Indian Journal of Science and Technology, *Vol 8(8), 748-756, April 2015*

ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645

Hybrid Anchor System to Eliminate End Peeling of Flexurally Strengthened Reinforced Concrete Beam

Md Ashraful Alam[1*], M. T. E. Amin[1], Mohd Zamin Jumaat[2] and Zakaria Che Muda[1]

[1]Department of Civil Engineering, Universiti Tenaga Nasional, Selangor, Malaysia
[2]Department of Civil Engineering, University of Malaya, Malaysia

Abstract

The main aim of this article is to review the existing anchor systems and to propose new technique of end anchor to eliminate premature end peeling of plate bonded flexurally strengthened reinforced concrete beam. The proposed hybrid anchor system consists of connector and anchor plate. The connector and anchor plate of hybrid anchor system would resist the interfacial shear stress and normal stress respectively, thus, it could prevent the premature end peeling and reduce the size of the anchor plate significantly.

Keywords: Connector, CFRP Laminate, End Anchors, Flexural Strengthening, Plate End Debonding, Reinforced Concrete Beam, Steel Plate

1. Introduction

The demand of retrofitting Reinforced Concrete (RC) structure has been increased because of the damage of the structures, changes of uses of structures or because of flexural deficiency of structures due to under design. Strengthening of old structures are cost effective as compared to complete replacement of the damaged or deficient structures. A significant number of research works have been conducted over last decades to strengthen RC structures using various methods such as mechanically fastened fiber reinforced polymer composite, sprayed fiber-reinforced polymer composites, near surface mounting, externally bonded steel plate and CFRP laminate[1–15]. Because of several advantages, externally bonded method using steel plate and Fiber Reinforced Polymer (FRP) laminate was found to be the most popular choice.

However, premature debonding of plates due to plate end debonding and intermediate crack induced (IC) debonding were found to be the main disadvantages of externally bonded method[1,14]. Researchers investigated that plate end debonding was most common as compared to IC debonding[2–5,14]. And it could be happened due to formation of high interfacial stresses at the end of the plate[6,14]. Thus elimination of this debonding failure is crucial to obtain the full strength and ductility of strengthened beam.

Various techniques of anchoring systems such as transverse anchors, ductile anchors, U-jacket anchors, near-surface mounted rod anchors and U and L shaped anchor plates had been proposed by past researches to mitigate end peeling[14,15,30,31]. As compared to others, end anchor with U and L-shaped wrap and plates were found to be the most effective to eliminate plate end debonding failure of flexurally strengthened RC beams[6,12–15].

Although the effect of U and L-shaped end anchors to eliminate premature debonding failure had been investigated[14], effective methods to reduce the dimension of those anchor plates are seldom found. In most of the cases, larger lengths of end anchors were provided. However, since excessive interfacial shear and normal stresses at end of the plate caused plate end debonding failure[6,14], a hybrid anchor system could be proposed to optimize the dimension of the anchor plates. The main objective of this

**Author for correspondence*

research is to review the existing anchoring system and to propose a new hybrid end anchor system to reduce the dimension of the anchor plate for preventing plate end debonding failure of flexurally strengthened RC beam.

2. Existing Methods of Strengthening

The research works have been conducted over last decades on various techniques of strengthening RC beams are summarized below:

2.1 Steel Plate Concrete Composite (SPCC)

Nie et al.[17] and Nie and Zhao had introduced SPCC technique in strengthening RC beam for cyclic load[18], as shown in Figure 1. They investigated that through this method the weight of structure could be increased a bit; however, the concrete cover and crack were not exposed at the bottom of the beam (Figure 1). Since, the plate enhanced to resist the tensile stress, the load bearing capacity and flexural stiffness of the beam could be significantly improved using SPCC technique[17,18]. Nevertheless, the corrosion of plate, high installation cost and weight of steel plate were the main drawbacks of this method.

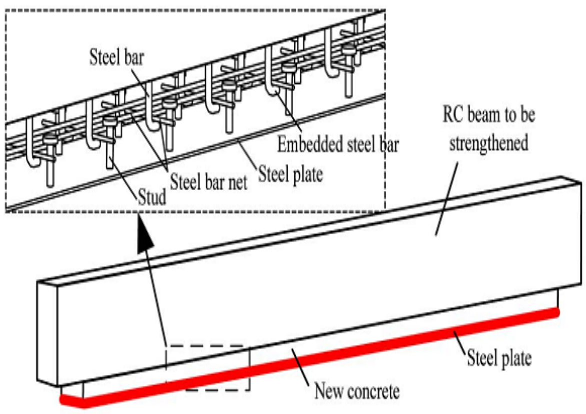

Figure 1. Alam: RC beam strengthening by SPCC technique[17].

