Vulnerability Reduction for Bridge Piers

By

Dr. Nasim Uddin and Nadim Shehab Farhat
Department of Civil and Environmental Engineering

and

Dr. Uday Vaidya and J.C Serrano-Perez
Department of Materials Science & Engineering
The University of Alabama at Birmingham
Birmingham, AL

Prepared by

UTCA

University Transportation Center for Alabama
The University of Alabama, The University of Alabama at Birmingham,
and The University of Alabama in Huntsville

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16. Abstract

Concrete bridge piers are designed to withstand large compressive axial loads but often fail under eccentric out-of-plane loads such as those created by an impact or explosion. In the wake of recent terrorist attacks, such loading is of increased concern. Retrofitting the piers with continuous-fiber-reinforced thermoplastic polymers could reduce vulnerability to these loads. Fiber-reinforced composites are relatively new materials that show great promise in concrete retrofit. Presently, fiber-reinforced thermoset polymers are used to add stiffness and tensile strength to concrete bridge members; however, there has been no effort to utilize the superior impact resistance of continuous-fiber-reinforced thermoplastic polymers to protect bridge piers against out-of-plane loading.

The overall objective of this research was to pioneer a new and promising technology to reduce the vulnerability of bridges to dynamic loads that deliver immense energy to the structure in a very short time, such as impacts from trailer trucks, blasts, or earthquake effects. Low-cost long-fiber thermoplastics are emerging as affordable technology for rapidly producing thick structures with integrated attachment points and features that can reinforce bridge structures for collision and impact loads.

For the purpose of this study, samples were cast as 6" diameter x 24" cylinders, concrete prisms, small size concrete cylinders and concrete panels with a glass/polypropylene (PP) face sheet. These specimens were created to study various aspects of the processing, and behavior of the concrete and composite specimens. The cylinders were used to study the enhancement in compressive strength and ductility created by glass-fiber-reinforced PP reinforcing jackets. The prisms were used to determine the shear strength of the bond between the thermoplastic wrap and the concrete specimens through the in-plane shear test, and the strength of the bond through the pull-off test. The thin panels laminated with glass/PP were used to determine the impact resistance of a composite panel through projectile ballistic testing. A finite element numerical model was then created using LS-DYNA software to predict the results of the ballistic impact testing, thus establishing a baseline model for simulating the impact behavior of bridge piers.

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Executive Summary

Concrete bridge piers are designed to withstand large compressive axial loads, but often fail under eccentric out-of-plane loads, such as those created by an impact or explosion. Presently, thermoset fiber-reinforced polymers (FRPs) are used to add stiffness and tensile strength to concrete bridge members, but there has been no effort made to utilize the superior impact resistance of thermoplastic (TP) technology to protect bridge piers against out-of-plane loading. The overall long term objective of this research is to pioneer a new and promising TP technology to reduce the vulnerability of bridges to dynamic loads that deliver immense energy to the structure in a very short amount of time, such as impact from threats like collisions from trailer trucks, blasts or earthquake effects. Low cost long-fiber thermoplastics are emerging as affordable technology to rapidly produce thick-structures with integrated attachment points and features that can reinforce bridge structures for collision and impact loads.

The various steps conducted during the course of this feasibility study involved: (1) an extensive literature review that was carried out on composites in general, and thermoplastics in particular to show that thermoplastic materials have a very significant potential in transportation infrastructure applications; (2) manufacture of low-cost thermoplastic composite wraps; (3) bond characterizations tests on the thermoplastic material which showed that there is no considerable bond between concrete and TP; (4) development and implementation of a successful method for retrofitting concrete cylinders with glass-reinforced polypropylene(glass/PP) confining jackets; (5) ballistic impact tests conducted on concrete panels reinforced with glass/PP as well as plane glass/PP panels, to determine the energy absorption capacity and ballistic limit; and finally (6) a finite element analysis to replicate the ballistic impact test results.

The retrofitting method included use of a heater which provided excellent results for the small scale specimens; but the method could not be replicated successfully to the larger scale specimens due to an air circulation problem. The problem is currently being worked out with the manufacturer Watlow, Inc., to scale up the retrofitting method from the small scale lab specimens to a larger scale specimen, and to eventually create a retrofitting method that can be easily implemented in real life applications. The development of the retrofitting method included the following tasks: (a) determining a heating profile that will allow maximum bonding between the composites without causing deterioration in the confining jacket, (b) determining the length of overlap of the confining jackets that will allow adequate confinement and a passive type of failure mode, (c) development of a retrofitting technique that will provide temporary confinement to the confining jacket during placement in the thermoplastic heater. The results of this project have clearly shown the success and distinct advantages of using glass/PP confining jackets to enhance the ductile behavior of concrete cylinders and ballistic impact performance of the glass/PP reinforced concrete panels.

Based on the results from this fundamental study, input parameters were developed and verified; and systematic numerical modeling is currently being performed to include bridge piers subjected to actual impact loading. In addition scale up issues from the lab sample to the actual pier are being addressed, and preparation of ½ to ¼ scale lab experiments is currently in progress to develop a design methodology for this novel technique

Section 1.0
Introduction

1.1 Research Objectives

While it is well established that thermosets are an effective means of reinforcement of concrete, against both compressive axial loads and out-of-plane seismic loads, less research has been completed on the reinforcement of concrete with thermoplastic composites. Previous research has focused on improving compressive strength and stiffness of columns, while improvement in impact resistance has been largely unexplored. Therefore, the objectives of the current project were established as follows:

1. Execute an extensive literature review and assess existing concepts and loading requirements.
2. Study the feasibility of using new and innovative continuous-fiber thermoplastic composite structures using low-cost fabrication techniques that can be effectively integrated into new and existing bridge structures, providing effective operational performance functions as well as protection against various types of loading scenarios conduct the study in the following three steps:
   a. Investigate the improvement in energy absorption, ductility, and prevention in spalling of concrete provided by the thermoplastic wrap.
   b. Investigate the resistance of the thermoplastic to a debonding failure and determine whether sandblasting pre-treatment of the surface is necessary and practical.
   c. Investigate the improvement in impact resistance provided by the thermoplastic wrap.

1.2 Introduction

A barge striking a bridge on Interstate 40 in Oklahoma on May 26, 2002, caused the catastrophic failure of the bridge, killing fourteen people (Figure 1-1a). On May 23, 2003, a truck slammed into the center supports of a bridge on I-80 near Big Springs, Nebraska, causing the overpass to collapse (Figure 1-1b). A similar collision occurred on I-45 in Texas.

(a)   **(b)**
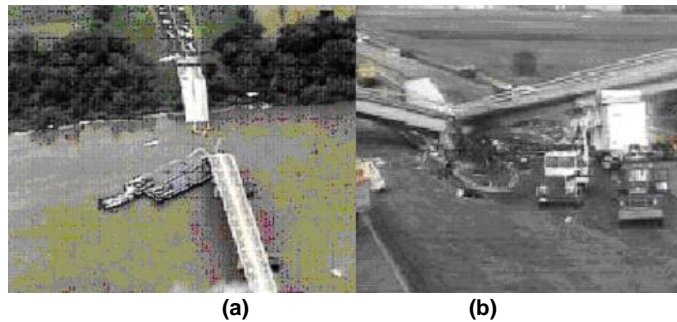
Figure 1-1. Bridge failures due to impact loads
(a) barge striking bridge on I-40 in Oklahoma, (b) accident on I-80 in Nebraska

These and other recent collapses of concrete bridge piers have demonstrated that the structures, while very strong under compression, are vulnerable to out-of-plane loading. In addition, out-of-plane loads can be caused by potential terrorist attacks. After the recent terrorism events in the United States, it is abundantly clear that the transportation-related physical infrastructure needs significant re-evaluation and revamping for risk and vulnerability assessment. Most structures are not designed with blast or impact loading in mind. Therefore, existing structural elements, e.g., bridge girders and piers, must be strengthened to increase the resistance to the dynamic loads. One of the most common ways to reinforce a structural element for earthquake or blast loading is to increase its mass. This increase can be achieved by applying additional concrete and steel reinforcement. Reinforcing structures using this technique can be time consuming and expensive. For this reason, a need has arisen for an expedient and efficient method for reinforcing existing highway bridge structures.

Most casualties and injuries sustained in terrorist attacks are not caused by the blast itself but rather by the disintegration of bridge bents (Figure 1-2). Bridge structures situated in regions of extreme natural or man-made events must be capable of dissipating energy without experiencing severe structural damage. Ensuring that bridge structures are able to withstand a blast or impact and not produce deadly collapse is an important part of minimizing injuries to the occupants of these facilities.

