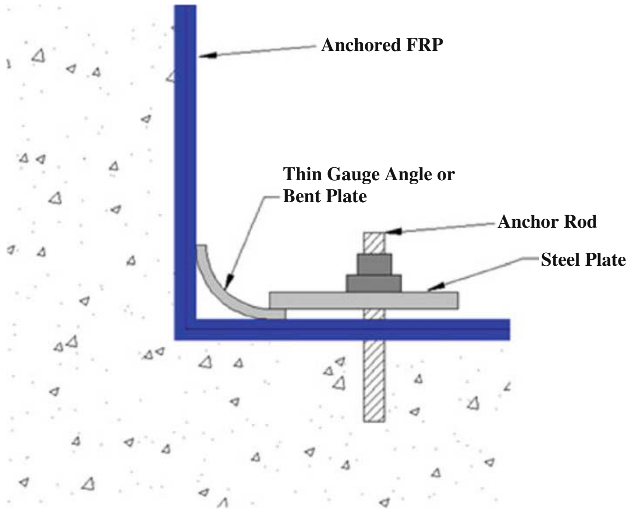


Fig. 12 Ductile anchorage system (adapted from Hall et al. 2002).

Grelle (2011) developed a Type III anchorage system based partially upon recommendations by Hiotakis (2004) and Hall et al. (2002) to anchor flexural FRP at the base of repaired columns in large-scale tests. The system, shown in Fig. 13, was fabricated by welding a quarter-pipe section to a steel plate with stiffeners between the pipe and plate, which was bolted to the adjacent footing with adhesive anchor bolts. The quarter-pipe was placed in the reentrant corner at the column-to-footing interface to anchor the flexural FRP, which was extended around the corner and onto the footing. Because a plastic hinge was expected to develop at the base of the column, the anchor bolts were placed a distance away from the column on the footing. Load and strain monitoring in the anchorage indicated that it was effective in providing a Type III force transfer mechanism. Premature failure of the anchorage system, however, was noted due to bearing of the deflected column on the anchorage and adhesive anchor failure resulting from crack development in the footing.

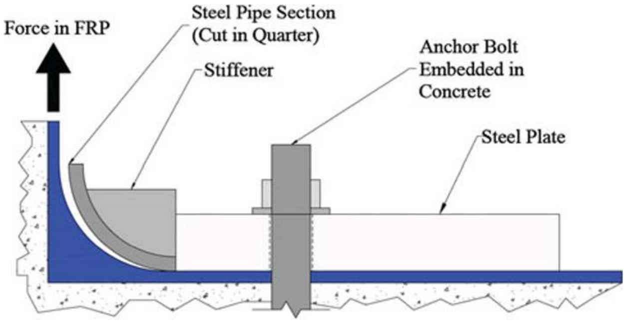


Fig. 13 Anchorage system studied in Grelle (2011).

5. FRP Anchorage System Testing

Proper anchorage testing methods are important due to the critical role they play in determining the design strength of the FRP system. Improper selection of an anchorage test method could lead to an overestimation of the strength of the anchorage system. Two general types of tests are reported in the literature: tests that include the full FRP strengthening system, and independent anchorage system tests. Data from tests that include the full FRP strengthening system, while still very useful, may have limited applicability to the general state of knowledge of a particular anchorage system because of the specificity of the application and system tested. Additionally, Kalfat et al. (2011) pointed out that it is difficult to evaluate the performance of an anchorage system from studies that do not report adequate strain data, or from tests in which the failure mode was not FRP debonding or FRP rupture. Because so few studies have reported results of independent anchorage tests, however, it is crucial that future research selects and executes these types of tests correctly. It is important to note that simplified methods of testing anchorage systems independently are certainly not a substitute for representative tests involving full FRP strengthening systems. However, simplified tests can focus on the most basic variables needed to evaluate the fundamental mechanics of anchorage behavior. This would allow for a comparison between representative testing, or tests that evaluate an FRP-strengthened structural member containing an anchorage system, and independent testing. At present, little published literature exists that correlates data from representative testing with those from independent testing. These correlations, however, are crucial for industry acceptance of new anchorage systems as a viable method to increase the design strength of an FRP strengthening system. The need for such testing is also substantiated by the requirements in ACI 440.2R (2008) that a proposed form of FRP anchorage should be "heavily scrutinized" and should undergo "representative physical testing". A diagram of the research process necessary for industry acceptance of anchorage systems is shown in Fig. 14.

