First Middle East Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures
8 – 10 February 2011, Dubai, UAE

SMAR 2011

Repair of reinforced concrete bridge systems with composites

Azadeh Parvin[1], and David Brighton[1]

[1]University of Toledo, Toledo, United States

ABSTRACT: Many of the existing bridges are in need of repair and strengthening due to various reasons including design flaws, fatigue and deterioration of steel reinforcement, increase in traffic volume, and accidental impact loads during collisions between vehicles and bridge girders or piers. The use of fiber reinforced polymers (FRP) materials to repair and strengthen the deficient infrastructures has become very popular due to FRP well known advantages such as high strength-to-weight ratio, corrosion resistance, light weight, and ease of applications. This paper presents a review of existing experimental investigations of FRP shear and flexural strengthening of reinforced concrete beams. The amount of gain in flexural or shear capacities and the type of failure modes are summarized. Various forms of FRP retrofit are also discussed.

INTRODUCTION

Most bridges are inspected every 24 months and are rated based on the conditions of various bridge components. In 1996, 34.2 percent of bridges were classified as structurally deficient or functionally obsolete. By 2006, that percentage fell to 27.6 percent (United States Department of Transportation 2009). There are still many bridges in need of repair or replacement.

Deficient bridges can be caused by design flaws, deterioration due to environmental impact, increase in service loads, and accidental impacts. Design flaws can occur when engineers improperly design a structure due to poor methods of analysis and lack of experience or when contractors fail to follow the plan and procedure outlined by the engineer. Pre-1970s' buildings and bridges were constructed according to older design and failed to meet the current codes and standards. These structures can be subjected to higher live loads than they were originally designed for.

The environment can also play a devastating role on infrastructure. Natural disasters such as hurricanes, tornadoes, tsunamis, and earthquakes can damage or destroy structures in a matter of seconds. On the other hand, saltwater, deicing chemicals, and freeze-thaw cycles can cause deterioration over a longer period of time.

Accidental impact can also damage to civil infrastructure. Every year, several overheight vehicles impact the bridge girders despite the regulations and practices set in place by governing bodies to restrict such occurrences from happening. Placement of barriers and guardrails does not always protect the bridge columns from vehicular collision damage. The damage caused by such impacts can lead to concrete cover spalling or cracking, reinforcement damage or exposure, or in worse cases, structural failure. Figure 1 shows damage caused by an overheight vehicle striking a bridge girder and spalling of the concrete cover.

Figure 1. Damage caused by an overheight vehicle and spalling of concrete cover of a bridge girder.

One method of repair that has become increasingly popular in recent years is by use of FRP materials due to their excellent mechanical properties, high strength, corrosion resistance, durability, light weight, ease of application, reduced construction time, efficiency, and low life cycle cost. The earliest type of FRP material used was glass fibers embedded in polymeric resins and appeared after World War II for space exploration and air exploration (Bakis et al. 2002). In the following years, a variety of fiber materials were introduced to the market including aramid, boron, carbon, and kevlar. The repair and strengthening of reinforced concrete structures can be done through the external reinforcement using FRP strips, sheets, and plates, or by near surface mounting (NSM), FRP spraying, and FRP prestressing. In the following sections various forms of FRP applications and strengthening are discussed.

FRP sheets and strips

FRP sheets and strips consist of wide or narrow fabrics, respectively which are dipped into polymeric binder and then set into place. FRP strips are often used when FRP sheets are too difficult to place or where only a minimal amount of FRP reinforcing is needed. Numerous investigations have been performed on the retrofit of reinforced concrete members with shear and flexural deficiencies using FRP sheets and strips (Mayo et al. 1999; Bousselham and Chaallal 2006; Demers et al. 2006; Zhao et al. 2007; Mosallam and Banerjee 2007; Ibrahim and Mahmood 2009; Di Ludovico et al. 2010).

Bousselham and Chaallal (2006), Mosallam and Banerjee (2007), and Ibrahim and Mahmood (2009) conducted research on improving the shear capacity of the beams. Mayo et al. (1999), Demers et al. (2006), and Zhao et al. (2007) studies involved increasing the flexural load capacity of the beams. Di Ludovico et al. (2010) further investigated the effect of impact on beams strengthened with FRP sheets.

FRP plates

FRP plates may be pre-cured through pultrusion process. Once the concrete surface is prepared, the epoxy is applied to the plate and pressed into the concrete surface. FRP plates are often desired over the FRP sheets or strips for their ease of placement due to their rigidity. Investigations have been performed on strengthening of reinforced concrete beams with shear and flexural deficiencies using FRP plates (e.g., Stalling et al. 2000; Nanni et al. 2004).