However, blast-resistant construction can also provide protection against natural hazards such as earthquakes and extreme wind events, for which there are building code requirements. Features typically added to improve blast resistance, such as reinforcing splices that increase ductility, impact-resistance glazing, and restraints on nonstructural elements, will improve building performance during earthquakes and extreme wind events, as well.

Figure 1-2. Example of damage to and existing bridge structure due to Northridge earthquake

Moreover, the collapse of and severe damage to many buildings and bridges in recent earthquakes have highlighted the need for the seismic retrofitting of seismically insufficient structures. Reinforced concrete (RC) columns, being the key lateral and vertical load resisting

members in RC structures, are particularly vulnerable to failures in earthquakes; therefore the retrofitting of these columns is often the key to a successful seismic retrofitting strategy. As a result, retrofitting of building and bridge columns has been carried out all over the world using fiber-reinforced polymer (FRP) composites. This work is supported by a great deal of research.

1.3 Fiber Reinforcement

Composite materials are formed by the combination of two or more materials to achieve superior physical and chemical properties. The main components of the composite materials are the fibers and the matrix. The fibers provide most of the stiffness and strength, while the matrix fastens the fibers together, providing the load transfer between the fiber and the composite.

Fibers are used in composites because they are stiff, strong, and lightweight. These properties are made possible because of the preferential orientation of molecules along the fiber direction and because of the reduced number of defects present in the fibers when compared with the bulk material. For example, the tensile strength of bulk E-glass (E for electrical) is low (1.5-5.8 Gpa); however, the same material in fiber form reaches 72.3 Gpa, mainly due to the reduction in the number and size of surface defects (Barbero 1999).

1.3.1 Fiber Types

The most common fiber types used in composite applications are glass, carbon, and Aramid. Boron, silicon carbide (SiC), alumina, and other fibers are used in some specialized applications. The optimum type of fiber for a particular application depends on the desired mechanical and environmental properties, as well as the cost of the fibers, as can be seen in Table 1-1 (Barbero 1999).

1.3.1.1 Glass Fibers

Glass fibers have typical properties of hardness, corrosion resistance, and inertness; they are also lightweight, flexible, and inexpensive. These properties make glass fibers attractive in low-cost infrastructure applications. All glass fibers have a similar stiffness, but different strengths and resistance to environmental degradation. E-glass fibers are used when high tensile strength and good chemical resistance are required, which makes these fibers a preference in structural applications because of their good mechanical performance, corrosion resistance, and low cost. S-2 glass fibers (S for strength) have the highest strength, but their limitation is that they are considerably more expensive (Barbero 1999).

Table 1-1. Typical properties and costs of glass, carbon and aramid fibers

Fiber Data	Fiber Density (lb/in^3)	Fiber Tensile Strength (ksi)	Fiber Tensile Modulus (Msi)	Strain (%)	Fiber Specific Tensile Strength (10^6 in)	Tensile Ratio	Fiber Specific Tensile Modulus (10^8 in)	Typical Price Per Pound ($)
Glass								
A-glass	0.089	480	10	7.8	5.4	1.1	6	.65-.90
C-glass	0.092	480	10	7.8	5.2	1.1	6	.75-1.00
E-glass	0.094	500	11	4.76	5.3	1.1	6	.75-1.00
S-2 glass	0.09	700	14	5.15	7.8	1.5	12	6.00-8.00
Carbon								
Heavy tow	0.063	525	33	1.59	8.3	5.2	44	9.00-12.00
Medium tow	0.065	740	35	2.11	11.4	5.4	61	15.00-20.00
Low tow	0.065	900	43	2.09	13.8	6.6	92	40.0-70.0+
Aramid								
Kev29	0.052	525	6	8.75	10.1	1.2	12	12.0-14.0
Kev149	0.053	504	27	1.86	9.5	5.1	48	25.0-30.0

1.3.1.1.2 Carbon Fibers

Carbon fibers, also known as graphite fibers, are lightweight and strong with outstanding chemical resistance. They are highly used in the aerospace industry. Contrary to glass fibers, which have one stiffness value, carbon fibers are available in a broad range of stiffness values. Two main raw materials used when manufacturing carbon fibers affect their properties. These are Polyacrylonitrile and pitch Polyacrylonitrile fibers. They govern the high performance markets in aerospace applications since they are made with a variety of stiffness and strength values. Pitch fibers are less expensive but have lower strength (Barbero 1999).

1.3.1.1.3 Aramid Fibers

The best known aramid fibers have trade names such as Kevlar, Technora, and Twaron. Aramid fibers have high energy absorption during failure, which makes them ideal for impact and ballistic protection. They have a low density, allowing them to have a high tensile strength-to-weight ratio and a high modulus-to-weight ratio, which makes them especially attractive for aircraft and body armor type applications. Aramid fibers are made of polymer materials, which give the fibers the characteristics of the polymer. These fibers have a low compressive strength; in addition, they creep, absorb moisture, and are sensitive to Ultraviolet light. Their mechanical properties also vary considerably with temperature (Barbero 1999).

1.3.2 Fiber Forms

Most fibers can be obtained as prepreg tape in which fibers are held together by an epoxy resin and a fiberglass backing. The production of the prepreg tape is labor intensive and thus induces additional cost. Consequently, most of the new applications in composites tend to use fibers in their simplest, unprocessed forms. For example, pultrusion and filament winding use roving or tow and resin to produce the final product without intermediate operations. Woven or stitched

fabrics facilitate the fabrication of laminates in resin transfer molding and other processes (Barbero 1999).

1.3.2.1 Discontinuous and Continuous Fibers

Composites are reinforced with two different types of fibers: continuous or discontinuous. Continuous fibers are long fibers that usually attain maximum values in properties such as strength and stiffness due to the low number and size of surface defects. Continuous fibers are usually oriented along the direction in which the load is applied (Barbero 1999).

Discontinuous fibers are short fibers that are obtained by chopping the continuous fibers; they can also be directly produced as short-fibers to reduce fabrication costs. The aspect ratio (length over diameter) significantly affects the properties of short fiber composites. The orientation of the discontinuous fibers cannot be easily controlled and is assumed to be random, and these fibers usually have lower strength when compared to the continuous fibers (Barbero 1999).

1.3.2.2 Mat, Fabric, and Veil

A mat is formed by randomly oriented chopped filaments, short fibers, or swirled filaments loosely held together with a small amount of adhesive. A veil is a thin mat used as a surfacing layer to improve corrosion resistance of the composite. Veils and mats have fibers randomly oriented in all directions.

On the other hand, fabrics (Figure 1-3) are a two-dimensional reinforcement. Woven fabrics can be made by knitting but generally are made by weaving of yarns. Nonwoven fabrics are made directly of strands, without the intermediate twisting of the strands into yarns. Stitched nonwoven fabrics can be made into very heavy fabrics thus reducing the time and cost of composite processing, provided that they can be adequately infiltrated with resins. Fabrics can be created with off-angle layers (e.g., + or – 45°) allowing several advantages in design and performance.
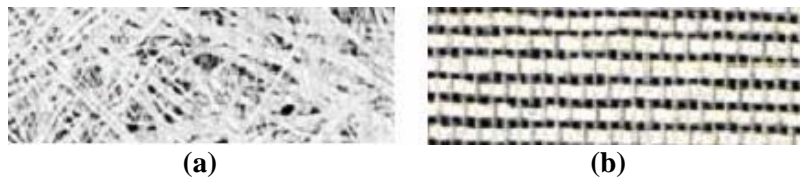
(a) **(b)**
Figure 1-3. Illustration showing the difference between
(a) randomly oriented fibers and (b) unidirectional woven fabric

1.4 Research on Seismic Retrofitting Using FRP

In the USA, seismic collapse or damage was experienced by columns built before the 1971 San Fernando earthquake under old design and construction practices. Major changes in seismic design philosophies in the USA were implemented after this earthquake. The building code in Japan was revised in 1981 to set more stringent requirements for seismic resistance as a result of developments after the 1968 Tokachi-Oki and the 1978 Miyagi-ken Oki earthquakes.

In general, structures designed using the new seismic design codes have performed well in subsequent earthquakes. However, structures designed using old codes do not meet the more stringent seismic design requirements of the new codes. Thus, seismic retrofitting of these older structures, particularly RC columns, has been an important issue in the USA and Japan. Similar situations exist in many other countries.

When a column is subjected to seismic loading its energy absorption capacity, rather than its load capacity, is the main concern. Traditionally, the former capacity is enhanced by RC jacketing or steel jacketing. Both methods have a number of disadvantages. In addition, steel and concrete jacketing result in a significant increase of column stiffness, which may lead to additional earthquake forces being experienced by the retrofitted columns.