The following sections discuss independent anchorage testing procedures that have been reported in literature. Additionally, the testing procedure applicability to the previously defined anchorage categories is briefly discussed.

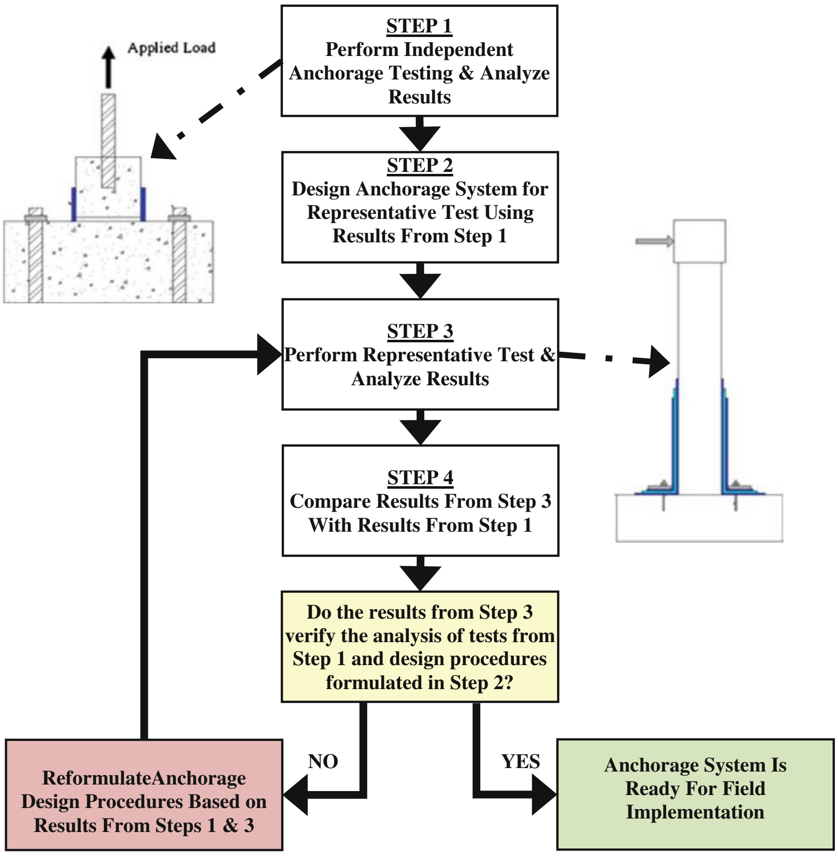


Fig. 14 Process leading to field implementation of new anchorage systems.

5.1 Direct Shear Tests

Direct shear tests include FRP that is bonded to a fixed concrete block, and tensile force is applied to the FRP. Such tests have been conducted by Spadea et al. (2001), Kalfat and Al-Mahaidi (2010), Sadone et al. (2010), Zhang et al. (2010), Niemitz et al. (2010), and Zhang and Smith (2012). Variations of this test include single-shear and double-shear tests, as well as some slight variations in test setup and specimen geometry. An advantage to direct shear tests is that the bonded length of FRP-to-concrete may be included, whereas pullout tests generally do not include the bonded FRP length. For certain anchorage applications, including a bonded length more closely simulates anchorage performance since the FRP-to-concrete bond is responsible for transferring much of the interfacial shear stress. Shear type anchorage test specimens can also be customized to simulate unique anchorage conditions, such as the 90° joint at a beam-column interface, a beam-footing interface, or the interface between a T-beam web and flange. Shear-type anchorage tests are applicable to Type II anchorage systems to study the interfacial shear debonding propagation, although combined Type I and Type II behavior might exist. Shear-type anchorage tests may also be used to measure Type I anchorage systems (associated with crack opening), although it is difficult to measure and isolate the different contributions of the combined Type I and Type II response.

Single-shear tests are the most basic test setup in this category. A single-shear test is shown in Fig. 15a. A major advantage to this test is its simplicity; because the force is applied directly to the FRP, the force in the FRP can be measured directly rather than determined indirectly from a local strain measurement or an assumed specimen behavior. Despite its simplicity, constructing a method to restrain the concrete block may provide some challenges. In addition, the test fixture should be designed so that it applies load directly and uniformly to the FRP while eliminating or minimizing eccentricity of the applied load.