2.2 Mechanically Fastened Fiber Reinforced Polymer Composite (MF-FRP)

MF-FRP method of strengthening was being proposed by Bank et al.[20] as shown in Figure 2. Nardone et al.[19] also proposed an analytical model that could able to predict the flexural behavior of RC structures strengthened with MF-FRP strips. The method had some advantages including high installation speed, minimal surface preparation was required to fix FRP laminate and the structure could be used immediately after strengthening. However brittle failure modes of structures, possible damage of concrete during installation of fastener and also difficulty to install fastener in presence of congested internal reinforcement were the potential shortcomings of this technique.

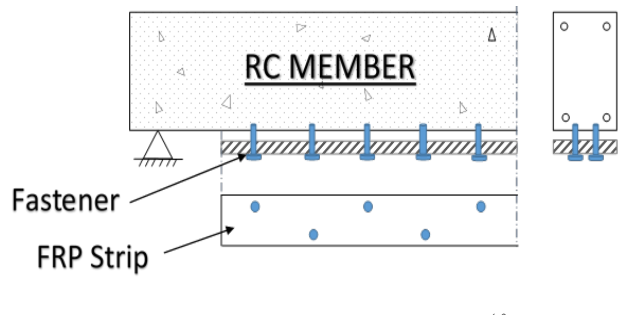

Figure 2. Alam: Fastener layout[19].

2.3 Sprayed Fiber–Reinforced Polymer Composites (SFRP)

In this method controlled length of chopped polymer matrix had been randomly sprayed on the soffit face of structure with epoxy adhesive. For the application, a spray gun with a chopper unit and epoxy containers were required. Lee and Hausmann investigated the strength and ductility of damaged and undamaged RC beams using SFRP method[21]. They concluded that SFRP was capable to increase the strength and ductility of strengthened beam substantially and the method was effective for repairing and strengthening of damaged RC beam as well.

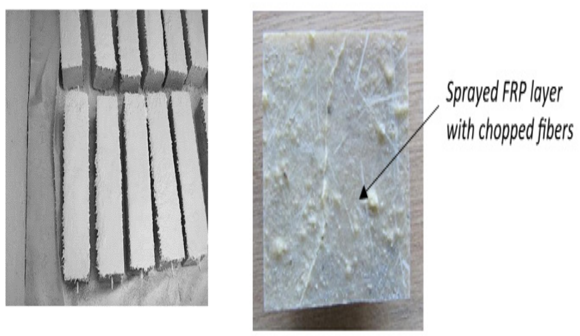

Figure 3. Alam: RC specimens after application of SFRP[21]

2.4 Near Surface Mounting (NSM)

NSM was first introduced in 1940s using steel bar to repair and strengthen structure[23]. However, because of corrosion, the steel had been replaced by CFRP and GFRP bars. In this method FRP strips were installed into opened thin grooves on concrete cover at tension region of strengthened beam as shown in Figure 4 Barros et al.[23] carried out a study on NSM strengthening technique using CFRP laminate strips. They investigated that NSM technique could increase 91% ultimate load as compared to control beam.

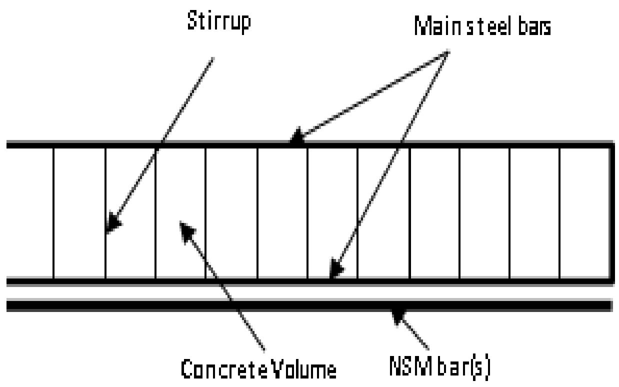

Figure 4. Alam: The position of NSM bar[24].

2.5 Discrete Fiber-Reinforced Polyuria (DFRP)

In DFRP strengthening system the fibers were sprayed rather than the traditional manual laid up of laminates[25]. Minimization of construction time due to ease of construction, provide multi-hazard benefits including mitigation of fragmentation due to blast and impact were the main advantages of this technique. Greene and Myers examined that through this method the ductility could be increased as high as 160% with various polyurea coating systems[25].

