Low Cost Thermoplastic Wrap
to Enhance Bridge Safety

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16. Abstract

The risk of damage to bridge piers from accidental loads remains a concern as roadways and waterways become more congested. Fiber reinforced composite materials are finding a wide array of civil infrastructure applications. Most of these applications utilize pre-preg thermosetting composites, the most common of which is carbon fiber reinforced polymer. Presently, there are no existing studies on thermoplastic materials for civil infrastructure. The ability to readily form thermoplastics and their inherent high impact resistance make them desirable in civil infrastructure applications. This research was an essential step towards developing thermoplastic confining jackets for bridge pier vulnerability reduction. This research focused on the development of thermoplastic composite material produced in continuous pultruded form thermoplastic polymer jackets for confining concrete columns. The effects of compression and impact loading of high strength concrete confined by a prefabricated polypropylene jacket were investigated. For comparison purposes similar specimens confined by carbon fiber/epoxy were also considered. The results from both loading cases demonstrated the superior performance of thermoplastic polymer jackets to displace inelastically without significant degradation of strength or stiffness. The thermoplastic jacket could act as an efficient transverse reinforcement to enhance confinement of potential plastic hinges and the shear strength of bridge columns. The research was not intended to develop a final product for an industrial application, but rather to develop a framework for pier wrap systems to explore the options available to the bridge designer for improving the behavior of thermoplastic wrapped piers as compared to conventionally strengthened piers.

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Executive Summary

The risk of bridge piers failing due to impact remains high. As roadways and waterways become more congested, the risk of accidental collision remains a concern. Bridge piers are designed for a variety of loading conditions, mainly compression, but often these structures fail when subjected to out-of-plane eccentric loading.

Moreover, as the nation's infrastructure continues to debilitate, primarily due to increased loading and natural aging, the demand for more durable materials becomes greater. Many of the reinforced concrete columns erected prior to the 1970s possess inadequate transverse reinforcement to provide sufficient confinement to the concrete core (Kestner et al. 1997). Concern has risen over corrosion of internal steel reinforcing bars due to the presence of chloride, since cracking and spalling of concrete columns has followed this phenomenon (Shi Zhang and Mai 2000). Also, seismic repair and defense against impact/blast loading have increased the need for more efficient materials. In order to slow down the degradation process, new technologies must be developed and new materials must be utilized (Teng et al. 2003). The Federal Highway Administration, several state departments of transportation, and numerous researchers have classified two critical areas for the implementation of new materials: retrofitting techniques for repair and rehabilitation of bridge components (Ballinger and Craig 1997; Roberts 2000; Teng et al. 2003) and the construction of new structures made from composite materials (Karbhari and Seible 1999; Saafi et al. 1999; Williams et al. 2000). Moreover, composite materials have continued to gain favor in civil engineering applications. Today, fiber reinforced composite materials are used in a wide array of civil infrastructure applications. Most of these applications utilize prepreg thermosetting composites, the most

common of which is carbon fiber reinforced polymer. Limited time has been spent investigating the usage of thermoplastic materials. These materials offer comparable material characteristics to those of thermosetting composites. The ability to readily form these materials and their superior impact resistance makes them much more desirable.

This research was aimed at developing thermoplastic composite and thermoplastic polymer confining jackets for bridge pier vulnerability reduction. Previous research (Uddin et al 2004) investigated fundamental characterization of thermoplastic composites (glass/polypropylene) and concrete bonding using several testing procedures, including surface bonding and in-plane shear testing. Uniaxial compression testing was carried out by wrapping cylinders with glass/polypropylene tape. It was observed that strain capabilities of the composite-concrete structure increased 15 fold over the plain specimens. In addition high-speed impact testing was conducted on a series of concrete plates with a layer of the glass/polypropylene composite bonded to the surface. The focus of the impact test was to study the ballistic performance of the material. The results from the tests indicated that the material provided an energy absorbing bond that had the desired effect of reducing damage against impact. The study also showed that the need to use a heat source for the application of the thermoplastic material can be abandoned, and the use of the thermoplastic tape in the form of split rings or jackets should be considered.

Based upon the above findings on glass fiber reinforced polypropylene wraps (thermoplastic composite), the present work was directed to confining concrete with prefabricated polypropylene (PP) jackets. Additionally, similar specimens of concrete confined by carbon fiber/epoxy (thermosetting composite) were also studied. Both static and dynamic testing was done to characterize the various specimens and to address design issues.

For static testing plain concrete, polypropylene jacket wrapped concrete and carbon/epoxy wrapped concrete columns were loaded to failure in uniaxial compression. It was observed that PP thermoplastic reinforcement wrap effectively restrained the lateral expansion of the concrete that accompanied the onset of crushing, maintaining the integrity of the core concrete and enabling much higher compression strains (compare to steel and carbon fiber wrap) to be sustained by the compression zone before failure occurred. For impact testing, 914 mm columns were prepared with the same diameters as the specimens used for compression testing. Impact testing was conducted using a drop-tower testing machine. The results conclusively demonstrated the superior impact resistance properties of PP wrapped specimens over the Carbon Fiber Reinforced Polymer CFRP.

The research was not intended to develop a final product for an industrial application, but rather to develop a framework to explore the options available to the bridge designer for improving the behavior of a confined pier as compared to a conventionally strengthened pier. A search is in progress for additional funding so that the proposed thermoplastic wrap/confinement approach can be evaluated in an actual bridge pier identified by the Alabama Department of Transportation, including details of attachments points, number of layers required, and processing temperatures to the point that the in-field process may be developed.