Double-shear tests utilize a symmetrical system so that load application presents fewer challenges than a single-shear test. Double-shear tests have been conducted by Hall et al. (2002), Ceroni et al. (2008), Pham (2009), Sami et al. (2010), and Kalfat and Al-Mahaidi (2010). Figure 15b shows an example of a double-shear anchorage test setup. Because of the specimen's symmetry, load can be applied to an object such as a concrete block to which the FRP is attached, which is generally simpler than devising a system to apply load directly and evenly to the FRP. Limitations of this system include its demand for system stability. Since debonding of FRP is a progressive failure, the initiation of debonding does not necessarily correspond with the ultimate strength of the FRP and anchorage system. However, debonding on one side of a double-shear test leads to system instability, and further testing would produce unequal loads in each side of the anchorage specimen. In general, this would suggest that double-shear anchorage tests tend to underestimate the strength of an anchorage system. While strain measurements may be taken on each side of the specimen for comparative purposes, they cannot be considered independent since their performances are dependent on each other. Also, double-shear tests are not as materially efficient as other anchorage testing systems.

5.2 Pullout Tests

Pullout tests are the most basic form of anchorage testing. Rather than including a bonded area ahead of the anchorage system as in a shear type test, a pullout anchorage test evaluates the anchorage's ability to transfer the force in the FRP sheet or plate to the concrete in the absence of interfacial shear transfer between FRP and concrete. Thus, effects of combined Type I and Type II behavior cannot considered. Pullout anchorage tests have the fewest number of variables among any form of anchorage test. The test, however, is useful only for certain anchorage applications. Pullout tests have been conducted by Piyong et al. (2003), Eshwar et al. (2005), Huang and Chen (2005), Ozbakkaloglu and Saatcioglu (2009), and Sami et al. (2010). Various basic double-sided pull-out tests reported in the literature are shown in Fig. 15c.

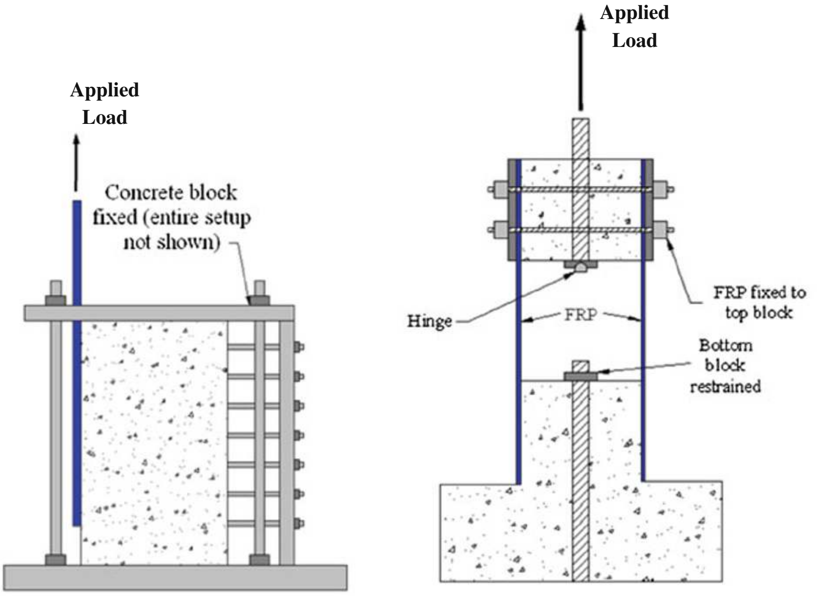
Pullout type anchorage tests are applicable to Type III anchorage systems because they can be used to evaluate the strength of the anchorage independent of the FRP bond to the concrete substrate.

5.3 Bending Tests

Bending tests have also been used to test FRP anchorages systems (Orton 2007; Pham 2009; Sami et al. 2010). Figure 15d shows a bending test setup. This type of test evaluates the interaction of the FRP strengthening system and anchorage for a strengthened beam application, which is often difficult using shear or pullout tests. Bending tests could be used to evaluate Type I, II, or III anchorage for flexural FRP. The authors are only aware of published studies in which Type I and II systems were evaluated with a bending type test.