Near surface mounting

Near surface mounting (NSM) consists of cutting a groove into the concrete surface. The groove is then filled half-way with the epoxy paste. The FRP rod is placed into the groove and the groove is then filled with more epoxy paste until the surface is leveled Nanni et al. (2004). Investigations into the retrofit of reinforced concrete members with shear and flexural deficiencies using NSM include Hassan and Rizkalla (2003), Nanni et al. (2004), Nordin and Biorn (2006), Teng et al. (2006), and Bianco et al. (2009).

Hassan and Rizkalla (2003), Teng et al. (2006), and Bianco et al. (2009) investigated the debonding failure of RC beams strengthened with NSM. Nordin and Biorn (2006) investigated the effects of prestressing with NSM bars. Nanni et al. (2004) studied the shear strengthening of beams with NSM.

Sprayed FRP

Sprayed FRP consists of a discontinuous fiber material encapsulated by a polymeric matrix resin. The biggest advantage for sprayed FRP is the simplicity of its application. The FRP is applied with a spray or chopper gun system. A better bond between the fiber and polymer is achieved, since the matrix resin also acts as the bonding agent between the concrete and FRP. The epoxy used for this kind of application has lower viscosity which allows for better penetration into the voids on the substrate surface Boyd et al. (2008). Recently, investigations have been performed on the retrofit of reinforced concrete beams with shear and flexural deficiencies using sprayed FRP (e.g., Lee and Hausmann 2004; Boyd et al. 2008).

FRP prestressing

Prestressing of FRP sheets has many benefits including the effective use of tensile strength, active load-carrying mechanism, enhanced durability and serviceability, effective stress redistribution of existing reinforcement, and improved shear and flexural capacities (Meier 1995; El-Hacha et al. 2001; Wight et al. 2001; Kim et al. 2005). The application of prestressed FRP can become more cumbersome due to the required anchoring system needed to maintain the prestressing in the FRP. Numerous investigations have been performed on the retrofit of reinforced concrete members with shear and flexural deficiencies using FRP prestressing (Meier 1995; El-Hacha et al. 2001; Wight et al. 2001; Kim et al 2005; Kim et al. 2008). The studies by Kim et al. (2005), and Kim et al. (2008) also involved the anchoring techniques of FRP prestressing, and the effects of FRP prestressing on the damaged girders due to impact loading, respectively.

Flexural Strengthening of Beams

Traditional methods of flexural repair for the beams include external post-tensioning, splicing of internal strands, and steel jacketing. These methods often only restore a portion of the ultimate capacity of the damaged member and are left vulnerable to corrosion (Di Ludovico et al. 2010).

In recent years FRP-strengthening has become an increasingly popular alternative to the traditional methods of repair.

Flexural failure of FRP-retrofitted beams is controlled by two primary failure modes. The first type of failure is due to the crushing of the concrete in the compression zone prior to the attainment of ultimate tensile strain in the outermost FRP layer. This occurs in sections with large amount of FRP reinforcement. Failure by FRP rupture occurs when sections have smaller amount of FRP reinforcement. Failure by concrete crushing is desired due to greater deformability which leads to a more gradual mode of failure (Bakis et al. 2002). A summary of some recent studies on the flexural strengthening of beams are presented in Table 1.

Table 1. Summary of research on flexural strengthening of beams

Authors	Specimen ID	Retrofit	Displacement	Increase in load (kN)	Failure mode
Di Ludovico et al. 2010	S4	CFRP	----	152	FRP debond
	S5	CFRP	----	195	FRP debond
Boyd et al. 2008	1	GFRP	----	198	Flexure
Zhao et al. 2007	B1	CFRP	----	53	Peeling
	B2	CFRP	----	60	Peeling
	B3	CFRP	----	79	FRP debond
	B4	CFRP	----	94	Peeling
	B5	CFRP	----	79	Peeling
	B6	CFRP	----	77	Peeling
Demers et al. 2006	1	GFRP	11 mm	----	FRP Pull-out
	2	GFRP	11 mm	----	FRP Pull-out
	3	GFRP	17 mm	----	FRP Pull-out
	4	GFRP	19 mm	----	FRP Pull-out
	5	GFRP	15 mm	----	FRP Pull-out
	6	GFRP	22 mm	----	FRP Pull-out
Wight et al. 2001	B	CFRP	46%	105	FRP debond
	C	CFRP	63%	135	FRP rupture
	D	CFRP	59%	110	FRP rupture
Stallings et al. 2000	1	CFRP & GFRP	8%	----	----
	2	CFRP & GFRP	7%	----	----
	3	CFRP & GFRP	11%	----	----
	4	CFRP & GFRP	12%	----	----
Mayo et al. 1999	1	CFRP		50	FRP rupture

Shear Strengthening of Beams

Traditional methods of retrofit for the beam shear strengthening may involve steel or concrete jacketing. In most scenarios, beams requiring shear strengthening were often replaced. The shear capacity can be improved by partial or full FRP wrapping of the beam in the lateral direction. The FRP is bonded to beam with the fibers as parallel as possible to the principal tensile stresses.