Section 1
Introduction

1.1   Background

Bridges are critical to a nation's civil infrastructure. Bridge structures are vital to maintaining a steady flow of traffic over both land and sea. Other than the standard day-to-day wear, bridges are becoming vulnerable to a number of threats. Collisions due to impact from trucks and barges have become increasingly common. According to a U.S. Coast Guard and American Waterways Operators report (2003), between 1992 and 2001 there have been roughly 2700 incidents in which bridges have been struck by barges causing death, injury, and millions of dollars in damage. One of the most recent accidents involving barge-pier interaction is the I-40 highway in Oklahoma in May 2002. The accident caused the catastrophic failure of the bridge and 14 people lost their lives. Similarly, bridges that span over land are vulnerable in much the same way as those that cross waterways. These destructions can be brought about by large trucks on roadways. This type of accident is not limited to the United States. In October of 2004, a bridge collapsed in Moscow after a truck collided with one of its piers.

With the continued growth of cities and the continued increase in shipping traffic, these occurrences will continue to increase. These accidents have proven the susceptibility of bridge piers to out-of-plane loading. Coupled with recent threat of terrorist activities, vulnerability of these structures is now a unique issue. The most vulnerable points on a bridge are its piers. These pier structures, though quite strong under compression, are not as sturdy when subjected to out-of-plane loading. Consolazio et al. (2002) conducted a series of barge impacts on some of the piers of the St. George's Island Causeway Bridge. The impacts were not extreme enough to collapse the bridge, but were strong enough to generate data to help designers better understand the nature of impact events. When such an impact has occurred, two types of failure were reported. The first was "breaching," whereby an explosion or a collision at the base of a column destroyed part of the cross-section rendering the structure incapable of carrying its own dead loads. The second type of failure was called "global failure." Here, when an impact or pressure wave from a blast occurred the structure was subject to shearing or flexural failure. Although a structure may incur damage from an impact, prevention of catastrophic failure is the ultimate goal. With emerging materials and advances in thermoplastic composites technologies, there is added promise to design and develop impact resistant bridge structures.

Previous work with composite materials in infrastructure application focused primarily on the use of thermosetting fiber reinforced plastic (FRP) composites for strength/stiffness enhancement with minimal consideration given to impact and blast loading (Cantwell and Smith 1999; Uddin and Vaidya, 2002). Most of these applications utilize prepreg thermosetting composites, the most common of which is carbon fiber reinforced polymer. However, several potential disadvantages are associated with FRP jackets. Some FRP materials are susceptible to damage from ultraviolet radiation and temperature variation. They posses uncertain fire resistance properties and may emit potentially toxic fumes when burned. Additionally, FRPs have a limited strain capacity relative to conventional material such as steel. Finally FRP materials are relatively expensive.

Limited time has been spent investigating the usage of thermoplastic materials. These materials offer comparable material characteristics to those of thermosetting composites. The ability to readily form these materials and their superior impact resistance makes them much more desirable. The focal point of this project was to investigate the effectiveness of confining concrete columns with a prefabricated PP wrap to protect against impact loading and delay structural collapse under a catastrophic event. The work compared the effects of static and dynamic loading of thermoplastic polymer confinement with the most common composite strengthening approach, i.e., carbon fiber wrapping. Two series of tests were performed in this research; uniaxial compression testing of cylinders and impact loading of columns.

1.2   Research Objectives

The objectives of this research were:
1. To investigate effectiveness of confining concrete columns with prefabricated PP wrap.
2. To investigate the effects of static loading on plain concrete, polypropylene jacketed specimens and carbon fiber wrapped concrete cylinders.
3. To compare the energy absorption characteristics of columns confined by PP and CFRP.
4. To develop a design framework for uses of the proposed stiffening/strengthening technique.

1.3   Literature Review

The majority of the work involving the application of composite materials to civil infrastructure has focused on thermosetting plastics, primarily carbon fiber for strengthening bridge columns (Ballinger and Craig 1997). There are a limited number of studies that have investigated the dynamic behavior of composite strengthen concrete.

Jerome and Ross (1996) investigated the dynamic loading of concrete beams externally reinforced with various layers of carbon fibers. The beams were simply supported in a drop-tower testing machine. They concluded that peak loading occurs during a dynamic loading state; peak displacements occur under static loading; displacement is the limiting factor in determining a beam's fracture toughness; and the beams have (for a given height) a fixed energy absorption capacity, further indicating the brittle nature of concrete when loaded dynamically. Erki and Meier (1999) investigated reinforced concrete beams externally strengthened for flexure with CFRP and steel plating and subsequently subjected to impact loading. The procedure for dynamic loading was to raise one end of the beam to a series of different heights and allow it to fall under its own weight. Their tests yielded acceptable results for the usage of CFRP laminates, although the composite was unable to produce the same energy absorption capacity as beams externally reinforced with steel plates. Cantwell and Smith (1999) investigated static and dynamic response of concrete specimens externally strengthened with CFRP laminates. The beams contained no internal reinforcement. They reported significant improvement in both the flexural strength of the beam and the dynamic strength when a relatively thin layer of CFRP laminate was added. Uddin, Farhat and Vaidya (2004) studied the usage of a glass/PP thermoplastic tape to confine concrete structures. The study investigated several testing procedures, including bonding, in-plane shear, uniaxial compression, and plate impact testing. Compression testing was carried out by wrapping cylinders with the glass/PP tape. The results indicated that, although the ductility of the structure increased dramatically, no improvement was made in the compressive strength of the concrete. It was observed that strain capabilities of the composite-concrete structure increased 15 fold over the plain specimens. High-speed impact testing was conducted on a series of concrete plates with a layer of the composite bonded to the surface subject to impact. This research focused on breaching failure. As mentioned earlier, breaching occurs due to blast/impact that causes portions of the structure to be destroyed, rendering the structure unable to carry its self-weight or dead load. The focus of this test was the study of ballistic performance of the material. The results from the tests indicated that the material provided a energy absorbing bond that had the desired effect due to the reduction in damage of the composite. Finite element modeling using LS-DYNA was used in validating the ballistic testing.