2.6 Externally Bonded Steel Plate and CFRP Laminate

Now a day externally bonded steel plate and CFRP laminates are the most practical choice. Corrosion and other disadvantages limited to use steel plate as compared to CFRP laminate[19,29,31]. In general, carbon (CFRP) and glass (GFRP) are the main fibers that are used in FRP materials. However, CFRP laminate is found to be more compatible with steel as compared to GFRP laminate. Wet lay-up using sheets and fabrics, prefabricated laminates and bars are the main types of CFRP. Superior mechanical and non-corrosive properties are the main advantages of CFRP laminate.

3. Problems Related With Plate Bonding Method

Researchers investigated that plate bonding method using CFRP laminate and steel plate is the most effective method of strengthening RC beam because of their potential advantages. However, debonding of plates and laminates is the critical issue of this method to obtain the ultimate strength of strengthened beam. The debonding could be divided into two categories i.e. plate end debonding and IC debonding. Plate end debonding originates near the end of the plate and propagates towards the concrete either along the tensile steel reinforcement (end cover separation) or along the interface of plates (end interface debond). Whereas, IC debonding originates either from a flexural crack at mid-span of beam (flexural crack debond) or an inclined flexural-shear crack at shear span of beam (shear crack debond)[14,26,28]. In general, plate end debonding is found to be more common in plate bonded method of flexural strengthened RC beam.

4. Mechanism of End Peeling

A significant number of research works have been conducted to investigate the causes of plate end debonding failure of strengthened beam. According to Smith and Teng, due to discontinuity of plate, concentrated interfacial shear and normal stresses at end of plate causes the plate end debonding failure16. The typical interfacial shear and normal stress diagram of strengthened beam proposed by Smith and Teng is shown in Figure 516. It could be seen that the shear and normal stresses are concentrated near the end of the strengthening plate. The highly concentrated shear and normal stresses cause cracks at end of the plate which initiate the debonding of flexurally strengthened plate[14]. Smith and Teng also investigated that the higher un-plated length, thicker plate and plate with high modulus of elasticity influenced to have higher interfacial shear and normal stresses at end of the plate[16]. The type of debonding also depends on the level of stress concentrations. The higher interfacial stress causes the debonding of plate at the level of internal reinforcement, otherwise, the plate would debond at concrete adhesive interface. In both cases plate end debonding failure was found to be catastrophic and brittle in nature[14].

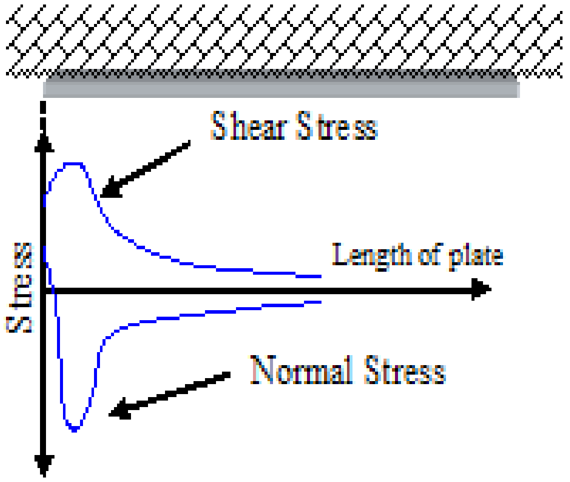

Figure 5. Alam: Shear and Normal stress[16].

5. Existing Methods of Anchoring

The present research works focus on preventing premature plate end debonding failure using various anchor systems to obtain the highest flexural capacities and ductility of strengthened beams. The existing anchor systems for strengthening of RC beams are summarized in Table 1 and the brief descriptions are shown below.

5.1 U and L Shape End Anchor

Jumaat and Alam experimented on the behavior of U and L shaped end anchors system to prevent end peeling of steel and CFRP laminate strengthened beam14. As

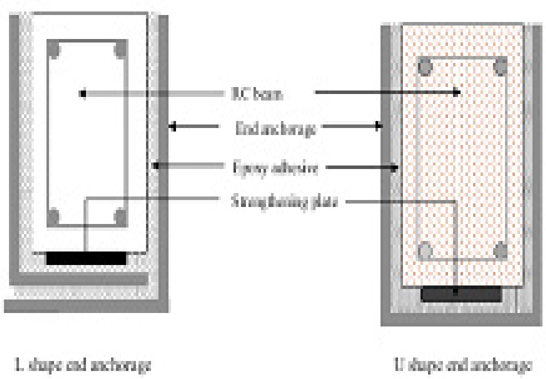

Figure 6. Alam: Details of U and L end anchors[14].

per their investigations, the side plates of U and L shaped end anchors could increase the shear strength and thus the shear crack would be minimized at end of the plates. Furthermore, the shapes of U and L end anchors clamped the beam which would reduce the cracks due to normal stress. Finally, plate debonding was prevented and it allowed the beam to fail by flexurally as per its reinforced design[14].

