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Columns strengthening by composites

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ABSTRACT: The addition of FRP materials to upgrade the deficiencies or to strengthen the structural components prior to collapse can save lives and reduce the damage to infrastructure, and the need for their costly replacement. The retrofit with the FRP materials with desirable properties provides an excellent replacement for traditional materials including steel jacket to strengthen the reinforced concrete structural members. The present paper provides a review of some of the progress in the area of FRP-strengthening of columns for several loading scenarios including impact load. The existing studies have shown that the use of FRP materials restore or improve the member original design strength and in some cases allow the structure to carry an increased load that it was not designed for. It was also concluded that there is a need for additional research on the columns under impact load. The compiled information will prepare the ground work for further evaluation of FRP-strengthening of columns that are deficient in design or are in serious need for repair due to additional load or deterioration.

1 INTRODUCTION

Natural disasters such as hurricanes, tornadoes, tsunamis, and earthquakes and accidental impacts can damage or destroy deficient structures in a matter of seconds. On the other hand, the saltwater, deicing chemicals, and freeze-thaw cycles can cause structural deterioration over a longer period of time. Majority of older buildings and bridges were constructed according to older design codes. These structures are vulnerable during extreme events and need to be retrofitted to meet the current codes and standards.

Traditional retrofit techniques include concrete and steel jacketing. These methods are time consuming and labor intensive. They also increase the cross-sectional area of the member. One popular method of repair is the use of fiber reinforced polymers (FRP) because of their excellent mechanical properties, high strength, corrosion resistance, durability, light weight, ease of application, reduced construction time, efficiency, and low life cycle cost (Ibrahim and Mahmood 2009; Stallings et al. 2000).

2 STRENGTHENING OF COLUMNS

The repair and strengthening of reinforced concrete columns includes external FRP wrapping, FRP encasement, and FRP spraying. Columns can be strengthened to increase the axial, shear, and flexural capacities for a variety of reasons such as lack of confinement, eccentric loading, seismic loading, accidental impacts, and corrosion. In the following sections, these topics are discussed in further detail.

2.1 *FRP confinement of columns*

FRP sheets or encasement can be used to increase the axial load carrying capacity of the column with minimal increase in the cross-sectional area. Confinement consists of wrapping the column with FRP sheets, prefabricated jacketing, or in situ cured sheets with fiber running in circumferential direction. The use of confinement increases the lateral pressure on the member which results in more ductility and higher load capacity. Confinement is less effective for rectangular than circular shape RC columns due to the confining stresses that are transmitted to the concrete at the four corners of the cross-section. The confinement effectiveness improves with the increase in the corner radius (Bakis et al. 2002). Recent studies (Wu et al. 2009; Matthys et al. 2006; Toutanji et al. 2010) show that FRP materials can be used to effectively increase the load carrying capacity of columns under axial loading. Examples of experimental data on the effect of FRP strengthening of axially loaded columns are shown in Table 1. The range of increase in axial load capacities of the columns varies from 6 to 176 %. The increase depends on several variables including the properties and the amount of FRP reinforcement, concrete strength, and axial load level.

Table 1. Representative experimental data on FRP-retrofitted axially loaded columns

Authors	Test ID	Retrofit	Increase in Load (%)	Failure Mode
Toutanji et al. 2010	K9	CFRP	14.89	FRP fracture
	K10	CFRP	8.51	FRP fracture
	K11	CFRP	6.38	FRP fracture
Wu et al. 2009	L-C-1	AFRP	68.55	FRP fracture
	L-C-2	AFRP	176.74	FRP fracture
	L-D-1	AFRP	2.02	FRP fracture
	L-D-2	AFRP	30.54	FRP fracture
	L-D-3	AFRP	61.21	FRP fracture
	M-C-1	AFRP	50.74	FRP fracture
	M-C-2	AFRP	112.80	FRP fracture
	M-C-3	AFRP	136.66	FRP fracture
	M-D-1	AFRP	6.76	FRP fracture
	M-D-2	AFRP	19.55	FRP fracture
	M-D-3	AFRP	29.44	FRP fracture
	H-C-1	AFRP	21.83	FRP fracture
	H-C-2	AFRP	52.15	FRP fracture
	H-C-3	AFRP	102.12	FRP fracture
	H-D-1	AFRP	-0.18	FRP fracture
	H-D-2	AFRP	14.78	FRP fracture
	H-D-3	AFRP	9.98	FRP fracture
Matthys et al. 2006	K2	CFRP	59.23	FRP fracture
	K3	CFRP	59.87	FRP fracture
	K4	GFRP	61.79	FRP fracture
	K5	GFRP	13.66	FRP fracture
	K8	CFRP/GFRP	32.98	FRP fracture