Tang and Saadatmanesh (2003) investigated the impact response of reinforced concrete beams externally strengthened with two types of composite laminates; carbon and Kevlar. They concluded that the laminates were effective in increasing the resistance to impact loading.

1.4   Scope of Study

This research project focused on the effects of impact loading on high strength concrete confined by a prefabricated PP jacket and comparing the results with similar specimens confined by CFRP. In order to accomplish this, an experimental program was designed that included both static and dynamic load tests. The neat PP selected for the study was George Fischer beta (β)-PP, 140 mm diameter with 13 mm wall thickness. It was milled to two different thicknesses: 6 mm and 3 mm. Next, the PP was cut into two sizes: 254 mm long segments for cylinders and 914 mm long segments for columns. A total of six cylinders and two columns were prepared from the PP. A high-strength concrete mixture with an average compressive strength of 50 MPa was used for the testing. The cylinders were tested to failure under axial compression using a Tinius-Olsen Universal Testing Machine. The columns were placed in a steel frame and placed in compression. They were subsequently impacted with an instrumented tup hammer in an Instron drop-weight testing machine. The following effects of confinement were evaluated for these tests: stress-strain relationship, deformation capacity, changes in ductility and strength, energy absorption and method of failure.

1.5   Experimental Program

The experimental program (Table 1-1) was an essential part of the project to ensure validity of this novel technique. The aim was to demonstrate that proposed retrofitting contributes to the shear resistance by acting as additional transverse reinforcement through confining the piers so that concrete spalling and longitudinal steel bar buckling are suppressed. Therefore, the overall objective of this proof-of-concept experimental program is twofold:

1.   Evaluate the effectiveness of thermoplastic composite PP protective enclosures in enhancing column performance and maintaining functionality of the column after failure.
2.   Evaluate the effectiveness of the PP protective enclosures in enhancing the energy absorption effectiveness and ductility by using ballistic impact testing.

Table 1-1. Table of specific tests

Task	Specimens	Test Plan & Purpose
a) Static Compression Testing (12 cylinders of 152 mm x 304 mm)	3- control sample, 3 samples wrapped with 3 mm PP jackets, 3 samples wrapped with 6 mm PP jacket, and 3 samples wrapped with 1-ply unidirectional carbon fibers.	Static in-plane compression loading. Purpose - Assess baseline performance and maintain functionality of the cylinder after failure.
d) Impact Testing (4 columns of 152 mm x 914 mm)	1 control sample, 1 sample wrapped with carbon fiber, 1 sample wrapped with 3 mm PP jacket, and 1 sample wrapped with 6 mm PP jacket.	Columns exposed to impact. Purpose- determines impact resistance of the concrete columns laminated with thermoplastic composite.

Section 2
Experimental Program: Compression Loading

The purpose of uniaxial compression tests of the concrete cylinders was to evaluate the axial strength and strain capabilities of the specimen configurations under consideration. Two variables were investigated; confinement material (neat PP and CFRP) and thickness of the neat PP confinement.

2.1   Specimen Details

Twelve concrete cylinders were prepared. Table 2-1 provides results from the compression testing, and an average compressive strength of the concrete was noted to be 50 MPa. The cylinders were grouped as follows; three plain samples (to act as control specimens); three 3 mm and three 6 mm thick PP samples; and, three 1-ply unidirectional carbon fibers. A specimen designation system was established for these samples and will be used throughout this report. The first letters denote the type of specimen, "Cy" for cylinder. The second letter establishes the confinement type, "N" for plain samples, "C" for carbon FRP, and "P" for polypropylene wrapped cylinders. The next letter denotes the type of concrete, "B" for high strength. The first number in the scheme is for the confinement thickness (mm) or number of plies. Finally, the last number represents the sample number. For example, CyPB6-1 would be the first sample of high strength cylinders confined with 6 mm polypropylene. Appendix A provides a complete illustration of the specimen details.

Plain specimens and those confined with CFRP were standard 152 mm x 304 mm concrete cylinders. It was decided to keep the dimensions of the PP confined cylinders as close as possible to that of the standard test cylinders. All samples were wet cured for 28 days and then removed and allowed to dry before testing.

Table 2-1. Compressive strength of concrete mixture

Concrete batch ID	Specimen ID	f'_c, Compressive Strength (MPa)
	1	51.2
	2	48.3
B	3	50.6
	Average	50.1
	Std. Dev.	1.53

Note: B = high strength concrete.