5.2 End-Cap Anchor

Kim et al[29] investigated a technique for replacing the steel anchors with nonmetallic anchors. They investigated the effects of this anchor on strengthened RC structures with FRP laminates. In this anchoring system, the end-cap anchor was fixed on the beam with base plate. Stiffeners were also provided to prevent local buckling of the base plate during the prestressing of the CFRP sheets. A typical stress contour is shown in the Figure 7.

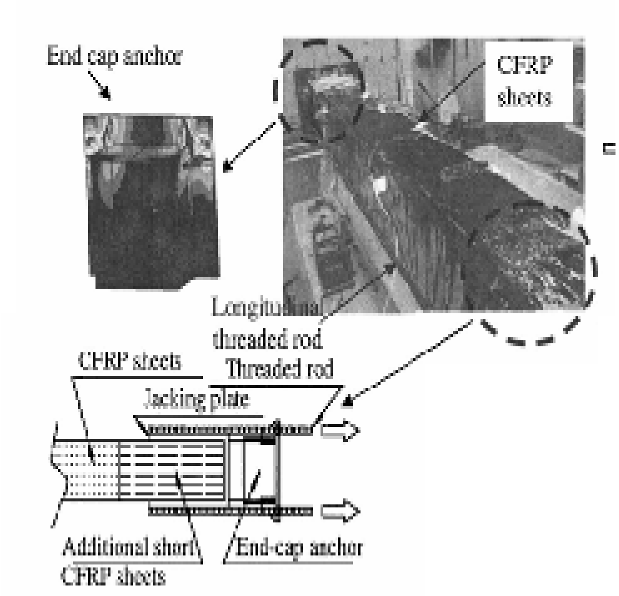

Figure 7. Alam: End cap anchor system[29].

5.3 Transverse Anchors

Transverse Anchor system is also proposed by Kim et al[29]. In this method mechanical anchors were installed using threated rod which was welded with rectangular steel plate in U-wrap strengthening system. Steel support plate was prepared to mount the lateral anchor plates with nuts. They also recommended that the lateral anchor plate could be replaced with other materials such as GFRP laminate. A typical set up of this anchor system is shown in Figure 8.

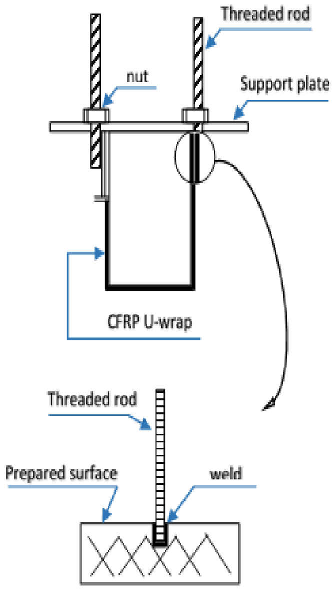

Figure 8. Alam: Transverse U-shaped anchor[29].

5.4 Ductile Anchor System

Galal and Mofidi proposed ductile anchor system for strengthening of reinforced concrete beams using CFRP sheet[30], as shown in Figure 9. The ductile anchor consisted of one steel plate, two threaded holes, one steel angle, two steel tensile link members, four high tensile threaded rods and one heavy duty Hilti bolt. The steel angle was fastened by the heavy duty Hilti bolt with 45° inclination. The two tensile links connected the angle of the steel plate using nuts. Basically, they used ductile anchor at beam column joint of strengthened beam. As per their investigations, ductile anchor had increased 27% failure load of strengthened beam as compared to control T-beam. It also enhanced the ductility of strengthened beam by increasing 91% mid-span deflection of beam than the control beam[30].

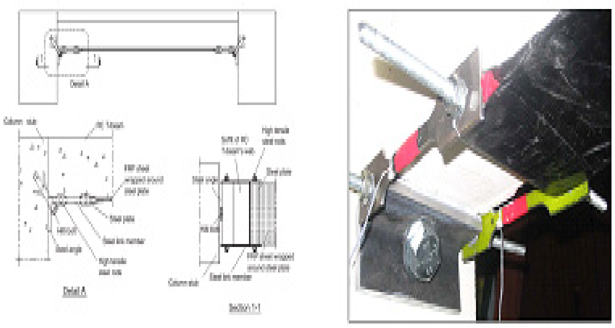

Figure 9. Alam: Hybrid FRP/ductile steel anchor system[30].