In the mid 1980s, Katsumata et al. (1987, 1988) first proposed the use of FRP composite materials to retrofit existing RC columns to achieve improved seismic resistance. They tested five circular and 10 rectangular quarter-scaled columns with and without laterally wound carbon fiber strands to study their performance under combined axial and cyclic lateral loads. Later, Matsuda et al. (1990) identified two retrofitting methods for RC bridge columns using FRP composites: (a) strength-oriented retrofitting, and (b) ductility-oriented retrofitting. In the first method, FRP plates were longitudinally bonded to increase the flexural strength of the column (i.e., longitudinal bonding of the FRP); in the second method, FRPs with fibers or main fibers in the hoop direction were wrapped around the column (i.e., lateral bonding of the FRP) to enhance its ductility as proposed by Katsumata et al. (1987, 1988). Both methods were found to improve the energy absorption capacity of the column.

A successful example of FRP seismic retrofitting of RC columns is a seven-storey hotel in Los Angeles. The columns in this hotel suffered significant diagonal cracks as a result of the magnitude 7.5 Landers earthquake on June 28, 1992, which was centered 175 km away from the building. The retrofitting of these columns using glass-fiber-reinforced plastic (GFRP) jackets was completed a few weeks before the 1994 Northridge earthquake, and the building suffered no damage during this earthquake.

1.5 Strengthening of Axially and Eccentrically Loaded Columns

In the early 1990s, constructing an additional reinforced concrete cage and installing grout-injected steel jackets were the two common methods for strengthening a deficient RC column (Ballinger et al. 1993). Steel jacketing is more effective than caging because the latter results in a substantial increase in the cross-sectional area and self-weight of the structure. However, both methods are labor intensive and difficult to implement on site. In addition to being heavy, steel jackets are also poor in resisting weather attacks (Ballinger et al. 1993, Demers and Neale 1999). In recent years, the technique of strengthening RC columns using FRP composites has been used increasingly to replace steel jacketing (Ballinger et al. 1993; Saadatmanesh et al. 1997; Seible et al. 1997). The most common form of FRP column strengthening involves the external wrapping of FRP sheets/straps.

The strengthening of existing RC columns using steel or FRP jacketing is based on the well-established fact that the lateral confinement of concrete can substantially enhance its axial compressive strength and ductility (Richart et al. 1928, 1929; Ahmad and Shah 1982; Mander et al. 1998). Many studies have been conducted on compressive strength and stress-strain behavior of FRP-confined concrete (e.g., Fardis and Khalili 1981; Ahmad et al. 1991; Harmon and Slattery 1992; Demers and Neale 1994; Howie and Karbhari 1994; Nanni and Bradford 1995; Karbhari and Gao 1997; Mirmiran et al. 1998a; Demers and Neale 1999; Miyauchi et al. 1999; Purba and Mufti 1999; Saafi et al. 1999; Toutanji 1999; Rochette and Labossiere 2000; Xiao and Wu 2000; Zhang et al. 2000). These studies have shown that FRP-confined concrete behaves differently from steel-confined concrete (Mirmiran et al. 1997; Samaan et al. 1998; Saafi et al. 1999; Spoelstra and Monti 1999), so design recommendations for steel-confined concrete columns cannot be applied to FRP-confined columns, despite the apparent similarity between these types of columns.

1.6 Methods of Strengthening Columns

A number of different techniques have been developed for strengthening existing RC columns using FRP composites. The aspects described in this section are common to both strengthening under static loads and seismic retrofitting, but specific issues in seismic retrofitting are addressed in an upcoming section of this report. The methods for strengthening can be placed into the following three categories in terms of the method adopted for constructing the FRP composite: (a) wrapping, (b) filament winding, and (c) prefabricated shell jacketing.

1.6.1 Wrapping

In situ wrapping has been the most common technique for column strengthening using FRP composites. In this method, unidirectional fiber sheets or woven fabric sheets are impregnated with polymer resins and wrapped around columns in a wet-lay-up process, with the main fibers oriented in the hoop direction. A column can be fully wrapped with FRP sheets in single or multiple layers, but it can also be partially wrapped using FRP straps in a continuous spiral or discrete rings.

The compressive strength enhancement of concrete due to external wrapping of FRP was first demonstrated by Fardis and Khalili (1981, 1982). This concept was first applied to the strengthening of real RC columns in Japan in the mid 1980s [American Concrete Institute (ACI) 1996]. There have been many reports of the application of this technique in the retrofitting of bridge and building columns since then (e.g., ACI 1996; Neale and Labossiere 1997; Tan 1997).

1.6.2 Filament Winding

The principle of filament winding is similar to wrapping, except that the filament winding technique uses continuous fiber strands instead of sheets/straps so that the winding can be processed automatically by means of a computer-controlled winding machine. An FRP jacket with controlled thickness, fiber orientation, and volume fraction can be produced by this process. The idea of confining concrete by winding continuous resin-impregnated fiber strands was first

mentioned by Fardis and Khalili (1981). The first winding machine for column retrofitting was developed in Japan in the mid 1980s (ACI 1996).

1.6.3 Prefabricated Shell Jacketing

Existing RC columns can also be strengthened using prefabricated FRP shells. The shells are fabricated under controlled conditions using fiber sheets or strands, with impregnation by resins before field installation. They can be fabricated in half-circles or half-rectangles (Nanni and Norris 1995), in circles with a slit, or in continuous rolls (Xiao and Ma 1997), so that they can be opened and placed around the columns. To achieve effective FRP confinement, full contact between the column and the FRP shell is essential. This contact can be ensured by either bonding the shell to the column using adhesives (Xiao and Ma 1997), or injecting shrinkage-compensated cement grout or mortar into the space between the shell and the column (Nanni and Norris 1995). An interesting application of prefabricated shells is for formwork in modifying column shapes as part of a strengthening measure. This has recently been discussed by Teng et al (2002), who suggested that square or rectangular columns can be strengthened by reshaping them into circular or elliptical columns in which a prefabricated FRP shell is used to provide both the permanent formwork and the required confinement after the curing of concrete.

1.6.4 Comparison of Strengthening Methods

Each of the methods discussed above has its advantages and disadvantages, as listed in Table 1-2. Overall, external wrapping appears to be the most popular method because its advantages (flexibility and ease in site handling) appear to be far more important than its disadvantages. Filament winding bears much similarity to wrapping because both involve a wet-lay-up process, so in the rest of this chapter the term "wrapping" is used to cover both methods, except when specific distinction has to be made between the two.

1.6.5 Constructional Aspects

Before FRPs are applied using any of these techniques, the column should be properly prepared to provide a hard, dry, and clean surface. Any damaged or deteriorated parts should be removed and the surface patched with good concrete, cement mortar, or epoxy putty as appropriate. The repaired surface should be toweled.

Table 1-2. Comparison of different methods of column strengthening (Teng 2002)

Method	Advantages	Disadvantages
Wrapping	Flexibility in coping with different column shapes Ease in site handling, without the need for special equipment	Least quality control Most labor intensive
Filament winding	Improved quality control Reduced on-site labor	Reduced flexibility in coping with different column shapes Special equipment required
Prefabricated shells	Best quality control Least on-site labor Useful for column shape modification	Limited flexibility in coping with different column shapes High prefabrication cost

Strengthening rectangular columns by wrapping requires that their corners be rounded. This is necessary to reduce any detrimental effect of the sharp corners on the tensile strength of the FRP and to enhance the effectiveness of confinement. If rectangular prefabricated shells are used instead, the shells are generally slightly oversized and their corners rounded, with the small gap between the shell and the column filled with expansive or nonexpansive cement grout (Nanni and Norris 1995). The same rounding treatment should be applied to other column shapes with corners.

Whether wrapping or prefabricated shell jacketing is used, one or more vertical joints exist in the FRP. They should be made strong enough that FRP joint failure does not become the strength-controlling failure mode, because otherwise the strength of the FRP is not fully utilized. When the FRP is wrapped continuously, a sound confinement can be achieved by extending the end of the final layer of the FRP to form sufficient overlap. When an FRP shell with a vertical slit in each layer is used, an additional FRP strip should be bounded over the vertical seam (for a shell consisting of a large number of FRP layers) to avoid concentration of seam weakness. In the latter case, the effective number of layers should be taken as the total number minus one to account for the weakening effect of the slits (Xiao and Ma 1997).

In most cases, the FRP confinement obtained is passive in nature, with hoop tensile stresses developing in the FRP as the concrete expands. Active confinement methods with FRP jackets have also been explored (Saadatmanesh et al. 1997). The FRP jacket is slightly oversized so that active confinement is achieved. The space between the FRP shell and the original column is then filled with expansive cement grout or pressure injected with epoxy resin (Priestly and Seible 1995; Saadatmanesh et al. 1997). Alternatively, the fibers may be prestressed during wrapping so confining pressure is developed to the column before any subsequent expansion of concrete occurs.