2.2   Confinement Materials

2.2.1   Unidirectional Carbon/Epoxy: Unidirectional SikaWrap Hex 103C carbon fiber was used as fabric reinforcement. An example of this fiber is shown in Figure 2-1. Material data are provided in Table 2-2.

305 mm

559 mm

Figure 2-1. Unidirectional carbon (SikaWrap Hex 103C), fiber direction shown

Table 2-2. Material data for carbon FRP (SikaWrap 2002)

	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation (%)	Nominal thickness (mm)
SikaWrap Hex 103C	958	73	1.33	1

The carbon fiber of 305 mm x 559 mm segments was wrapped around and bonded to the concrete surface using a two-part epoxy resin/hardener, Sikadur 300, a low viscosity resin. This resin was applied to both the concrete surface and the carbon fiber. The fibers were oriented such that they provided reinforcement in the hoop direction (perpendicular to the applied compression load). The samples were left to cure for at least 48 hours.

2.2.2 Prefabricated PP Wrap The PP used for these tests was George Fischer beta (β)-PP and measured 140 mm outer diameter, 13 mm wall thickness, and 5 m in length. This material was chosen because it had many desirable characteristics such as high impact strength, abrasion resistance, low weight, and a sizable operating temperature range. This material was manufactured from a Group 1, Class 2, beta (β) nucleated homopolymer conforming to the requirements of ASTM D-4101 (George Fischer 2004). Table 2-3 provides the material properties for the polypropylene.

Table 2-3. Material data for β-PP (George Fischer 2004)

	Minimum tensile strength (MPa)	Tensile modulus (GPa)	Long-term temperature limit (°C)	Elongation (%)
β-PP	30	2.0	80	120

Note: β-PP = beta-nucleated polypropylene.

It was of interest to investigate the influence of the thickness of the polypropylene for load-bearing and confinement. The polypropylene reinforcement was meant to act as passive reinforcement. Since hollow polypropylene jackets of 140 mm outer diameter were only available in 13 mm thickness, a decision was made to machine it to less than its original 13 mm wall thickness.   254 mm long segments of polypropylene were machined to 3 mm and 6 mm using a standard lathe. Once machining was complete, 25 mm wide rings were taped to either end of the 254 mm segments to produce a 305 mm sample. After the samples were ready, they were placed in standard plastic cylinder molds. Sand was poured around the outside of the 3 mm thick samples to ensure stability when the concrete was poured into them. Once the concrete had been poured, 24 hours later, the samples were placed in a submersion tank for a 28-day curing period. After curing the end rings were removed. Due to the problems seen with normal strength concrete, a cutting saw was used to remove part of the exposed ends of the concrete. On an average the remaining concrete exposure was roughly 13 mm on either end of the cylinders.

2.3   Instrumentation

Unidirectional electrical resistance strain gauges were placed at mid-height of the specimens to measure axial and lateral strain. The gauge orientations of the plain and polypropylene jacketed samples were zero degrees for axial strain and 90° for lateral strain, and a backup gauge was added at 45°. This arrangement is shown in Figure 2-2. Since the carbon fiber was unidirectional, strains were recorded for that direction only.

Compression loading was conducted using a Tinius-Olsen Universal Testing Machine. The load was applied at a constant rate of 103 kPa/s. A MegaDAC data acquisition system was used to record load and strain data. For the plain and CFRP confined cylinders, steel end caps were placed on either end of the specimens to provide even loading. For the PP confined cylinders, rubber pads were successfully utilized as the end caps, since no standard steel end cap size would fit the shape.

Figure 2-2. Strain gauge orientation

Section 3
Results and Discussion: Compression Loading

Compression loading was carried out on a series of high strength concrete cylinders. Three different confinement configurations (plain, unidirectional carbon fiber, and a prefabricated PP wrap) were evaluated.

3.1   Stress-Strain Response

Figure 3-1 shows comparison of the test data for two cylinders for confined high strength concrete. Stress-strain data for the individual confinement materials can be found in Figures 3-2 through 3-5.

A review of the response curves in Figure 3-1 demonstrates that PP confinement produces a significant increase in the ductility of the concrete. However, it was unable to achieve similar compressive strength to that of CFRP wrap concrete. For example, specimen CyCB1 reached a maximum axial stress of 98 MPa (Figure. 3-2), whereas PP wrapped specimens CyPB3 and CyPB6 could reach maximum 54 and 52 MPa respectively. It was obvious that isotropic

Figure 3-1. Comparison of stress versus strain for cylinders (averaged values)
Figure 3-2. Stress versus strain for CyCB1 cylinders

CFRP wrapped around the circumference of the concrete did not affect the stiffness of the concrete up to the peak concrete unconfined strength f'_c. In this range, stiffness of the unconfined concrete was very similar to the CFRP wrap concrete. However, that was not the case for the PP wrapped concrete. The PP, being more-or-less orthotropic, increased the stiffness to a certain degree. Moreover, both CyPB3 and CyPB6 specimens achieved a similar stiffness.

CFRP wrapped specimen CyCB1 achieved an axial strain at a peak stress of 0.0056mm/mm, which is 3.5 times the average axial strain of the unjacketed cylinders. PP wrapped specimen CyPB3 achieved a maximum strain of 0.0166 mm/mm, which is 9.2 times the average axial strain of the unjacketed cylinders. Specimen CyPB6 achieved a maximum strain of 0.0181 mm/mm, which is 10.1 times the average axial strain of the unjacketed cylinders. Both PP wrapped specimen recorded a maximum strain more than three times that of the CFRP wrapped specimen. On the other hand, maximum transverse strains at failure of 0.010 mm/mm (Figure 3-3) and 0.015 mm/mm (Figure 3-4) were recorded across the middle gage length for CyPB3 and CyPB6 respectively.