5.5 Surface-Bonded Flat Anchorage system (SBFA)

SBFA anchorage system is a new technique and very few researches has been carried out. Mofidi et al[31] applied the SBFA anchorage system for beams strengthened using the Externally Bonded (EB) method. The details of SBFA anchoring system is shown in Figure 10.

Figure 10. Alam: Elevation with surface-bonded CFRP laminate end-anchorage system[31].

5.6 Double-Aluminum-Plate Mechanical End-Anchorage System (DAMA)

Mofidi et al[31] proposed DAMA anchoring system for strengthening of reinforced concrete T beam using externally bonded fabrics. In this system, the fabrics were anchored through the beam using aluminum plates and bolts as shown in Figure 11.

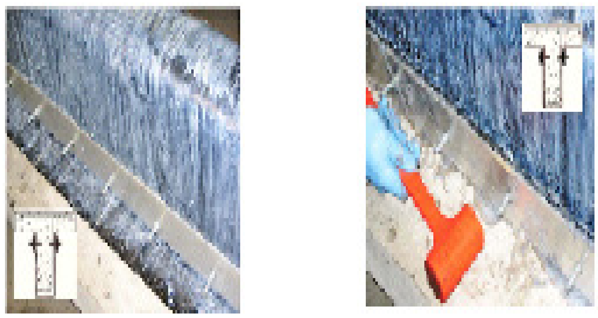

Figure 11. Alam: Elevation DAMA: (a) first aluminum plate installed; (b) second aluminum plate installed[31].

5.7 Embedded Round CFRP Bar End-Anchorage System (ERBA)

The details of ERBA anchoring system is shown in Figure 12. This anchoring system could be applied in externally bonded method of strengthening RC beam[31].

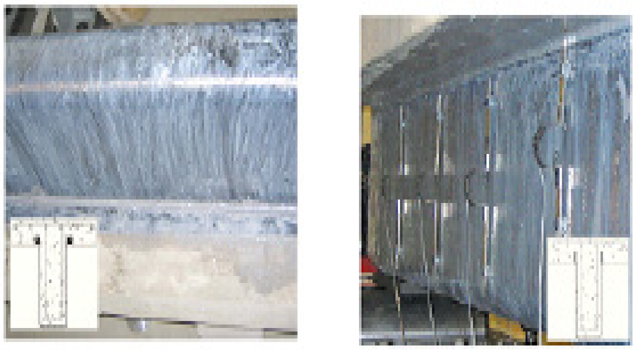

Figure 12. Alam: ERBA anchor system[31].

5.8 FRP Anchors

The FRP anchor system is a promising form of end anchors since it could be applied in various strengthening applications such as beams, slabs and walls. The FRP anchors could be referred as spike anchors, fiber anchors, fiber bolts and FRP dowels[10]. The form of spike FRP anchor is shown in Figure 13.

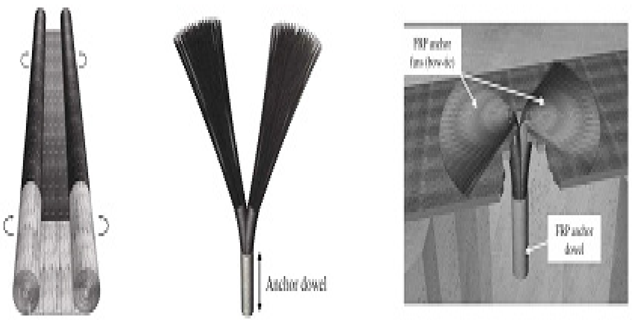

Figure 13. Alam: Spike anchor[10].

The spike FRP anchor could be simply manufactured in research laboratory or in construction site. Normally, the spike is made from loose or bundled glass fiber, carbon fiber and carbon sheet as shown in Figure 13(a). Recently Koutas and Triantafillou conducted their study on the role of spike anchors in three-sided jackets (U-jackets) of reinforced concrete T-beams, strengthened in shear[36]. Orton et al[32] reported that FRP anchors were capable to increase the efficiency of material usage up to 57%, indicating that FRPs with end anchors are able to achieve a desired strengthening capacity and require less material than unanchored FRPs. In addition, it was found that a greater number of small anchors and reduced spacing were more effective to develop the capacity of the FRP fiber. As larger spacing did not cover the entire width of the FRP, it causes partial debonding[32].

