# Strengthening of Bridge Columns Subjected to an Impact Lateral Load Caused by Vehicle Collision

## Phase I Final Report

**PI: Azadeh Parvin, D.Sc.**
**Associate Professor**
**Department of Civil Engineering**
**College of Engineering**

**Prepared for The University of Toledo University Transportation Center**
**and the U.S. Department of Transportation**

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# DISCLAIMER

## EXECUTIVE SUMMARY

Fiber reinforced polymer (FRP) materials have gained wide acceptance for repair and retrofit of existing infrastructures or to design new infrastructures due to their desirable properties (high strength to weight ratio, light weight and consequent ease of field placement, corrosion resistance, durability, and low maintenance cost among others). There is a need to strengthen the deficient and aging civil infrastructure or new structures that are identified with certain design flaws against sudden loads including impact, blast, natural disasters, or increased traffic loads over time. The addition of FRP materials to upgrade the deficiencies or to strengthen the structural components prior to collapse can save lives and damage to infrastructure, and reduces 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 damaged reinforced concrete structural members that are repairable. Additionally, there are a number of accidental vehicle-bridge component collisions reported every year that result in loss of lives and severe property damages. These outcomes suggest that some of these bridges are not impact proof.

In this phase of the project, a literature review was performed on the FRP-strengthening of concrete bridge members and structural components to evaluate its use and benefits. In particular, the FRP strengthening of columns for several loading scenarios including impact load is discussed. Various forms of FRP strengthening techniques are also introduced. 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 help prepare the ground work for further evaluation of the bridges that are in serious need for repair or replacement either due to accidental impact or deterioration, and to propose an innovative and reliable bridge repair technique that is fast, durable and cost efficient.

## INTRODUCTION

Many bridges are in need of repair or replacement. Deficiency in bridges can be caused by design flaws, deterioration due to environmental impact, increase in service loads, and accidental impacts (Parvin and Brighton 2011).

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-1970’s buildings and bridges were constructed according to older design codes and need to be retrofitted 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 infrastructures. Natural disaster 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.

Every year, several overheight vehicles strike the bridge girders despite the regulations and practices set in place by governing bodies to restrict such occurrences from happening. Additionally, 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 worst cases, structural failure. Fig. 1 shows damage caused by an overheight vehicle striking a bridge girder.

Natural disasters, vehicle collisions, and explosions have made engineers reevaluate current reinforced concrete structures for their effectiveness against resisting such loads. Previous 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. In recent years, one method of repair that has become increasingly popular is the use of fiber reinforced polymers 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 (Ibrahim and Mahmood 2009; Stallings et al. 2000). The earliest type of FRP material used was glass fibers embedded in polymeric resins and appeared after World War II for space and air exploration (Bakis et al. 2002). Later on a variety of fiber materials were introduced to the market including aramid, boron, carbon, and Kevlar.

**Fig. 1.** Damage Caused by Overheight Vehicle Collision

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. Brief description of various forms of FRP is provided in the following sections.

## 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. FRP sheets and strips have been used to enhance the axial, shear, or flexural capacities of reinforced concrete members. Toutanji et al. (2010), Wu et al. (2009), and Matthys et al. (2006) investigated the axial capacity of FRP confined columns. Bousselham and Chaallal (2006), Ibrahim and Mahmood (2009), and Mosallam and Banerjee (2007) conducted research on improving the shear capacity of beams by FRP sheets and strips. Mayo et al. (1999) and Zhao et al. (2007) studied the flexural capacity and the bond of externally FRP-strengthened beams. Finally, Di Ludovico et al. (2010) employed external CFRP laminates to restore the loss in flexural capacity of damaged beams due to an impact load.

### FRP Plates

FRP plates consist of FRP fabric pre-impregnated with the binder material and allowed to cure before being attached to the desired member. FRP plates are often desired over FRP sheets or strips due to their rigidity for the ease of placement. Researchers including Stalling et al. (2000) and Nanni et al. (2004) have studied the retrofit of reinforced concrete beam members with shear or flexural deficiencies using FRP plates.

### Near Surface Mounting

Near Surface Mounting (NSM) consists of cutting a groove into the concrete surface. The groove is then filled half-way with an 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 Nanni et al. (2004), Teng et al. (2006), Bianco et al. (2009), Nordin and Biorn (2006), and Hassan and Rizkalla (2003).

### 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 voids on the substrate surface (Boyd et al. 2008). Lee and Hausmann (2004), and Boyd et al. (2008) studied the retrofit of reinforced concrete members with shear and flexural deficiencies using sprayed FRP.

### 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 of reinforced concrete members (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. Kim et al. (2005) investigated the anchoring techniques of FRP prestressing. The effects of FRP prestressing on girders damaged by the impact load were also considered in another study by Kim et al. (2008). Meier (1995), El-Hacha et al. (2001), and Wight et al. (2001) investigated the strengthening of beams using FRP prestressing. Columns have been upgraded for lateral impact or seismic loads using prestressed FRP strips (Motavalli et al. 2011).

## STRENGTHENING OF COLUMNS

Columns can be strengthened to increase the axial, shear, and flexural capacities for a variety of reasons including: lack of confinement, eccentric loading, seismic loading, impact loading, and corrosion. In the following sections, these topics are discussed in further detail.

### FRP Confinement of Columns

Traditional methods to increase the load carrying capacity of columns include steel and concrete jacketing which lead to a much larger cross-sectional area for the column. 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-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 |

### 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). Traditional methods for the upgrade of eccentrically loaded columns include concrete and steel jacketing. These methods are successful in increasing the structural capacity of the column but are labor intensive, difficult to implement on site, and significantly increase the cross-section of the column. FRP retrofitting has none of the previous mentioned problems. 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. 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 strength and normal 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 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 |
| 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 |

## 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.

### 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.

### 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 the different 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).

### 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 Clearwell 2 | 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 | CFRP & GFRP |
| D.S. BROWN | Mountainview Overcrossing | 2004 | Reno, NV | Seismic, Flexural & 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 |

## CONCLUSIONS

This report has provided a review of recent experimental research and field application projects on the FRP retrofit of reinforced concrete structures. 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. With more field application projects, FRP will continue to grow in popularity as a retrofit material over traditional materials due to its superior material properties such as lightweight, resistant to corrosion, and ease of application which results in shortening the construction time.

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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