Figure 3-3. Stress versus strain for CyPB3 cylinders

Figure 3-4. Stress versus strain for CyPB6 cylinders

Initial matrix cracking formed in the jacket of specimen CyCB1 at an axial stress of 75 MPa. Rupture and debonding of strands of fibers from the matrix material of the CFRP jacket first occurred at a stress of 90 MPa. The specimen failed after a large number of strands of fibers ruptured and debonded form the jacket. Once

ruptured, the fibers within these strands no longer contributed strength to the CFRP and thus confinement to the concrete. When the CFRP jacket can no longer provide confinement, the specimen unloaded. The rupture debonding of strands was concentrated along the middle gage length, though some also occurred within the top and bottom regions to a lesser extent.

On the other hand, indication of initial concrete cracking was observed in the jackets of CyPB3 and CyPB6 at an axial stress of 54 MPa and 52 MPa respectively. Once confinement was engaged, behavior of the concrete was a function of the circumferential stiffness of the confinement. Typically, three stages were seen in the stress-strain curves of CFRP confined specimens. In the first region, it was the concrete that carried the axial load, due to minimal lateral expansion of the concrete core. Second, a nonlinear transition range began when the concrete started to expand and generated greater lateral strain. Finally, the confinement took effect and the stiffness remained at a constant rate. No debonding occurred along the PP. However the PP wrapped cylinder showed a very small gain in compressive strength, almost insignificant. This can be explained by the bulging of PP that affected the post- f'_c (post-peak) behavior. The polypropylene allowed the concrete to compact and dilate the confinement material. The effect of dilation can be seen in Figures 3-3 and 3-4, since this phenomenon allowed the stress-strain curve to "flat-line." This reflected a ductile mode of specimen failure relative to a specimen, i.e., the CFRP jacket failed by sudden rupture of all the fibers in a region of the jacket. The bulging of jacket, however, was concentrated along the upper gage length, though some occurred within the bottom regions to a lesser extent.

Normalized strain data given by the ratio $\varepsilon_{tu}/\varepsilon_{to}$ (strain at failure of the confined cylinder by strain of the unconfined cylinder) is shown in Table 3-1. The 3 mm PP jacket produced an average ratio of 8.4, and the 6 mm PP jacket yielded an average ratio of 9.6, which is impressive when compared with the 15.6 average ratio of the glass/PP confinement reported in earlier research (Uddin et al, 2004).

Table 3-1. Summary of compression test results

Specimen ID	Maximum strength (MPa)	Maximum strain	$\varepsilon_{tu}/\varepsilon_{to}$	Change in strain (%)
CyNB0*	50	0.0018	---	---
CyCB1-1	98	0.0056	3.1	211
CyCB1-3	106	0.0032	1.8	78
CyPB3-2	54	0.0135	7.5	650
CyPB3-3	53	0.0166	9.2	822
CyPB6-1	50	0.0181	10.1	906
CyPB6-2	52	0.0159	8.8	783
CyPB6-3	50	0.0176	9.8	878

* - Average of the three specimens.

3.2   Failure Modes

The modes of failure observed during these tests varied depending on the confinement. The polypropylene confined samples exhibited a barreling effect on one end of the cylinder or on both ends in some cases. Figures 3-5 through 3-7 show the different ways in which the PP confined specimens failed. The ability to dilate considerably allowed the confined concrete to crush and compact inside the PP jacket. Yielding of the polypropylene was evident in a few places on the samples, and only one sample showed signs of material failure

(see Figure. 3-6). Sample CyPB6-1 showed signs of eccentric loading. Failure of the CFRP wrapped cylinders occurred due to some of the fibers rupturing near mid-height. Though Figure. 3-8 appeared to show minimal failure in the carbon fiber wrap, the specimen had attained its peak load bearing capacity.

Figure 3-5. Comparison of failure among CyPB3 cylinders

Figure 3-6. Tearing of polypropylene wrap (sample CyPB3-3)

Figure 3-7. Comparison of failure among CyPB6 cylinders

Figure 3-8. Comparison of failure among CyCB1 cylinders

Section 4
Experimental Program: Impact Loading

4.1   Specimen Details

Impact testing was conducted using a total of four concrete columns; one control specimen, one CFRP confined, and two confined by a polypropylene wrap of 3 mm and 6 mm thickness, respectively. The concrete was from the same batch that produced the high strength cylinders tested under uniaxial compression. The average compressive strength was approximately 50 MPa, as shown in Table 3-1. All columns tested had a length of 914 mm, so that the samples and test frame would fit beneath the impact machine. The plain specimen and the one used for the CFRP wrap had a diameter of 152 mm. The diameter of concrete in the PP jacket was 152.4 mm. A specimen designation system similar to that used for the cylinders was established for these samples and is described in Appendix A.

The sample preparation procedure for the polypropylene was the same as the cylinders used in compression testing, with one caveat. The columns were poured into 152 mm diameter sonotubes instead of plastic forms. Sample preparation for the CFRP wrapped column varied only by the orientation of the fibers. For the impact test, the fibers were oriented along the length of the column such that they provided reinforcement perpendicular to the axis of impact. For columns with CFRP wrap oriented around the column, as typically done in the retrofitting work, the wrap will not contribute towards the stiffness of the column against transverse impact loading.