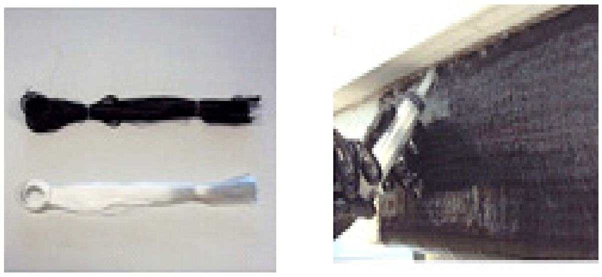

Figure 14. (a-b) Alam: The rolled sheet[10].

6. Effective Method of Anchoring

Through the analysis of exiting anchor systems, U shaped end anchor was found to be the most effective in eliminating premature plate end debonding failure[31]. The U shaped end anchors could resist interfacial shear and normal stresses significantly because of the nature of U shape of the anchor. Since the U shape anchor could prevent interfacial stresses, plate end debonding of strengthened beam could be eliminated significantly[14].

7. Proposed Method of Anchoring

Researchers investigated that basically the plate end debonding failure of strengthened beam occurred due to formation of high interfacial shear and normal stresses at end of the plate as shown in the Figure 15. Anchors would have significant effects to overcome this failure. As compared to others, end anchors with U and L shaped plates were able to prevent plate end debonding failure of flexurally strengthened RC beam completely[13].

However, the size of U and L shaped anchor plates could be reduced significantly by applying connectors together with those anchor plates as shown in Figure 16. This research is going to propose hybrid anchor system using anchor plate and embedded shear connector. In this particular system, shear connector would resist the interfacial shear stress and the anchor plate could resist the

References	Anchoring system		Strengthening Method		Mode of failure
	Type of anchor	Dimension (mm)	Material	Method	
Nie & Zhao[18]	Steel Plate Anchor system	4700 X 230	Steel plate	Steel plate composite method	Fatigue failure of the steel plate and flexural failure on the concrete.
Nardone, Lignola, Prota, Manfredi & Nanni[19]	Mechanically fastened FRP	650 X 50 X 3.2	FRP strips	Mechanically fastened fiber reinforced polymer composite	cleavage, sustained bearing, shear-out, net tension, and Pry-out failure.
Almusallam & Elsanadedy[24]	-	Ø12, Ø14, Ø16	GFRP	near-surface mounted GFRP bars	NSM rod debonding and concrete cover separation
Jumaat & Alam[14]	U and L shape end-Anchor	250 X 125 X 250, 250 X 125	Steel plate	U and L shaped end-anchorage system	Flexure
Kim, Wight & Green[29]	U-wraps	750 X 150 X 0.33	Prestressed CFRP	Non-metallic Anchor Systems	Premature debonding failure
Galal & Mofidi[30]	Ductile Anchor System	160X 40 X13	Hybrid FRP	new hybrid FRP sheet/ ductile anchor system for flexural strengthening	Concrete crushing, FRP rupture and debonding failure
Mofidi et al[31]	U-jackets end-anchor	20 X 2.5	CFRP laminate	Surface-Bonded Flat Anchorage	Shear
Mofidi et al[31]	U-jackets end-anchor		CFRP laminate	Double-aluminium-plate mechanical end-anchorage	Flexure
Mofidi et al[31]	U-jackets end-anchor	9.5	CFRP laminate	Embedded round CFRP bar end-anchorage system	Shear
Mofidi et al[31]	U-jackets end-anchor	20 X 2.5	CFRP laminate	Embedded flat CFRP laminate end-Anchorage system	Flexure

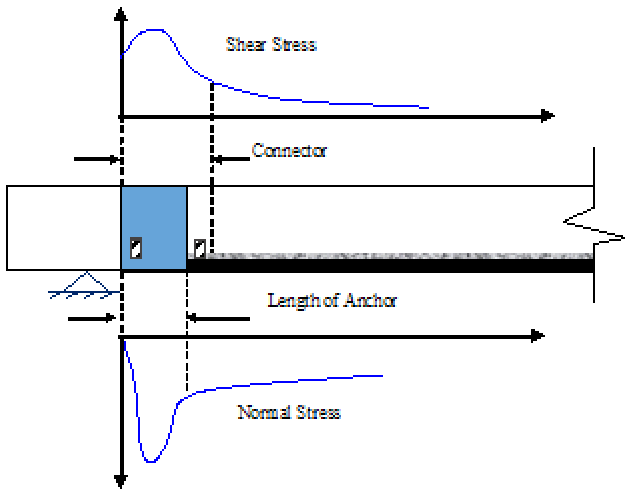

Figure 15. Alam: Hybrid anchor system calculation from shear and normal stress.