There are two main modes of failure for FRP-retrofitted beams; debonding of the FRP from the concrete surface, or tensile rupture of the FRP sheet at stresses lower than the FRP tensile strength. This happens due to stress concentrations at the debonded areas or rounded corners. The mode of failure depends on the wrapping scheme, anchorage length and system, bond condition, axial rigidity of the FRP, strength of the concrete, and method of attachment (Bakis et al. 2002). Table 2 provides a summary of recent available studies on shear strengthening of the beams.

Table 2. Summary of research on shear strengthening of beams

Authors	Test	Retrofit	Increase in load (kN)	Failure mode
Ahmed et al. 2010	SC-9.5-2	CFRP	104	FRP stirrup rupture
	SC-9.5-3	CFRP	168	FRP stirrup rupture
	SC-9.5-4	CFRP	264	Flexure
Ibrahim & Mahmood 2009	B1C-90	CFRP	56	----
	B1G-90	GFRP	47	----
	B2C-90	CFRP	19	----
	B2C-90-0	CFRP	29	----
Mosallam & Banerjee 2007	B20R	CFRP	56	Flexure
	B21R	GFRP	37	Flexure
	B22R	CFRP	44	Shear failure
	B5	CFRP	66	Flexure
	B3	GFRP	52	Shear
	B19	CFRP	41	Shear
Bousselham & Chaallal 2006	DB-S0-0.5L	CFRP	108	Shear
	DB-S0-1L	CFRP	129	Shear
	DB-S0-2L	CFRP	133	Shear
	DB-S1-1L	CFRP	38	Shear
	DB-S1-2L	CFRP	41	Shear
	DB-S2-1L	CFRP	69	Shear
	DB-S2-2L	CFRP	88	Shear
	SB-S0-0.5L	CFRP	32	Shear
	SB-S0-1L	CFRP	59	Shear
	SB-S0-2L	CFRP	61	Shear
	SB-S1-0.5L	CFRP	29	Shear
	SB-S1-1L	CFRP	-12	Shear
	SB-S1-2L	CFRP	6	Shear
	SB-S2-1L	CFRP	22	Flexure
	SB-S2-2L	CFRP	3	Flexure
Nanni et al. 2004	S2	CFRP	30	Shear
	S3	CFRP	32	FRP rupture

Shear and Flexural Strengthening of Beams Subjected to Impact Loading

Every year, several vehicles with overheight loads impact bridge structures, despite the regulations and practices set in place by governing bodies to restrict such occurrences from happening. The damage caused by such impacts can lead to concrete spalling or cracking, reinforcement damage or exposure, girder misalignment, connection failure or in worse cases structure failure (Boyd et al. 2008). FRP repair can be more economical than traditional methods, especially when the time and installation costs of the repair system are drastically reduced (Di Ludovico et al. 2010).

Limited studies have been reported on FRP-strengthening of beams subjected to impact loads (see Table 3).

Table 3 Summary of research on FRP-retrofitted beams subjected to impact loading

Authors	Specimen ID	Type of test	Retrofit	Displacement	Increase in load (kN)	Failure mode
Di Ludovico et al. 2010	S4	Flexure	CFRP	----	152	FRP debonding
	S5	Flexure	CFRP	----	195	FRP debonding
Boyd et al. 2008	1	Flexure	GFRP	----	198	Flexural
Kim et al. 2008	1	Flexure	CFRP	6.30%	----	----

CONCLUSIONS

This paper involves a review of recent experimental research on FRP retrofit of reinforced concrete beams. The existing studies have shown that the use of FRP materials improves the member original design strength and can even carry an increased live load that it was not designed for. With the increased demand in the field applications and development of additional design standards, the FRP materials will continue to grow in popularity for the retrofit of structures due to their excellent properties and durability. Furthermore, considerable savings can be achieved due to low maintenance and life cycle costs.

REFERENCES

Ahmed, EA, El-Salakawy, EF, and Benmokrane, B. 2010. Shear performance of RC bridge girders reinforced with carbon FRP stirrups. Journal of Bridge Engineering, ASCE, 15(1): 44-54.

Bakis, CE, Bank, LC, Brown, VL, Cosenza, E, Davalos, JF, Lesko, JJ, Machida, A., Rizkalla, SH, and Triantafillou, TC. 2002. Fiber-reinforced polymer composites for construction state-of-the-art review. Journal of Composites for Construction, ASCE, 6(2): 73-87.