4.2   Test Setup and Instrumentation

4.2.1   Instrumentation. Two unidirectional electrical resistance strain gauges were used for each column. One gauge was placed on the bottom surface of the column underneath the point of impact (mid-span), the other gauge was located at quarter span on the top surface. Strain data were recorded separately from the rest of the impact

data, using a DATAQ, Inc. Model DI-510-32 system. In an effort to illustrate a similar loading situation, the columns were placed inside a testing jig and subjected to axial compression.

The jig was composed of 19 mm thick steel plates held together by four threaded rods. One side of the frame was locked in place before testing. The other end was allowed to move in order to insert and remove each column before and after testing. Double nuts were used on each rod of the floating end of the frame to ensure the compression load would not relieve itself. The frame is shown in Figure 4-1.

Figure 4-1. Testing jig used for column testing

4.2.2   Impact Testing System. The system used for impact testing was an Instron Model 8250 drop-weight impact machine with an instrumented striker (tup) assembly. The striker used for this test was flat and had an impact area of 76 mm x 102 mm. The assembly, without additional weights, weighed approximately 2.45 kg. For this study, the impact weight was increased by adding a 22.7 kg plate to the frame, bringing the total striker assembly to 25.1 kg. The hammer contained an internal load cell which was used to record the contact load between the falling assembly and the column during the impact event. The load cell was rated for a maximum load of 44 kN. A drop height of 30 cm was used for all tests, since the combination of this height and the weight of the striker assembly produced loading close to that of the maximum allowed by the load cell. In previous studies using this machine, load-time plots reported peak-loads several times the expected value. Conclusions from similar tests were drawn by Suaris and Shah (1983), that this loading was not indicative of the material properties but instead was a result of inertial effects of the samples. Though these effects have been accepted and calculated before for testing metals, concrete creates a more complex problem due to the relatively small fracture strain and increased size of test specimen (Server et al. 1977). As in previous testing, a rubber pad was added to the striker to eliminate the inertial effects or "ringing" generated from the impact of the steel hammer and concrete specimens.

The testing machine used DynaTup software to generate the data produced during impact loading. Load versus time and impact velocity were measured directly from the software. For a forced object traveling in a straight line, standard equations of motion were used to express velocity, deflection, and energy absorption.

Section 5
Results and Discussion: Impact Loading

5.1 Results Details:

Three different confinement configurations were evaluated: plain, unidirectional carbon fiber, and prefabricated PP wrap. Deflection, velocity, and energy absorption were recorded. Strain was measured using unidirectional strain gauges and recorded using a DATAQ, Inc. recorder. Data from the tests are presented in Table 5-1.

After testing and subsequently failing the plain concrete column (CoNB0), it was clear that it would be impossible to fail the PP confined columns. The polypropylene columns (CoPB3 and CoPB6) were impacted an average of five times. This was done to see if the material would exhibit any signs of weakening, and if not the data would be averaged for the five tests. Since the carbon fiber confined sample was assumed to be stiffer than the PP confined columns, only two tests were conducted. All samples were impacted from a height of 30 cm to

keep the load cell free from damage. Due to the limitations of the drop-tower machine, the impact loading was classified as low velocity impact or less than 10 m/s (Bartus 2003). Average impact velocity for these tests was 2.4 m/s.

Table 5-1. Summary of impact test results

Specimen ID	Peak load (kN)	Maximum deflection at midspan (mm)	Maximum strain	Change in strain (%)
CoNB0	38	3.38	0.0024	---
CoCB1	45	2.72	0.0057	143
CoPB3	36	4.52	0.0047	101
CoPB6	34	5.00	0.0058	148

Figure 5-1 shows the load versus time plot. The inertial effects were reduced and were not visible in this plot due to the addition of the rubber pad to the striker. This phenomenon was evident in tests conducted by Erki and Meier (1999). Several things can be observed from the figure. First, the initial peak was the actual peak load. The subsequent peaks of smaller amplitude were simply rebounds of the tup. Since it was the most stiff, CoCB1 had the largest peak load of all specimens with a value of 45 kN. As expected, CoPB3 and CoPB6 had (desirable) lower peak loads of 36 kN and 34 kN, respectively, since these specimens were less stiff than CoCB1. Since CoNB0 cracked under the loading, it seemed not to have the second peak, but had a third after a little rest due to a delayed rebounds of the tup for the cracking. The dynamic bending load increase on the other hand was highest for the less-stiff columns (CoPB3 and CoPB6) and gradually declined in value with increased stiffness.

Figure 5-1. Load versus time for tested columns

This trend was also observed by Jerome and Ross (1996). Using the energy balance approach, the initial kinetic energy of the impactor deformed the structure during impact. Since the specimens used for this study were short columns and subjected to a compression sufficient enough (corresponding to $1/8\ P_o$ where $P_o=0.85\ A_g f'_c$) to provide fixity at the end against the impact, the stiffness was far too great to allow failure. It has been shown that the energy dissipated during vibration of composite structures is negligible (Caprino et al. 1999). The load versus displacement curve (Figure 5-2) shows that, CoPB6 deflected more than 5 mm and

Figure 5-2. Load versus displacement for tested columns

CoPB3 deflected about 4.5 mm. These deflections are much higher than CFRP wrapped column CoCB1, which deflected about 2.6 mm, about half of the deflection of the PP wrapped columns.