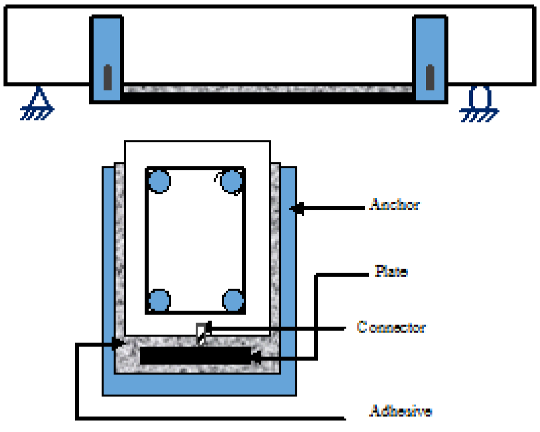

Figure 16. Alam: Proposed U-shaped hybrid anchor system with connector.

normal stress. Thus, the dimension of the plates would be significantly optimized.

8. Conclusion

Premature plate end debonding failure is the most critical point for flexural strengthening of reinforced concrete beam using externally bonded plates. U and L shaped anchor system proposed by past researchers was found to be the most effective way to prevent it. Although those anchor systems could prevent premature debonding failure, the dimension of anchor plates could not be reduced significantly by the existing method. In this article a new hybrid anchor system has been introduced to optimize the dimension of those anchor plates. As the shear and normal stresses are the main reasons for premature debonding failure, connectors could be installed to prevent the shear stress and anchors to prevent the normal stress. The combination of connector and anchor is named as hybrid anchor system which could significantly reduce the size of the anchor plates. Future research should focus on examining the effects of the proposed hybrid anchor system to reduce the dimension of those anchor plates.

9. Acknowledgement

The study was carried out at the Department of Civil Engineering, Universiti Tenaga Nasional, Malaysia under the research grant of 08012012 ERGS. The authors would like to thanks to MOHE for providing the grant to conduct the research and the Department for facilitating the study.

10. References

1. Smith ST, Teng JG. FRP-strengthened RC beams. A review of debonding strength models. Eng Struct. 2002; 24:385–95.
2. Saadatmanesh H, Malek AM. Design guidelines for flexural strengthening of RC beams with FRP plates. J Compos Construct. 1998; 2(4):158–64.
3. El-Mihilmy MT, Tedesco JW. Prediction of anchorage failure for reinforced concrete beams strengthened with fiber-reinforced polymer plates. ACI Structural Journal. 2001; 98(3):301–14.
4. Yao J, Teng JG. Plate end debonding in FRP-plated RC beams-II: strength model. Eng Struct. 2007; 29:2472–86.
5. Yang J, Ye J, Niu Z. Simplified solutions for the stress transfer in concrete beams bonded with FRP plates. J Engineering Structures. 2008; 30:533–45.
6. Bahn BY, Harichandran RS. Flexural behaviour of reinforced concrete beam strengthened with CFRP sheets and epoxy mortar. J Compos Construct. 2008; 12(4):387–95.
7. Hussain M, Sharif A, Basunbul A, Baluch MH, Al-Aulaimani GJ. Flexural behavior of precracked reinforced concrete beams strengthened externally by steel plates. ACI Structural Journal. 1995; 92(1):14–22.
8. Garden HN, Hollaway LC. An experimental study of the influence of plate end anchorage of carbon fiber composite plates used to strengthen reinforced concrete beams. J Composite Structures. 1998; 42:175–88.
9. Jones R, Swamy RN, Charif A. Plate separation and anchorage of reinforced concrete beams strengthened by