2.2 *Strengthening of columns subjected to eccentric axial load*

In field applications, most columns are not under perfect concentric loading. This produces a nonuniform confining stress due to the strain gradient which in turn reduces the effectiveness of the column (Parvin and Wang 2001). Recently, research has been conducted on the eccentric axial loaded column retrofitted with FRP sheets. Parvin and Wang 2001 studied the effects of the jacket thickness and various eccentricities on the CFRP-retrofitted columns. El Maaddawy (2009) examined the effect of eccentricity to section height ratio on the confinement of axially loaded columns. Yi et al. (2006) conducted experiments on FRP-retrofitted columns with various fiber orientations. Li and Hadi (2003) and Hadi (2006) evaluated the effectiveness of CFRP and GFRP sheets on high and normal strength strength concrete, respectively. Hadi (2007) compared the effectiveness of CFRP and GFRP-retrofitted columns to steel jacketed columns. Examples of data obtained in research conducted on eccentrically loaded columns are shown in Table 2. Again, the FRP retrofit clearly enhanced the capacity of eccentrically loaded columns as compared to as-built columns.

Table 2. Representative data on FRP-retrofitted eccentrically loaded columns

Authors	Test	Retrofit	Eccentricity (mm)	Increase in load (%)
Hadi 2007	G0	GFRP	50	11.94
	G1	GFRP	50	38.82
	G3	GFRP	50	57.84
	C0	CFRP	50	55.11
	C1	CFRP	50	109.42
	C3	CFRP	50	124.64
Hadi 2006	C2	CFRP	42.5	7.35
	C3	CFRP	42.5	4.99
	C4	CFRP	42.5	-1.84
	C6	CFRP	42.5	22.57
Parvin and Wang 2001	C11	CFRP	7.6	44.40
	C21	CFRP	7.6	79.00
	C12	CFRP	15.2	47.87
	C22	CFRP	15.2	80.98
El Maaddawy 2009	FW-e1	CFRP	37.5	37.21
	FW-e2	CFRP	54	24.24
	FW-e3	CFRP	71	8.28
	FW-e4	CFRP	107.5	3.26
	PW-e1	CFRP	37.5	27.91
	PW-e2	CFRP	54	21.21
	PW-e3	CFRP	71	3.45
	PW-e4	CFRP	107.5	1.09
Yi et al. 2006	C10L-1	CFRP	175	5.00
	C01L-1	CFRP	175	6.70
	C01S-1	CFRP	35	7.70
	C02S-1	CFRP	35	13.30
	C10L-3	CFRP	175	13.40
	C01L-3	CFRP	175	4.60
	C20L-3	CFRP	175	22.00
	C11L-3	CFRP	175	21.00

2.3 Strengthening of columns subjected to impact loads

With consistently increasing traffic in recent years, vehicular collisions with bridge columns have become more of a prevalent issue (Parvin and Kulikowski 2011). Vehicles often strike columns or piers despite the measures put in place such as guardrails and barriers. Such impacts can lead to concrete spalling or cracking, reinforcement damage or exposure, girder misalignment, connection failure or in worst cases structure failure (Boyd et al. 2008). Most column designs account for static loading only, while an impact load due to a vehicle collision is highly dynamic. There are certainly many existing bridges that could be deficiently designed in the case of vehicular impact. Several studies have been conducted concerning the dynamic effects of a high impact vehicle collision with bridge piers and columns (El-Tawil et al 2005; Ferrier and Hamelin 2005; Tsang and Lam 2008; Thilakarathna et al 2010). FRP retrofit can offer a quick and economical repair as compared to traditional methods. However, studies looking into the FRP retrofit of columns for impact loads are extremely limited. Ferrier and Hamelin (2005) performed experimental investigation on as-built and CFRP-strengthened RC beams and columns. The specimens were subjected to static and dynamic impact loads. For the static load tests that were conducted on three RC beams, the ultimate load of the CFRP-strengthened specimen was 62 % higher than the as-built specimen. In the dynamic test, it was observed that the CFRP-strengthened RC column load capacity was 88% higher than an as-built specimen. Through both static and dynamic tests, it was found that the use of CFRP material significantly increased the strength of RC columns under impact loading.