From the energy versus time curve (Figure 5-3), it appeared that energy absorption of the PP was higher than that of the carbon fiber confinement. Energy absorption for the 3 mm PP wrap was higher than for the 6 mm wrap. Specimen CoCB1 absorbed 62 joules, whereas specimens CoPB3 and CoPB6 absorbed about 78 and 70 joules, respectively.

Figure 5-3. Energy versus time for tested columns

The displacement versus time plot (Figure 5-4) indicated that the PP wrap produced higher deflection than the CFRP wrap column and unconfined column. This effect was due to the ability of the material to compress and further absorb the energy from impact.

Transverse flexural strain values recorded across the middle gage length showed that CoPB6 and CoCB1 had equivalent strain values at the point of impact, with increased capability of approximately 145 percent over the unconfined concrete. The increase in ductility of sample CoPB3 was slightly less with an increase of about 100

percent.

Figure 5-4. Displacement versus time for tested columns

5.2   Discussion:

Based on the results, it appeared feasible that retrofit with thermoplastic PP jackets could follow the same principles and equations as those for CFRP jackets with appropriate modifications in design details. However additional testing results, including hysteretic responses of the PP-retrofitted RC columns, will be essential to adequately quantify the design details including thickness and location of the wraps. It is also imperative that additional tests be carried out to confirm the results of this research project. Preliminary guidelines for field implementation of PP wrap systems are shown below:

(1) Existing RC columns can be strengthened using prefabricated PP or glass reinforced PP (glass/PP) shells. They can be fabricated in half circles, half rectangles, or circles with a slit in continuous rolls, so that they can be opened and placed around columns (Figure 5-5). Two half shells of PP or glass/PP plate rolled to a radius of 0.5 to 1.0 in. (12.5 to 25 mm) larger than the column radius can be positioned over the area to be retrofitted and the vertical seams may be site-welded (using ultrasonic welding) to provide a continuous tube with a small annular gap around the column. For effective confinement to be achieved, full contact is essential between the column and the PP or glass/PP shell. This can be ensured by either bonding the shell to the column using adhesives, or injecting shrinkage-compensated cement grout or mortar into the space between the shell and the column.

(2) Prefabricated PP or glass/PP shells can be used as a stay-in-place forms for a precast modular bridge pier system for new bridge pier construction

D

t_j

D

t_j

¼ in to 1 in thickness wrap

grout gap 1″

(25 mm) typical

Original Column

Figure 5.5. Schematic of proposed PP or glass/PP shell design for pier retrofitting

Section 6.0
Summary and Conclusions

Bridge columns that are expected to sustain breaching and large inelastic rotation in plastic hinges during impact loading are a prime concern for the retrofit design to enhance the breaching and ductility capacity. Ductility will normally be provided by column plastic hinges. It is the plastic rotation of the potential plastic hinge that is of greatest interest. The available plastic rotation capacity, and hence the ductility capacity, depends on the distribution of transverse reinforcement within the plastic hinge region. Transverse reinforcement provides the dual function of confining the core concrete, thus enhancing its breaching strength and enabling it to sustain higher compression strains, and restraining the longitudinal compression reinforcement against buckling. Many of the current bridge retrofitting applications utilize prepreg thermosetting composites, the most common of which is CFRP. However, CFRPs possess a limited strain capacity relative to conventional material such as steel, and they are expensive.

This chapter discusses the results of static cylinder tests and impact tests of concrete columns. As summarized in the following paragraphs, low cost thermoplastic reinforcement wrap such as PP acts to restrain the lateral expansion of the concrete that accompanies the onset of crushing, maintaining the integrity of the core concrete, and enabling much higher compression strains (compared to CFRP wrap) to be sustained by the compression zone before failure occurs. It also demonstrated superior energy absorption and deformability compare to CFRP wrapped columns during impact testing. The following is a brief summary of the results that support the findings.

6.1 Uniaxial Compression Loading

The purpose of this research was to compare the plastic strain capacity of concrete specimens confined with thermoplastic polymer PP wrap and thermoset CFRP wraps.   The summary of the findings is given below.

1. *Effect of Confinement Thickness.* No appreciable differences in load-bearing and uniaxial concrete compressive strength were observed for the 3 mm or 6 mm PP jackets. This may be due to the high strain capacity within the PP, which masks the influence of the wall thickness (within the 3 mm – 6 mm wall thickness range considered here).
2. *Ductility.* Both PP thicknesses illustrated a significant improvement in ductility when compared to the unconfined concrete. This enhancement is comparable, and even higher than the ductility improvements of the CFRP wrapped cylinders.
3. *Compressive Strength.* Neither series of polypropylene jacketing could produce a significant increase in compressive strength. This was expected due to the ability of this material to bulge and dilate. As mentioned before, axial strengthening applications are not the intended application of this material. However resistance to load in the transverse direction was expected, which is directly related to sustaining higher compressive strains. It should be noted that a large increase in the flexural strength due to retrofitting is undesirable, as it may lead to overloading of adjacent structural elements (Priestly et al. 1996).
4. *Stress-Strain Response*. The stress-strain response of PP confined concrete is multi-linear in nature and demonstrated a very high strain at failure compare to CFRP. Although the first region of the stress-

strain response is dependent on the concrete core, the later regions rely on the capabilities of the jacketing. This multi-linear trend is typical for FRP confined concrete specimens.