epoxy-bonded steel plates. The Structural Engineering. 1998; 66(5):85–94.
10. Smith ST, Hu S, Kim SJ, Serancino R. FRP-strengthened RC slabs anchored with FRP anchors. J Engineering Structures. 2011; 33(4):1075–87.
11. Chahrour A, Soudki K. Flexural response of reinforced concrete beams strengthened with end-anchored partially bonded carbon fiber-reinforced polymer strips. J Compos Construct. 2005; 9(2):170–7.
12. Hosny A, Abdelrahman A, Elafandy T. Performance of reinforced concrete beams strengthened by hybrid FRP laminates. J Cement and Concrete Composites. 2006; 28:906–913.
13. Ceroni F, Pecce M, Matthys S, Taerwe L. Debonding strength and anchorage devices for reinforced concrete elements strengthened with FRP sheets. J Composites, Part B. 2008; 39:429–41.
14. Jumaat MZ, Alam MA. Behaviour of U and L shaped end anchored steel plate strengthened reinforced concrete beams. Eur J Sci Res. 2008; 22(2):184–96.
15. Kim Y, Wight RG, Green MF. Flexural strengthening of RC beams with prestressed CFRP sheets: Using nonmetallic anchor system. J Compos Construct. 2008; 12(1):44–52.
16. Smith ST, Teng JG. Interfacial stresses in plated beams. Eng Struct. 2001; 23:857–71.
17. Nie J, Wang Y, Cai CS. Experimental research on fatigue behaviour of RC beams strengthened with steel plate-concrete composite technique. J Struct Eng. 2011; 137:772–81.
18. Nie JG, Zhao J. Experimental study on simply supported RC beams strengthened by steel plate-concrete composite technique. J Build Struct. 2008; 29(5):50–6.
19. Nardone F, Lignola GP, Prota A, Manfredi G, Nanni A. Modeling of flexural behaviour of RC beams strengthened with mechanically fastened FRP strips. J Composite Structures. 2011; 93:1973–85.
20. Bank LC, Oliva MG, Arora D, Borowicz DT. Rapid strengthening of reinforced concrete bridges. Wisconsin highway research program. Madison, WI: Wisconsin Department of Transportation; 2003. Report no. 03–06.
21. Lee HK, Hausmann LR. Structural repair and strengthening of damaged RC beams with sprayed FRP. J Composite Structures. 2004; 63:201–9.
22. Sena-Cruz JM, Barros JAO. Bond between near surface mounted CFRP laminate strips and concrete. J Composite Structures. 2004; 8(6):519–27.
23. Sena-Cruz JM, Barros JAO. Modelling of bond between near-surface mounted CFRP laminate strips and concrete. J Composite Structures. 2004; 82(17–19):1513–21.
24. Almusallam TH, Elsanadedy HM. Experimental and numerical investigation for the flexural strengthening of rc beams using near-surface mounted steel or GFRP bars. J Construction and Building Materials. 2013; 40:145–61.
25. Greene CE, Myers JJ. Flexural and shear behaviour of reinforced concrete members strengthened with a discrete fiber-reinforced polyurea system. J Compos Constr. 2013; 17:108–16.
26. Al-Amery R, Al-Mahaidi R. Coupled flexural–shear retrofitting of RC beams using CFRP straps. J Composite Structures. 2006; 75:457–64.
27. Sayed-Ahmed EY. Numerical investigation into strengthening steel I-section beams using CFRP strips. Proceedings Structures Congress, Structural Engineering and Public Safety; Reston, VA. ASCE; 2006.
28. Triantafillou TC. Strengthening of structures with advanced FRPs. Prog J Struct Eng Mater. 1998; 1(2):126–34.
29. Kim YJ, Wight RG, Green MF. Flexural Strengthening of RC Beams with Prestressed CFRP Sheets: Development of Non-metallic Anchor Systems. J Compos Construct. 2008; 12:35–43.
30. Galal K, Mofidi A. Strengthening RC beams in flexure using new hybrid frp sheet/ductile anchor system. J Compos Construct. 2009; 13(3):217–25.
31. Mofidi A, Chaallal O, Benmokrane B, Neale K. Performance of End-Anchorage Systems for RC Beams Strengthened in Shear with Epoxy-Bonded FRP. J Compos Construct. 2012; 16(3):22–331.
32. Orton SL, Jirsa JO, Bayrak O. Design considerations of carbon fiber anchors. J Compos Constr. 2008; 12(6):608–16.
33. Fanning PJ, Kelly O. Ultimate Response of RC Beams Strengthened with CFRP Plates. J Compos Constr. 2001; 5:122–7.
34. Hammoud RA, Soudki K, Topper TH. Fatigue flexural behaviour of corroded reinforced concrete beams repaired with CFRP sheets. J Compos Constr. 2011; 15:42–51.
35. Anania L, Badala A, Failla G. Increasing the flexural performance of RC beams strengthened with CFRP materials. J Construction and Building Materials. 2005; 19:55–61.
36. Koutas L, Triantafillou TC. Use of Anchors in Shear Strengthening of Reinforced Concrete T-Beams with FRP. J Compos Construct. 2013; 17:101–7.