1.7 FRP Jackets with Horizontally Oriented Fibers

External FRP jackets can enhance both the shear capacity and the ductility of columns against seismic attacks. Such FRP jackets can be formed either in a wet-lay-up process by wrapping fiber sheets or winding fiber strands with resin around the column so the fibers or main fibers are generally horizontally oriented, or by prefabrication. Under shear forces, the tensile stresses in the FRP contribute to the overall shear resistance of the column, similar to the effects of FRP in shear strengthening of beams. Under flexure the FRP provides confinement, which enhances the strength and ultimate strain of the concrete. The enhancement to the ultimate concrete strain is particularly important for seismic retrofitting because it allows a much greater ductility level to be achieved in elastic deformations.

Details of FRP jacketing methods for columns were discussed in an earlier section and are not repeated here. For shear strengthening, the FRP jacket is generally required to cover the entire column height; however, for plastic hinge confinement and for lap splice clamping, the FRP jacket is generally only needed in the plastic hinge and nearby regions. Small gaps (around 20 mm) have been recommended between the ends of the FRP jacket and any adjacent transverse structural member to prevent direct axial loading of the jacket.

If shape modification is adopted for more effective confinement in the seismic retrofitting of rectangular columns, this shape modification needs to be implemented only for the plastic hinge and nearby regions. This is different from the strengthening of axially loaded columns, for which this shape modification should extend over the full column height. The gaps between the ends of the column and the ends of the additional concrete should be appropriately larger than those gaps for columns without shape modification to avoid direct loading of the additional concrete and the FRP jacket.

1.8 Ductility of Retrofitted RC Columns

The purpose of the seismic retrofitting of RC columns is to achieve a sufficient level of deformation ductility to dissipate seismic energy before one of the failure modes becomes critical. A large number of studies testing concrete specimens under cyclic loading (Priestley and Seible 1995; Saadatmanesh et al. 1997, Seible et al. 1997; Xiao and Ma 1997) have shown that lateral FRP confinement is effective in enhancing ductility of RC columns under seismic attacks.

1.9 Ultimate Conditions of Retrofitted Columns

Most of the cited studies involved testing the overall performance of RC columns after FRP retrofitting. In these studies, the specimens were retrofitted to such a degree that none of the typical failure modes discussed earlier was observed before the test was stopped at a sufficiently high ductility level, or at the occurrence of a nonfatal secondary failure such as local delamination of FRP. While useful in demonstrating the effectiveness of FRP seismic retrofitting, the results from these studies do not provide sufficient information for a precise definition of the ultimate condition of the column in any of the failure modes, except to show that a particular retrofitting design is sufficient to prevent failure in these modes at the desired ductility level. Only a limited number of the studies involved the ultimate condition of retrofitted columns failing in a particular mode.

1.9.1 Shear Failure

For shear strengthening, Priestley et al. (1996) believed that, unlike steel, the full tensile capacity of the FRP could not be used because the relatively large strain reached in the FRP would lead to a reduction in the shear resistance contributed by the concrete aggregate interlock under cyclic loads. However, there is another reason that this full tensile capacity cannot be used. The FRP is nonuniformly stressed in a shear failure, and because of its lack of ductility, is unable to reach its full tensile strength over the entire shear crack.

Priestly and Seible (1995) suggested that when the shear resistance contributed by FRP is calculated, the ultimate tensile strength of the FRP should be limited to a tensile stress corresponding to a strain of 0.004 to avoid degradation in concrete aggregate interlock. Mutsuyoshi et al. (1999) tested four rectangular columns with strong longitudinal steel reinforcement to study shear failure in RC columns under combined axial and cyclic lateral loads. The experimental results showed the yielding of the transverse steel reinforcement; however, finite-element analysis indicated that shear failure by concrete crushing could also be possible for columns with a large amount of FRP.

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1.9.2 Flexural Plastic Hinge Failure

For plastic hinge zone retrofitting of columns without lap-spliced longitudinal steel reinforcement, FRP confinement can enhance the ultimate strain of concrete. The ultimate condition of the FRP jacket is FRP rupture. Mutsuyoshi et al. (1999) tested four rectangular columns with strong shear reinforcement and without lap-spliced longitudinal reinforcement under combined axial and cyclic lateral loads. Two of the three columns wrapped with continuous-fiber-reinforced polymer showed rupture of the FRP at failure. The third column, which had the highest amount of continuous-fiber-reinforced polymer, showed crushing of concrete at the bottom without FRP rupture.

1.9.3 Lap Splice Failure

For plastic hinge zone retrofitting of columns with lap-spliced longitudinal steel reinforcement (Figure 1-4), FRP confinement must provide a clamping stress to avoid lap splice failure. For these columns, the dilation strain of concrete should be limited to 0.001; otherwise, relative movement and debonding of the longitudinal bars are likely to occur. Thus, the ultimate condition is characterized by the FRP jacket reaching a stress corresponding to a hoop tensile strain of 0.001.

Xiao and Ma (1997) developed an analytical procedure to predict the behavior of columns with lap splice deterioration. They suggested that debonding of the lap splice be allowed in the retrofitted column as long as the yield of the longitudinal bars could be developed. If this suggestion is adopted, a more liberal limit to the hoop strain in the FRP jacket is expected to be acceptable.

Figure 1-4. Lap splice failure at column base in the 1989 Loma Priesta earthquake (Priestley et al. 1996)

Section 2.0
Background

2.1 Civil Engineering Applications of Thermoplastic Composites

Thermoplastic composites, a relatively new material, evolved from conventional thermoset composites. Both thermoplastic and thermoset composites have been used extensively in the aerospace industry and are becoming ever more prominent due to their excellent strength-to-weight ratios. The U.S. market for thermoplastics is one billion pounds per year; about half of which is used in the automotive industry (Hartness et al. 2000). FRPs have been used to retrofit bridge structures. Reinforcement with FRPs has some significant advantages when compared with traditional steel reinforcement; FRPs offer a reduction in weight and are corrosion resistant, and the anticipated entire life-cycle cost of using composite materials will be lower than that of using steel (Plecnik and Henriquez 2000). Thermoplastic materials also possess the excellent properties of FRPs; furthermore, they offer considerable advantages.

2.2 Concerns with Infrastructure Applications of Thermoplastics

One reason that thermoplastics are less known to civil engineers is that until recently the processing and molding of thermoplastics were difficult. While FRPs have had limited use in civil engineering, the potential of thermoplastics remains largely unexplored. The present project investigated the potential.

Recent innovations have alleviated these problems (Johnson and Greene 2000). Another concern that has limited the use of thermoplastics is the perception of their weakness under extreme temperatures. Thermoplastics can be repeatedly softened by heat. Table 3 shows the maximum temperatures at which various plastics may be used. Clearly, although thermoplastics are more vulnerable than thermosets to extreme temperatures, normal temperatures in highway applications are well within the safety limits of thermoplastic materials.

The proposed application for composites in reinforcing bridge piers is to withstand high-energy impacts of a short duration. Although the continuous-use temperatures would be well within limits, one concern with this application is that these impacts could generate a considerable amount of heat, weakening the composite. It has been found that glass-reinforced thermoplastics tested to 204 °C experienced considerable weakening; the longitudinal and transverse tensile strengths were lowered to approximately 85 percent and 37 percent of their original values, respectively (Milke and Vizzini 1993). Whether the composites would be exposed to such temperatures in a short collision is not known. However, it is doubtful that softening would have a considerable effect on the initial resistance to the impact. At the very least, as the composite is being heated, it would provide a progressive and not catastrophic failure.

An important consideration in the application of composites to bridge piers is their environmental durability. Indeed, one major advantage of composites when compared with traditional steel reinforcement is their improved corrosion resistance. However, information on

other aspects of environmental durability is limited. Although there are some data indicating that composites are weakened by freeze-thaw cycles exists, no long-term data are available (Liao et al, 1995). Natural weathering has also been found to degrade composites.

Table 2-1. Maximum continuous-use temperatures of plastics Mazumdar (2002)

Materials	Maximum Continuous-Use Temperature (°C)
Thermosets	
Vinylester	60–150
Polyester	60–150
Phenolics	70–150
Epoxy	80-215
Cyanate esters	150–250
Bismaleimide	230–320
Thermoplastics	
Polyethylene	50–80
Polypropylene	50–75
Acetal	70–95
Nylon	75–100
Polyester	70-120
PPS	120–220
PEEK	120–250
Teflon	200–260

The use of composites has been limited by high initial cost, but it is believed that superior corrosion resistance will lead to lower long-term life-cycle costs. Also an issue is the increased difficulty in making connections; connections in composites are not as efficient or as easily designed as bolted and welded connections in steel (Plecnik and Henriquez 2000). However, the application in the current investigation involves no connections; therefore, this consideration is not an issue.