2.4 Strengthening of columns subjected to seismic loads

Reinforced concrete structures built prior to the modern day design codes may have been insufficiently designed to survive a severe earthquake. Numerous studies involve the FRP retrofit of reinforced concrete columns for seismic loads. Gu et al. (2010) investigated the effects of the FRP reinforcement length on the plastic hinge region and the drift capacity of FRP-retrofitted columns. Lacobucci et al. (2003) examined the increase in the ductility and energy dissipation capacities of FRP-retrofitted reinforced concrete columns. Wu et al. (2008) studied a new method of retrofitting square or rectangular reinforced concrete columns by embedding reinforcement bars into the plastic hinge zone to increase the ductility of the concrete in this region.

2.5 Strengthening of columns subjected to corrosion

Reinforced concrete columns are susceptible to corrosion from marine environments, fire, and deicing agents. FRP retrofitting of a reinforced concrete column involves jacketing the column with the FRP material and filling the voids between the jacket and the concrete surface with conventional or expansive grout (Pantazopoulou et al. 2001). In their study various types of diffusion barriers to protect GFRP-retrofitted columns were investigated. Tastani and Pantazopoulou (2004) examined the jacket characteristics and the repair method. Bae and Belarbi (2009) studied the effectiveness of CFRP sheet in protecting the RC columns from corrosion of the steel reinforcement. The research has shown that FRP retrofit was a practical alternative to conventional methods due to its superior performance in enhancing the strength and ductility of RC columns. Performance was markedly improved by increasing the number of FRP layers and by providing sufficient anchorage for each layer (Pantazopoulou et al. 2001; Tastani and Pantazopoulou 2004). FRP are very efficient as repair materials which can also decrease the rate of corrosion (Tastani and Pantazopoulou 2004; Bae and Belarbi 2009).

2.6 Field application projects related to FRP repaired columns

Recent field application projects for strengthening of structure and bridge columns with FRP are shown in Tables 3, 4 and 5. The types of repairs include: corrosion, confinement, axial, flexural, shear, and seismic strengthening. In the state of California external FRP retrofit is commonly done due to the need for seismic strengthening.

Table 3. Selected field application projects - columns retrofitted for axial loads or confinement

Agency	Structure	Date	Location	Type of Repair	Material
Quakewrap	Port Clinton Garage	2009	Port Clinton, OH	Axial	GFRP
FYFE Co. LLC	Corona Del Mar	2009	Orange Co. CA	Confinement	GFRP
D.S. BROWN	Medford Fire Station	2007	Medford, OR	Axial	CFRP
D.S. BROWN	Los Gatos Creek Bridge	2007	Santa Clara, CA	Axial	CFRP
Quakewrap	Cabana Hotel	2007	Miami Beach, FL	Axial	CFRP
Quakewrap	Rocky Mountain Hardware	2007	Hailey, ID	Axial	CFRP
D.S. BROWN	House Seismic	2005	Puako, HI	Axial	CFRP
D.S. BROWN	Childrens Hospital	2005	Seattle, WA	Axial	CFRP
D.S. BROWN	PNC Bank	2004	Lexington, KY	Axial	CFRP
D.S. BROWN	I-10 Overcrossing	2003	Los Angeles, CA	Axial	CFRP
Quakewrap	Plaza In Clayton	2003	St. Louis, MO	Axial	CFRP
D.S. BROWN	Dolphin Condos	2002	Malibu, CA	Axial	CFRP
D.S. BROWN	First Union Bldg	2002	Charlotte, NC	Axial	CFRP
D.S. BROWN	Precast Concrete Plant	2001	Boise, ID	Axial	CFRP
FHWA 2007	US 64 WB over Haw River	2000	North Carolina	Confinement	GFRP
FHWA 2007	Androscoggin River Bridge	1999	Mexico, Maine	Confinement	FRP
FHWA 2007	East Street Viaduct over WV Alt 14A	1999	West Virginia	Confinement	CFRP
FHWA 2007	I-96 over US 27	1999	Lansing, MI	Confinement	CFRP/GFRP
FHWA 2007	I-80 at State Street	1999	Utah	Confinement	FRP
Quakewrap	Phoenician Resort	1999	Scottsdale, AZ	Confinement	CFRP
FYFE Co. LLC	Harris Hospital Parking Garage	1994	Fort Worth, TX	Axial	GFRP