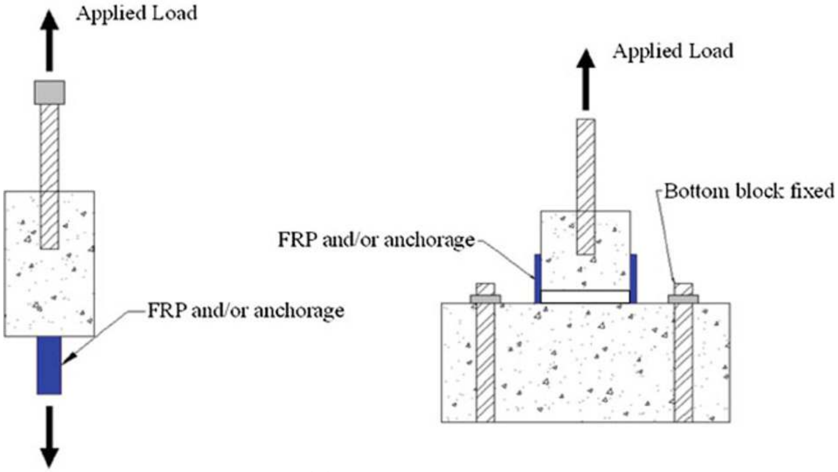
6. FRP Anchorage Design Guidelines

Few published guidelines currently exist for the design of FRP anchorage systems. While the current version of ACI 440.2R (2008) suggests that FRP performance can be improved with transverse wrapping anchorage, specific design guidelines for other types of anchorage systems are not included. Rather, the report states that "the performance of any anchorage system should be substantiated through testing." Similarly, the Italian CNR-DT 200/2004 guide (2004) states that if anchorage devices are used, the design strength must be evaluated by experimental tests that include the specific anchorage system, installation procedure, surface preparation, and expected environmental conditions. Anchorage design guidelines that have been qualified through independent testing agencies or based upon experimental data with a significant sample size do not yet exist. It

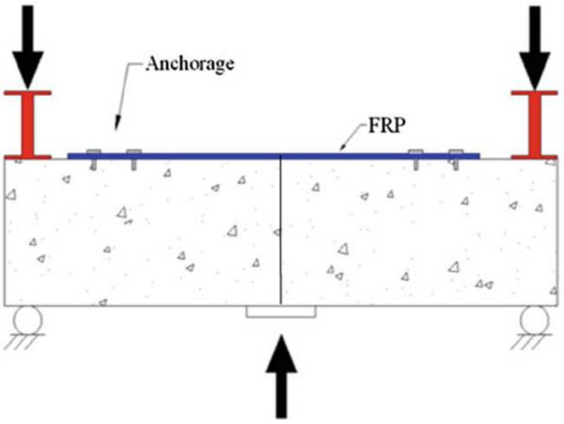


(a) **Single Shear Test (adapted from Kalfat& Al-Mahaidi 2010)**

(b) **Double Shear Test (adapted from Ceroni et al. 2008)**



(c) **Pullout Tests**



(d) **Bending Test**

Fig. 15 FRP anchorage testing types.

should be noted that while some proprietary anchorage systems have been used in practice, related design procedures have not yet contributed to the general state of knowledge for FRP anchorage.

7. Concluding Remarks

Selection of an anchorage system is certainly application driven and depends on the unique circumstances of the overall FRP strengthening system being applied to the RC structure. Despite the critical role they play in an FRP strengthening scheme, there is a general lack of extensive knowledge about the behavior of the various FRP anchorage systems. This paper synthesizes the current information on FRP anchorage systems so that engineers and researchers can work towards developing guidelines for their use. At present, an insufficient amount of testing has been performed to warrant the inclusion of anchorage behavior into current design guidelines and practices. Further, an insufficient amount of published test data exists to substantiate claims that any particular anchorage device is effective in delaying debonding or, as some researchers have suggested, preventing the debonding failure mode completely.

Because anchorage behavior is not widely understood due to lack of published data, the authors' experience suggests that some designers utilize FRP anchorage as a measure of redundancy in Type I and II applications, rather than designing the systems based on a quantifiable increase in strength or ductility. In these cases, anchorage strength may be roughly approximated or not quantified altogether. Additionally, Type III systems are seldom used due to the minimal amount of test data, especially on large-scale members, and design procedures available. Although this paper presents an extensive list of studies involving FRP anchorage systems, few of these studies focus specifically on anchorage behavior, and even fewer provide design recommendations applicable to practice. Additional research, including independent anchor tests with large sample sizes and representative tests on strengthened members that include anchorage systems, is needed before anchorage design guidelines gain industry acceptance.

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