Bianco, V, Barros JAO, and Monti, G. 2009. Bond model of NSM-FRP strips in the context of the shear strengthening of RC beams. Journal of Structural Engineering, 135(6): 619-31.

Bousselham, A and Chaallal, O. 2006. Behavior of reinforced concrete T-beams strengthened in shear with carbon fiber-reinforced polymer-an experimental study. ACI Structural Journal, 103.3: 339-47.

Boyd, AJ, Liang, NF, Green, PS, and Lammert, K. 2008. Sprayed FRP repair of simulated impact in prestressed concrete girders. Construction and Building Materials, 22(3): 411-16.

Demers, M., Labossiere, P, and Mercier, C. 2006. Glass FRP jacketing of prestressed concrete beams, 7th International Conference on Short and Medium Span Bridges. University of Sherbrook, Canada, Web. May 2010.<http://www.docstoc.com/docs/20097711/GLASS-FRP-JACKETING-OF-PRESTRESSED-CONCRETE-BEAMS/>.

Di Ludovico, M, Prota, A, Manfredi, G. and Cosenza, E. 2010. FRP strengthening of full-scale PC girders. Journal of Composites for Construction, ASCE.

El-Hacha, R, Wight, RG, and Green, MF. 2001. Prestressed fibre-reinforced polymer laminates for strengthening structures. Progress in Structural Engineering and Materials, 3(2): 111-21.

Florida Department of Transportation. Rep. no. BC354-55. Web. May 2010.
<http://www.dot.state.fl.us/researchcenter/Completed_Proj/Summary_STR/FDOT_BC354_55_1.pdf>.

Hassan, T, and Rizkalla, S. 2003. Investigation of bond in concrete structures strengthened with near surface mounted carbon fiber reinforced polymer strips, Journal of Composites for Construction, ASCE, 7(3): 248-57.

Ibrahim, AM, and Mahmood, MS. 2009. Finite element modeling of reinforced concrete beams strengthened with FRP laminates. European Journal of Scientific Research, 30(4): 526-41.

Kim, YJ, Bizindavyi, L, Wight, RG, and Green, MF. 2005. Anchoring techniques for strengthening reinforced concrete beams with prestressed CFRP sheets. 3rd International Conference on Construction Materials (ConMat05) _CD-ROM_, Vancouver, B.C., Canada.

Lee, HK, and Hausmann, LR. 2004. Structural repair and strengthening of damaged RC beams with sprayed FRP. Composite Structures, 63: 201-09.

Mayo, R, Nanni, A, Gold, W, and Barker, M. 1999. Strengthening of bridge G270 with externally-bonded CFRP reinforcement. SP-188, American Concrete Institute, Proc., 4th International Symposium on FRP for Reinforcement of Concrete Structures (FRPRCS4), Baltimore, MD, 429-40.

Meier, U. 1995. Strengthening of structures using carbon fibre/epoxy composites. Construction and Building Materials, 9(6): 341-51.

Mosallam, AS, and Banerjee, S. 2007. Shear enhancement of reinforced concrete beams strengthened with FRP composite laminates. Composites Part B: Engineering, 38(5-6): 781-93.

Nanni, A, DiLudovico, M, and Parretti, R. 2004. Shear strengthening of a PC bridge girder with NSM CFRP rectangular bars. Advances in Structural Engineering, 7(4): 97-109.

Hakan, N, and Talisten, B. 2006. Concrete beams strengthened with prestressed near surface mounted CFRP, Journal of Composites for Construction, ASCE, 10(1): 60-68.

Stallings, JM, Tedesco, JW, El-Mihilmy, M, and McCauley, M. 2000. Field performance of FRP bridge repairs. Journal of Bridge Engineering, ASCE, 5(2): 107-13.

Tang, T, and Saadatmanesh, M. 2005. Analytical and experimental studies of fiber-reinforced polymer-strengthened concrete beams under impact loading. ACI Structural Journal, 102(1): 139-49.

Teng, JG, De Lorenzis, L, Wang, B, Li, R, Wong, TN, and Lam, L. 2006. Debonding failures of RC beams strengthened with near surface mounted CFRP strips. Journal of Composites for Construction, ASCE, 10(2): 92-105.

U.S. Department of Transportation Federal Highway Administration, 2009. 2008 Status of the nation's highways, bridges, and transit: conditions and performance. <www.fhwa.dot.gov/policy/2008cpr/es.htm#c3a>.

Wight, RG, Green, MF, and Erki, MA. 2001. Prestressed FRP sheets for post strengthening reinforced concrete beams. Journal of Composites for Construction, ASCE, 5(4): 214-20.

Zhao, M, Dong, Y, Zhao, Y, Tennant, A, and Ansari, F. 2007. Monitoring of bond in FRP retrofitted concrete structures. Journal of Intelligent Material Systems and Structures, 18(8): 853-60.