Table 4. Selected field application projects - columns retrofitted for corrosion

Agency	Structure	Date	Location	Type of Repair	Material
FYFE Co. LLC	Chula Vista Bayside Park Pier	2009	San Diego, CA	Corrosion	CFRP & GFRP
Quakewrap	Bay View Bridge	2007	Ft. Lauderdale, FL	Corrosion	CFRP
Quakewrap	I-90 Bridge at Cline Ave.	2006	Gary, IN	Corrosion	GFRP
Quakewrap	I-94 Bridge at S.R. 49	2006	Chesterton, IN	Corrosion	GFRP
Quakewrap	Tucson Main Library	2005	Tucson, AZ	Corrosion	GFRP
D.S. BROWN	Bahia Honda Bridge	2003	Florida Keys	Corrosion	CFRP
FYFE Co. LLC	Miramar Water Treatment Plant	2003	San Diego, CA	Corrosion	FRP
FYFE Co. LLC	Malibu Residence	2001	Malibu, CA	Corrosion	FRP
Quakewrap	I-40 Bridge	1997	Oklahoma City, OK	Corrosion	GFRP

Table 5. Selected field application projects - columns retrofitted for seismic loads

Agency	Structure	Date	Location	Type of Repair	Material
D.S. BROWN	Day’s Inn	2008	Portland, OR	Seismic	CFRP
Quakewrap	Ted Stevens International Airport	2008	Anchorage, AK	Seismic	CFRP
FYFE Co. LLC	Pasadena City Hall	2007	Pasadena, Ca	Seismic	FRP
FYFE Co. LLC	2025 South Figueroa	2007	Los Angeles, CA	Seismic	GFRP
D.S. BROWN	Vista House	2005	Portland, OR	Seismic	GFRP
Quakewrap	McKinley Tower	2005	Anchorage, AK	Seismic	FRP
D.S. BROWN	Mountainview Overcrossing	2004	Reno, NV	Seismic, Flex. & Shear	CFRP
D.S. BROWN	Mogul East & Mogul West	2004	Mogul, NV	Seismic/Shear	CFRP
D.S. BROWN	Glendale Parking	2002	Glendale, CA	Seismic	CFRP
FYFE Co. LLC	Sobrante WTP Clearwell Roof	2002	El Sobrante, Ca	Seismic	GFRP
FYFE Co. LLC	L.A. Sports Arena	2002	Los Angeles, CA	Seismic	GFRP
D.S. BROWN	Richmond Police HQ	2001	Richmond, CA	Seismic	CFRP
FYFE Co. LLC	Big Tujunga Canyon Bridge	2001	Los Angeles, CA	Seismic	FRP
FYFE Co. LLC	Arroyo Quemado Bridge	1999	Santa Barbara, CA	Seismic	FRP

3 CONCLUSIONS

This paper has provided a review of recent experimental research and field application projects on the FRP retrofit of reinforced concrete columns. The existing investigations have revealed that the use of FRP materials restore or improve the member original design strength and in some cases allow the structure to carry an increased load that it was not designed for. With development of additional design standards and increased demand in the field applications, FRP will continue to grow in popularity as a retrofit material.

From the review of the literature, it was also concluded there is a need to perform additional research on the FRP retrofit of concrete members subjected to impact loadings. With further investigations, life cycle costs will outweigh the higher upfront cost of FRP retrofit over conventional retrofit techniques.

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