2.3 Advantages of Continuous-Fiber Glass/PP

Thermoplastic composites consist of two elements: a thermoplastic matrix and a reinforcing fiber. These two components work complementarily to achieve dramatic strength improvement. The thermoplastic matrix provides the rigidity and the shape of the material, and transfers the load to the fibers (Mazumdar 2002). It also protects the fibers from abrasion (Vaidya 2001). The fibers are molecularly aligned, which allows them to bear remarkable loads; 70 percent to 90 percent of the load in a composite.

The concept of a composite formed by a material with fiber reinforcement is not new, or even devised by human beings; in fact, wood is one such composite, consisting of a matrix of glue reinforced with cellulose fibers (Mazumdar 2002). Composites made with thermosetting resins have been shown to possess some excellent properties such as high specific strength, good impact resistance, and excellent resistance to corrosion [A to Z of Materials (AZOM) "Polymer Matrix Composites" 2002]. However, thermoplastic composites have been found to exhibit these properties and to have considerable advantages over the older thermosetting composites. Thermosets are unstable in their prepregnated form, giving them a limited shelf life. Thermoplastics, on the other hand, have an unlimited shelf life (AZOM "Thermoplastic

Composites" 2002). While thermosets require a chemical process to cure and can emit hazardous materials, thermoplastics do not have these disadvantages (Johnson and Greene 2000). In addition, thermoplastics are less brittle and have improved impact resistance. When an impact does damage the composite, the damage is more perceptible in thermoplastic materials. On the other hand a thermosetting material may be weakened without any visible signs (Johnson and Greene 2000).

Fiber-reinforced plastics are available with both short fibers and continuous fibers. Short-fiber reinforcement is a less expensive way to improve the properties of the plastic. Reinforcement with short glass fibers increases the cost of the composite 1.5 to 2 times that of the original plastic. Continuous fibers are needed for high-performance applications, and it is this type of composite that is now competing with thermosets (Long 2000). The Southern Research Institute (SRI) uses a novel system, called the DRIFT process, to produce thermoplastic composites with continuous fibers at costs close to those of short-fiber plastics (Hartness et al. 2000). The DRIFT process involves hot-melt impregnation, a procedure in which the resin is melted and the fibers are impregnated into the resin at very high speed.

One advantage of the DRIFT process is that wraps can be created to a desired thickness, whereas conventional thermoset wraps are created with uniform thickness. Thus, to achieve the desired strength, it is not necessary to use multiple plies of material and risk an internal delamination at a layer face when the structure is subjected to impact.

The choice of glass-fiber-reinforced polypropylene (PP) is largely economically motivated. PP is one of the fastest-growing thermoplastics in production, and offers excellent properties at a moderate cost. Because of the low cost of long-fiber PP, it has been replacing the older and more expensive glass-mat thermoplastics (Mapleston 1999). PP has also been called the "least fussy resin" because it readily bonds to many types of reinforcement (Leaversuch 1999). Glass fibers are cost-effective and useful in a broad array of applications (Zebarjad et al. 2003). Materials reinforced with carbon or aramid fibers can be two to four times as expensive as glass fiber materials (Long 2000).

A property alluded to earlier that is of high importance in the present investigation is the impact strength of the material. In most cases, this strength is measured by "notched Izod" testing. The impact strength is given by the amount of momentum that the sample absorbs during breaking (Instron 2003). This property is extremely important in the current project because it is hoped that the thermoplastic material can absorb large amounts of momentum from impacts.

Table 2-2 demonstrates the favorable properties of the E-glass/PP used in this investigation. Glass-reinforced PP has been used extensively in impact-resistance applications. For example, this material has been used in automobile fenders, in an ammunition box that can withstand a seven-foot drop at –54 °C, and in a Black and Decker machine which can fall six feet without incurring damage (Stevens 1999).

**Table 2-2. Properties of reinforced plastics compared
(Hartness et al. 2000) and AZOM "Epoxy Laminate" 2002)**

Material	Tensile Strength (MPa)	Tensile Modulus (Gpa)	Tension Strain (%)	Impact Notched Izod (KJ/m)
40% E Glass/Polyethylene	110	6.9	2.23	1.360
40% E-Glass/Nylon 6	145	11.7	1.7	.209
60% E Glass/Polypropylene	669	29.7	2.42	No break
50% S-2 Glass/Polypropylene	455	17.4	3	No break
Epoxy/Kevlar	500	25	N/A	1.0

Section 3.0
Approach

3.1 Scope of Work

In the present work, we propose to investigate the feasibility of applying enclosures for columns and piers of bridges using thermoplastic composites to reduce vulnerability. The various tests conducted during the course of this feasibility study involved:
1. an extensive literature review that was carried out on composites in general, and thermoplastics in particular,
2. manufacture of low-cost thermoplastic composite wraps,
3. bond characterizations tests between concrete and polypropylene,
4. development and implementation of a method for retrofitting concrete cylinders with glass-reinforced polypropylene(glass/pp) confining jackets,
5. ballistic impact tests conducted on concrete panels reinforced with glass/pp as well as plane glass/PP panels, to determine the energy absorption capacity and ballistic limit, and finally
6. finite element numerical model to replicate the ballistic impact test results.

The successful development of the retrofitting method included the following tasks: (a) determining a heating profile that allows maximum bonding between the composites without causing deterioration in the confining jacket; (b) determining the length of overlap of the confining jackets that will allow for adequate confinement and a passive type of failure mode; (c) development of a retrofitting technique that will provide temporary confinement to the confining jacket during placement in the thermoplastic heater.

A significant amount of time was spent on the initial phase of the project to perform a complete and thorough literature survey. Most previous studies of composites in bridge structures focused on the use of thermoset prepreg composites to enhance strength/stiffness, with little consideration given to impact/blast types of loading. Recent work by investigators in the area of thermoplastic composites has shown a significant potential to produce cost effective solutions for protective enclosures that can be used in bridge members. The current research is a first step toward a long-term goal of studying the feasibility of new design concepts where thermoplastic protective enclosures are applied to new and existing bridge piers to reduce and even prevent the damage due to impact loads while protecting the occupants of the structure from serious injury. The work is new and open to significant development and consortis, and collaborative efforts will be required to develop and further improve future research.

3.2 Manufacture of Thermoplastic Composite Material to Be Used For Confining Column Jackets

SRI, in Birmingham, Alabama, developed new hot-melt impregnation technologies that are capable of combining various high strain-energy fibers with a wide variety of tough thermoplastic polymers to produce extremely low-cost composite products. Continuous low-cost carbon or

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glass-fiber tows are pultruded through a heated die. During this process, the individual filaments are wetted with a thermoplastic resin such as PP, PC, or nylon. The wet tow is then cooled; at the end of the line, the tow can be chopped into pellets of preferred length, maintained as continuous tow rods, or woven into tape form. If the tow is pelletized into long fibers, the resulting product has properties of superior strength and toughness when compared with those of unreinforced or short-fiber-reinforced thermoplastics. The strain-to-failure value of the long-fiber-enhanced concrete structure is expected to exceed traditional values by one order of magnitude.

The design and manufacture of the glass/PP have been completed in a conjunct effort by UAB and SRI. Representatives of the two institutions discussed the details of the material forms and quantities. Glass/PP tapes were manufactured at SRI and woven into 20 square yards of plain weave material (Figure 3-1).

Figure 3-1. Sample of PP tape produced by SRI

3.3 Retrofitting Concept

Thermoplastic composites offer significant advantages of tolerance to impact and blast damage. The new approach to solving the problem of catastrophic bridge failure involves designing a composite system that can be built quickly in place with existing technology. The steps required for strengthening a bridge structure include: (a) cleaning and priming the structural member surface(s), filling the cracks or pores flush with the surface of the structural members, (b) applying a thin layer of coating, and (c) placing the thermoplastic composite protective enclosure and pressing it firmly against the structural elements (Uddin and Vaidya 2002).

Although the proposed application is novel, thermoset and thermoplastic composites have already been shown to be efficacious in reinforcing concrete and masonry. Karbhari and Eckel (1993) investigated the use of resin-infused composite wraps to strengthen concrete columns under compressive axial load. It was found that a wrap of four layers of woven glass composite increased the compressive strength by 94 percent. Yao, et al. (2001) studied the effects of glass fiber tubes on seismic resistance of concrete columns and found that, under simulated earthquake conditions, the composite-reinforced columns performed significantly better than the columns with traditional steel reinforcement.