5. The mode of failure of PP wrapped specimens reflects a ductile mode of specimen failure relative to a specimen. For example, a CFRP jacket failed by sudden rupture of all the fibers in a region of the jacket. On the other hand the bulging of a PP jacket was typically concentrated along the upper gage length, though some also occurred within the bottom regions to a lesser extent. No separation or debonding from the concrete surface occurred along the PP.

6.2 Impact Loading

The impact tests were conducted to assess the energy absorption capacity of three concrete columns strengthened by PP confinement, CFRP confinement and an unconfined control specimen. The results conclusively demonstrated the superior impact resistance properties of PP wrapped specimens over the CFRP wrapped specimen. From the test results, the following conclusions were drawn:

1. Peak loading of the columns varied, based on the stiffness of the confinement. Since the PP confined columns were the least stiff, they also exhibited the (desirable) least peak loading from the impact resistant design perspective.
2. Deflection of the PP confined columns was greater than the unconfined and CFRP wrapped columns. This is very favorable given that this displacement was nearly six times greater than that of the plain specimen.
3. Transverse flexural strain values across the middle gage length showed that PP wrapped strain increased approximately 145 percent over the unconfined concrete. The increase in ductility of PP wrapped specimens was about 100 percent over CFRP wrap columns.
4. Energy absorption of the polypropylene was significantly higher than that of the carbon fiber confinement. Energy absorption for the 3 mm PP wrap was higher than that of the 6 mm wrap, which can be attributed to the lower stiffness of the former. PP wrap produced higher deflection than the CFRP wrapped column and unconfined column. This effect was due to the ability of the material to compress and further absorb the energy from impact.
5. Though failure was not possible for the PP wrapped specimens, the above results conclusively demonstrated that the usage of a thermoplastic prefabricated wrap can be a viable solution to the threat of impact.

<div align="center">

Section 7
Future Research

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The current study proposed a cost effective prefabricated thermoplastic wrap that has the potential to provide adequate protective measures for bridge piers. Currently ALDOT and many other state DOT's place newly

constructed piers outside of the clear zone or provide crash protection, but they have not instituted any crash protection program for existing bridge piers. Some states, such as Texas and Louisiana, have used crash attenuators or crash walls in front of piers adjacent to their Interstate highways for crash protection. The results from this study demonstrated that thermoplastic composite wrap has the potential to provide a less expensive retrofit and much more aesthetically pleasing solution for protecting crash-vulnerable piers in Alabama and other states.

This research was an important step towards developing thermoplastic confining jackets for bridge pier vulnerability reduction. It focused on the effects of compression and impact loading of high strength concrete confined by a prefabricated PP jacket. For comparison purposes similar specimens confined by CFRP were also considered. The results from both loading cases demonstrated the superior performance of thermoplastic polymer jackets to displace inelastically without significant degradation of strength or stiffness. The thermoplastic jacket could act as an efficient transverse reinforcement to enhance confinement of potential plastic hinges and the shear strength of bridge columns.

Thermoplastics are a new material for infrastructure applications in the field of civil engineering; for this reason, extensive small- and large-scale testing and material characterization are required to develop an adequate design guideline for the proposed method. This research was not intended to develop a final product for an industrial application, but rather to develop a framework for thermoplastic pier wrap systems by demonstrating the superior behavior of thermoplastic wrapped specimens as compare to conventionally strengthened specimens. To more fully understand the effects that static and dynamic loading have on PP confined concrete, more testing needs to be undertaken. To complement the results of the study and implement the proposed method, future works are needed in the following areas:

1. Produce a database of results on structural testing. Samples of varying diameter and length would aid in determining an adequate slenderness ratio to better explain the effects of flexural loading on polypropylene confined concrete. Along with this, varying the thickness of the confinement would help explain the relationship that layering has on the overall structure.
2. Produce a database of results for the confinement system on durability in alkaline environment, fatigue, creep, thermal effects, moisture absorption and UV radiation.
3. Tests of hysteretic responses of the both PP- and glass/PP-retrofitted RC columns will help adequately quantify the design details, including thickness and location of the wraps.
4. Extensive numerical modeling using the database will help develop design tools. Continue LS-DYNA modeling by further investigating the thermoplastic and concrete properties to obtain a more accurate and reliable model, and compare results from the modeling with the results from the newly tested samples.
5. Use the verified LS-DYNA model to further understand the physical behavior of PP and glass/PP-confined columns, and use the data obtained to develop a design methodology.
6. Manufacture of a ready-to-use, full-size PP and glass/PP confinement system for actual bridge piers (including details of attachments points, number of layers required, and processing temperatures, etc.) will help in developing the in-field process.
7. Full-scale pier demonstration would be of benefit, and this is currently being pursued by the researchers through the Alabama Department of Transportation.

Section 8
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Appendix A
Sample Identification

CyNA0-2

Sample Number:
1 = 1st sample of a particular series
2 = 2nd sample of a particular series

Confinement Thickness/Layers:
C: 1 = no. of plies
P: 3 = wall thickness, mm
    6 = wall thickness, mm
        N: 0 = plain concrete, no confinement

Concrete Type:
A: normal strength concrete
B: high strength concrete

Confinement Type:
N = No confinement
C = Carbon fiber
P = Polypropylene tubing

Sample Type:
Cy = Cylinder
Co = Column