A composite wrap is a type of concrete confinement. Harries and Kharel (2003) studied the topic of general concrete confinement, finding that the compressive strength of concrete increased as confining pressure was increased and that, as a result, spalling was prevented. The composite retrofitting provided passive confinement. As the concrete deformed, a confining pressure was induced in the deformed composite. The excellent tensile properties of composites allow the composites to exert high confining pressure, making them ideal for this type of confinement. On the other hand, some reinforcements are prestressed, which gives active confinement to the concrete (Kestner et al. 1997). Exterior reinforcement with composites not only prevents spalling, but also failure by bending moment. Tumialan, et al. (2003) investigated concrete and clay unreinforced masonry walls strengthened with FRP material. Flexure was provided to simulate the out-of-plane loads that would be produced in earthquakes and high-speed winds. The FRP was applied along the side of the wall in tension. The high tensile strength of the FRP allowed it to considerably strengthen the walls against flexure.

The present effort will explore thermoplastic composite material produced in continuous pultruded form to produce a cost-effective split product form of directionally oriented glass fiber in polyurethane (or polypropylene) thermoplastic matrix for a representative bridge column. Two split halves will encapsulate the column with on-site mounting feasibility. The advantage of using pre-fabricated thermoplastic forms is they can be thicker than conventional thermoset wraps (such as presently used in bridge structures, only from a standpoint of enhancing stiffness/tensile strength). It is feasible that under impact from unknown threats such as collisions from trucks/trailer or blasts, the structure has progressive failure potential, in place of catastrophic fracture presently witnessed. The tape and pultruded thermoplastic form have flexibility to accommodate curvatures encountered as part of the structure. The proposed reinforcement scheme is shown in Figure 3-2. The split halves can be connected by a combination of thermoplastic tape wraps around the halves and a secondary mechanical reinforcement. Furthermore, the rate of strain induced on the structure is severe. The pultruded and tape form of polypropylene/carbon and polypropylene/glass is expected to enhance failure stress by several orders of magnitude.

Joining thermoplastic tape rings to join the split halves. Secondary mechanical bonding will also be provided

Glass/PP pultruded split shells to encapsulate column structures
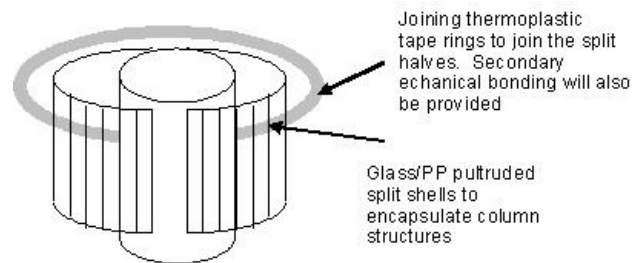
Figure 3-2. The proposed retrofitting technique

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3.4 Material Characterization and Structural Testing

The testing program (Table 3-1) 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. In addition, the retrofitting allowed the columns to achieve large inelastic flexural deformations, and enhance the resistance of lap splices to debonding or slippage through providing a clamping pressure. Therefore, the overall objective of this proof-of-concept experimental program (Table 3-1) is twofold:

Table 3-1. Table of specific tests

Task	Specimens	Test Plan & Purpose
a) Baseline column samples 6" X 12" cylinders	1- control and 3 samples wrapped with thermoplastic jackets	Static in-plane compression loading; Purpose - Assess baseline performance.
b) Pull-off test	3 - 3" x 4" x 16" prisms laminated with one layer of thermoplastic jackets	Purpose- determines shear strength of the bond between the thermoplastic wrap and the concrete surface.
c) In-plane Shear test	3 - 3" x 4" x 16" prisms laminated with one layer of thermoplastic tape	Purpose – determines behavior of the interface between the concrete substrate and thermoplastic tape.
d) Ballistic Testing	1 control and 4 - 8" x 11" concrete panels laminated with one layer of thermoplastic tape	Composite panels exposed to projectile impact. Purpose- determines impact resistance of the concrete panels laminated with thermoplastic composite and generates input parameters for FE modeling of piers.

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

Results from the static in-plane compression loading tests will be used to evaluate the peak strength and stiffness, and to identify potential debonding problems. An understanding of the stress-strain behavior of FRP-confined concrete is necessary for the design of FRP strengthening measures for a pier, particularly when the pier is subjected to combined bending and axial load and when its ductility is of concern. Such information would provide the basis for the development of design parameters and formulations for strategic external reinforcement of a bridge structure against impact, blast, or earthquake loading.

For ballistic testing, the fiber-reinforced structural panels produced through the cost-effective process were subjected to a series of high-velocity-impact tests in a gas gun set up at the UAB laboratory (Figure 3-3). The gun consists of a 22" barrel, a firing chamber, and a capture chamber. The sample is placed in the capture chamber. The gas gun can launch sabot-assisted projectiles of very high velocities. Sabots of 3.81-mm (1.5") diameter can be launched at velocities of 1,000 m/sec. These tests enabled the researchers to understand the penetration mechanisms and to quantify the damage that occurred. In the current work, the investigation

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mainly involved the dynamic response of the wall panels. A transparent optical window attached with chronographs recorded the incident and the residual velocity of the projectile.
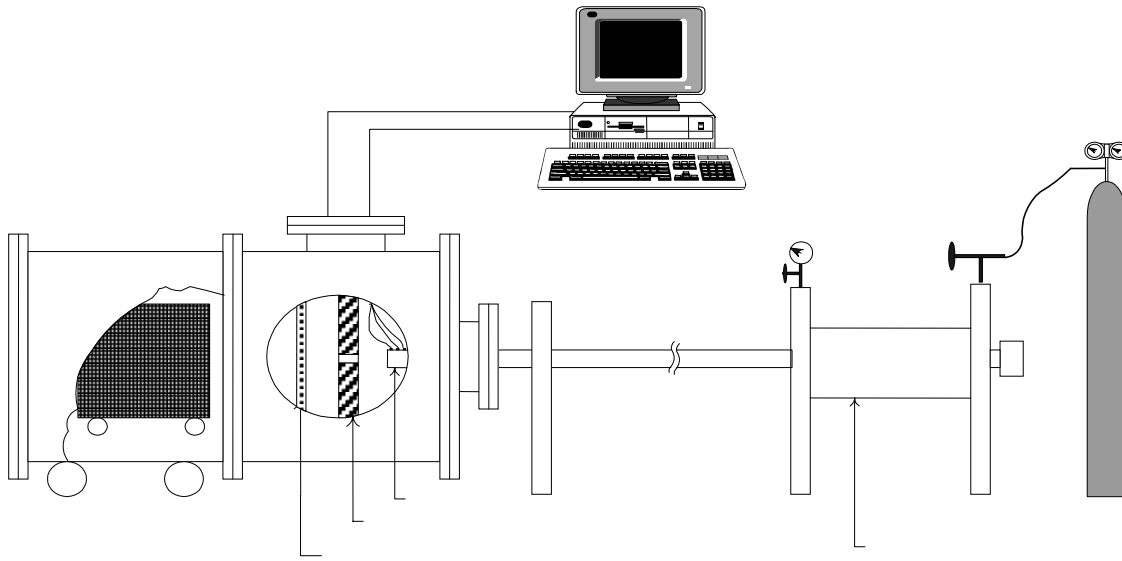
Figure 3-3. Schematic of the high-velocity gas gun showing the main features

Section 4.0
Experimental Program and Results

4.1 Introduction

The purpose of the current study was to investigate a new material that might prevent the catastrophic failure of bridge piers and allow progressive failure. The experimental program had two objectives: (a) to understand the nature of failure of concrete cylinders that are representative of a bridge pier and (b) to determine how compressive failure can be prevented by the thermoplastic wrap and how the wrap will change the mode of failure from a sudden or catastrophic type to a progressive type.

To the researcher's knowledge, the present study is the first attempt to examine the feasibility of use of thermoplastic wraps for concrete structures. Therefore, significant efforts were undertaken to understand the fundamental behavior of the retrofitting scheme including bonding. The first stages of testing involved determining the characteristics of the materials and behavior with the concrete specimens in terms of bonding and wrapping. Detailed systematic studies were done to assess the bond strength of the concrete and the thermoplastic tapes. The second step entailed accomplishing the proof of concept, which was achieved through compressive testing of composite
cylinders and
showing that the barreling effect (if achieved) would cause the samples to maintain integrity after failure due to high axial compressive loads and not the brittle sudden failure of concrete cylinders.

To apply thermoplastic tape around the concrete samples, a heating source was needed. Watlow, Inc. supplied a radiant heater. The heater demonstrated excellent performance with the 4"x 8" and 6"x12" samples, creating perfect bonding on the PP tape. However, some issues were encountered with the 6"x 24" samples, in which the desired bond strength was not attained. Research is in progress to resolve the larger specimen issue for laboratory and field specimens.

Laboratory testing showed that the glass/PP tape provided the required barreling effect. The testing also indicated that the tape provided the type of confinement that allowed a passive type of failure.

The second stage of testing included demonstrating the energy absorption capacity of the thermoplastic tape that would help bridge piers resist out-of-plane loads such as impact from trucks or possible explosions due to terrorist attacks. This was achieved by replicating impacts through ballistic testing using a fragment simulating projectile.

4.2 Specimen Construction Details

The laboratory research began with the construction of concrete samples for retrofitting with the thermoplastic wrap. Forty-eight 6"diameter) x 24" cylinders were cast, along with ten 3"x4"x16" prisms and eighteen 4"x8" cylinders. However, four cylinders, three prisms and three small size cylinders were used for the tests as described in Table 3-1.

Glass-reinforced PP is a relatively new material in the field of civil engineering, in which most previous research was focused on FRPs rather than on fiber-reinforced thermoplastics. As a result it was realized early in the project that many of challenges existed; therefore, a large number of samples was created. The remaining samples were needed to optimize the processing and for the future research. To ensure regularity and consistency of results, all samples were cast from the same batch. Since a large-capacity concrete mixer was not available in UAB's structural laboratory. A ready-mix company was engaged for that task. The nominal strength of the concrete that was specified for Sherman Ready-Mix was 4500 psi.

To obtain the 6"x 24" samples, 12-foot Sono-Tubes with 6" diameters were used for the molds and were cut to the required size. Some difficulty was encountered with maintaining a flat surface during the cutting of the tubes. Finally two 6"x12" plastic molds were glued together to obtain the required sample size. Vibrators were used to help consolidate the concrete to eliminate air bubbles and to reduce honeycombing.

The concrete was kept in the molds for 24 hours; then the samples were removed from the molds and placed in the curing tank for 28 days. After seven days, three 4"x8" samples were removed from the curing tank, allowed to dry, and subjected to compression testing according to the American Standard of Testing and Measurement ASTM C 39 standards. The same process was repeated at 28 days. The 7-day and 28-day strength measurements of this concrete are shown in Table 4-1.

Table 4-1: Data from compression testing of the concrete specimens

	Sample 1	Sample 2	Sample 3	Average	Std. Dev
7-day compressive strength (psi)	3726	4023	4169	3973	225
28-day compressive strength (psi)	6699	6683	6354	6579	194

4.3 Testing Matrix

As stated earlier, the glass-reinforced-PP material used for this research is new to the field of structural engineering, which meant that no previous research was found in the literature. This project had to evaluate specific properties and determine a baseline performance of the material. Table 3-1 illustrates the testing approach followed to establish this task.

4.4 Details of Thermoplastic Heater

The material used in the current research was thermoplastic. Unlike conventional thermoset materials that require an epoxy that can be hand laid, thermoplastics require a source of heat that allows the infused PP to melt and bond to the concrete surface after cooling.

A RAYMAX 1220 radiant heater produced by the Watlow Electric Manufacturing Company was used in this project. The heater was supplied with Series F 4 ¼ DIN industrial ramping controller. The controller provided programming of ramp-and-soak-processing applications, which allowed total control over the rate of the heating curve, the soak temperature and time, and the cooling rate of the specimens. This heater contains six ceramic fiber heating units with 24" lengths that circumferentially surrounded the column. Placed inside a 2.5"deep metal case, the heater provided an even heat source for the samples. In addition, the watt density and temperature can be tailored for temperatures to 1000 °F.

Any type of heating element configuration can be used for actual filed application, such as exposed, embedded coil, or foil elements. The basic studies from the heater tests will be mimicked for in-field bonding of the thermoplastic wrap to the concrete columns.

4.5.1 The Bonding Tests (Pull-Off Test)

Initial tests were performed to evaluate the fundamental behavior of the glass-reinforced PP with concrete by studying the bond strength between the fiber-reinforced thermoplastics and the concrete. The bond testing method employed on the thermoplastic tape is called the pull-off test. This test is dictated by ASTM standard D 4541-95. The procedure is designed to find the pull-off strength of a coating material applied to a concrete surface. In the case of resin-infused epoxy treatments, the pull-off strength is simply the adhesive strength of the resin. With the thermoplastic tape, the bonding was accomplished by heating the material since the resin was already infused with the glass fiber during the manufacturing process rather than being added to the glass fibers by the conventional hand-lay-up method. After the material was heated, the test was conducted.

In the pull-off test, a metal loading fixture known as a dolly or stud is attached normal to the surface of the specimen with the adhesive after the specimen is core drilled. A testing apparatus is used to apply increasing tension normal to the surface until a failure occurs. The maximum force is then noted. Also of importance is the mode of failure. Tension is exerted along the testing fixture, the adhesive, and the substrate. Failure will occur in the weakest plane (ASTM D 4541-95). If the concrete is weaker than the bond, pull-off debonding failure is not a major concern with this material. The pull-off test is not the only type of adhesion test; other tests give information on the shear strength of the bond.

A study of the effect of surface preparation was also required to observe whether the effect of a roughened surface through sandblasting would increase the bond strength of the thermoplastic tape. The pull-off test in the present project was performed with a Type 1 fixed-alignment adhesion tester using aluminum test fixtures. After the composite samples for the pull-off test

were created, prisms with both sandblasted (Figure 4-1) and unsandblasted surfaces were placed in the RAYMAX 1220 heater to achieve the required bond (Figure 4-2).

**Figure 4-1. Two 3"x4"x16" prism samples,
one sandblasted and prepared for pull-off testing**

When the composite prisms were removed from the oven, it was obvious that no significant bond had occurred between the thermoplastic tape and the concrete. An alternative method was attempted to create pressure on the specimen by placing a layer of breather cloth with a layer of Kevlar and steel plates on top of the thermoplastic tape. This to investigate whether added pressure would cause a bond between the thermoplastic tape and the concrete. When the sample was removed from the oven, it was concluded that the thermoplastic tape did not bond well enough to concrete to provide any significant surface bond strength. Therefore, the pull-off tests were determined inappropriate for the practical results.
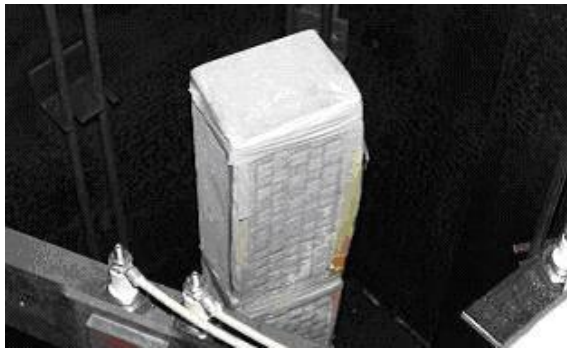
Figure 4-2. composite prism sample

4.5.2 In-plane Shear Test

This test is designed to determine the behavior of the interface between the concrete substrate and thermoplastic tape. This type of test is generally used to determine the properties and behavior of the formed interface under the chosen condition of surface preparation and processing. It can also be used to determine the shear strength of the bond between the thermoplastic tape and the concrete surface. Although this type of test is usually conducted when concrete beams are being retrofitted, the researchers decided to use it to provide information on the behavior of the material in this type of failure. The experiment was conducted by placing a known area of the thermoplastic tape on a prism of concrete and allowing part of the tape to extend farther than the concrete, as shown in the Figures 4-3. The tape was exposed to a tensile force until failure, and the type of failure and the ultimate load were recorded.

In a fashion similar to preparation for the pull-off tests, the concrete specimens reinforced with the thermoplastic tape were prepared for in-plane shear tests. However, the tests indicated zero to minimal in-plane shear strength.

4.5.3 Compression Testing

The objective of testing the cylindrical specimens in axial compression was to study the enhancement in axial strength and ductility provided by the confinement produced by the thermoplastic tape. External jackets provide confinement to the columns to which they are applied. This confinement could be either passive (Figure 4-4) or active in nature. Active confinement is when the system is prestressed, with the fibers in tension and the concrete in compression, before the application of a significant axial load. This prestressing is usually accomplished by injecting an expansive grout between the column and an oversized FRP jacket. The expansion of the grout induces tensile strains in the jacket, which in turn applies a constant confining pressure to the column.
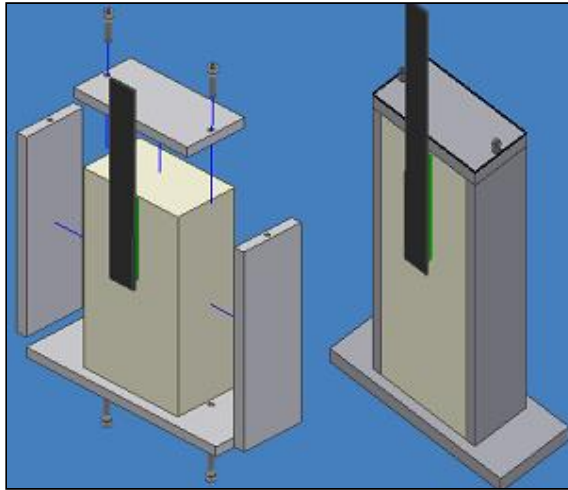

Figure 4-3. In-plane shear test set-up

In RC columns, confining pressures are passive in nature. That is, confining pressures are engaged by transverse dilation of concrete, which occurs along with principle axial strains, as is the case of transverse steel reinforcement. Traditionally, external jackets for RC columns were made with conventional materials such as steel or RC. The applications of these conventional materials were very effective in improving column behavior but had several limitations. Corrosion, deterioration, high installation costs, increased dead load on the structure, and practical issues concerning feasibility of installation all affected the use of these rehabilitation measures.

The use of glass-reinforced PP jackets offers several potential advantages over conventional steel and RC jackets. The glass-reinforced PP jackets have high strength-to-weight and stiffness-to-weight ratios. Thus, the material does not appreciably alter the member's weight, stiffness, or dimensions. These jackets can be installed relatively easily, result in reduced time and labor costs, are corrosion resistant, and cause minimal disturbance to the use and occupancy of the

structure during installation. In order to demonstrate the feasibility of the glass/pp wrap as a potential retrofitting method, the first challenge was to determine a technique to hold the thermoplastic wrap, thus providing a temporary confinement during heat treatment of the composite specimen while maintaining a constant pressure along the length of the specimen without providing heat insulation to the sample. Masking tape was used to anchor the thermoplastic tape while it was wrapped around the concrete specimen and to provide the initial anchor for the overlap. Chicken wire was then used to create the temporary confinement for the thermoplastic tape while the specimen was placed in the oven. This can be seen in Figure 4-5. Tie steel was also used to supply additional confinement to the thermoplastic tape.
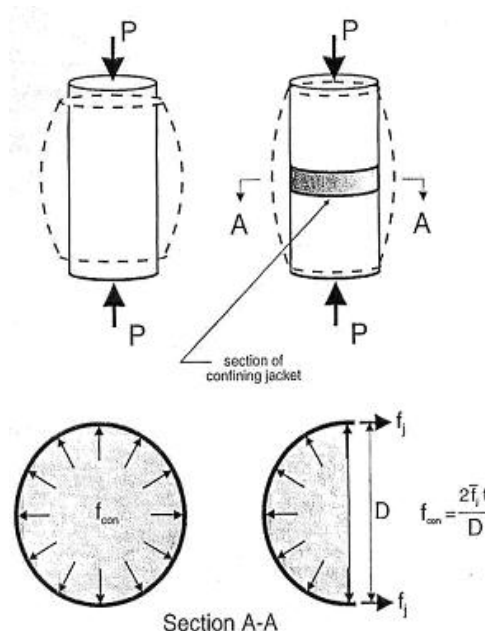

**Figure 4-4. Schematic representation of
passive confinement Kestner et al. (1997)**

**Figure 4-5. Manufacturing process for the confining jacket:
initial anchorage of thermoplastic wrap, and addition of chicken wire
and tie rod steel for temporary confinement during heat treatment**

The next step was to determine a profile for the RAYMAX 1220 heater that would create sufficient bonding on the overlap without causing any deterioration in the fibers or the PP matrix. Three samples were placed in the heater; the ramp rate was then set to 4 degrees Celsius per minute till it reached a temperature of 190 °C, where the sample was left to soak for varying time intervals. The soaking period for sample (a) was 3 hours, for sample (b) was 8 hours, and for sample (c) was 24 hours. Figure 4-6 shows the response of the thermoplastic tape. It was concluded that there was an increase in deterioration of the thermoplastic tape upon prolonged exposure to high temperatures.
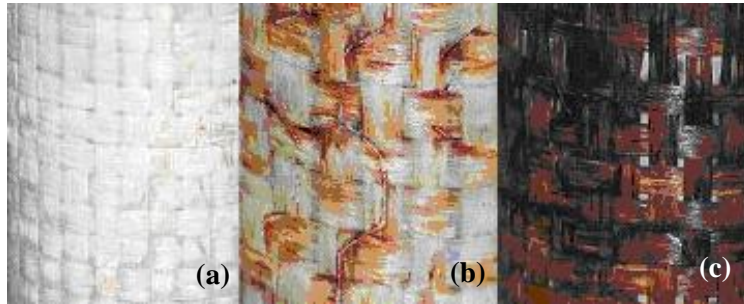

**Figure 4-6. Response of the thermoplastic tape to variable heat treatment**

After the completion of this first experiment, the soaking period was set for 2 hours. The ramp rate was kept as 4°C per minute, and a cooling rate was set as 2°C per minute (Figure 4-7).

Preliminary experimentation on bonding, as discussed in previous sections, showed that there was no considerable bond between the concrete and the PP tape. Therefore, the next step was to determine the required overlap length needed to cause a failure in the jacket fibers rather than in the overlap (Figure 4-8). In other words, since the bond between the confining jacket and the concrete cylinder is relatively weak, failure will occur in the overlap if the strength of the overlap bond is weaker than that of the thermoplastic tape. Confinement at that point is minimal and cannot be accounted for, which means that the desired capacity upgrade acquired from the confinement cannot be realized. However, if the overlap bond strength is stronger than that of the thermoplastic tape, confinement is ensured throughout the loading stage since the thermoplastic tape will sustain the load until failure in the fibers.

Cylinders with dimensions of 4"x 8" were used for this investigation to determine the required overlap length. Different 4"x 8" cylinders were wrapped with their overlap varying from 2" to 6" in 0.5"increments. These cylinders were then placed in the heater, the set profile was run, and the samples were allowed 24 hours to cool. The cylinders were then placed under axial compression, and the mode of failure of the wrap was observed. This test showed that specimens with overlap lengths of 4" or more experienced the type of failure required while maintaining the integrity of the overlap. For further experiments, an overlap length of 5" was used.
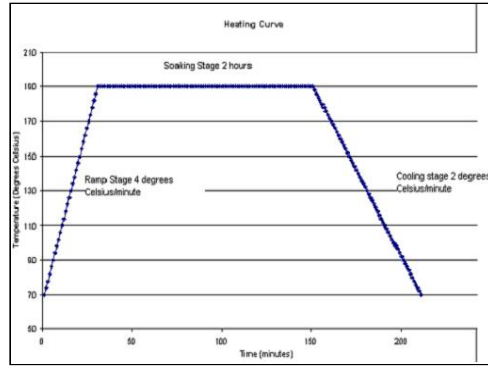
Figure 4-7. Heating profile used for the specimens
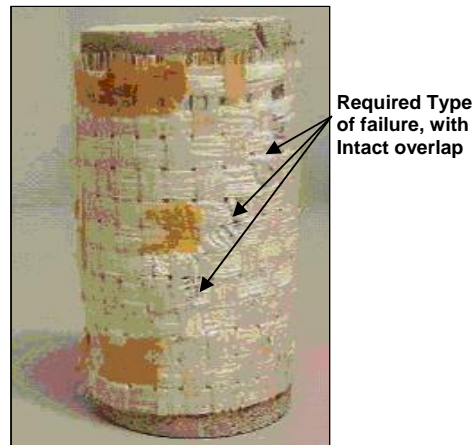
Figure 4-8. Failure in jacket longitudinal, fibers with an intact overlap

The next step after determining the heating parameters of the material was to perform axial compression testing on 6"x12" samples to determine the behavior of the composite column and the improvement in ductility and compressive strength provided by the thermoplastic wrap.

Axial compression testing was performed on one 6"x12" plain concrete sample and three 6"x12" composite cylinders. The results were analyzed, graphed, and compared with the results from the control sample. Strain gages were placed on the samples to obtain the load strain curve, with 0 °, 90°, and 45° orientation. Since the confining jacket was designed to not carry axial load, the 90° strain gage was not expected to record any strain data; therefore, the data acquired from that strain gage were reported as a proof of concept for sample CC1 (Figure 4-9). The 45° stain gage was used as a backup to the 0° strain gage since the results from the 45° stain gage were not accurate. The data required from this test were the data acquired from the 0° strain gage, which were reported for the tested samples. The strain gages were connected to a Mega Deck data acquisition system that recorded the data obtained from the strain gages. A Tinius Olsen universal testing machine with a 600-kip capacity was used to test all the samples till failure.

The results of the compression testing were analyzed and compared with a control concrete specimen. The samples were 6"x12" with the confining jacket consisting of one layer of thermoplastic tape. The composite cylinders were labeled CC1, CC2, and CC3, with their results reported respectively; the plain concrete sample was labeled PC. The results showed an almost threefold increase in ductility of the composite column when compared with the ductility of the control specimen and indicated no increase in the compression capacity. Figures 4-10 though 4-17 illustrate the findings.
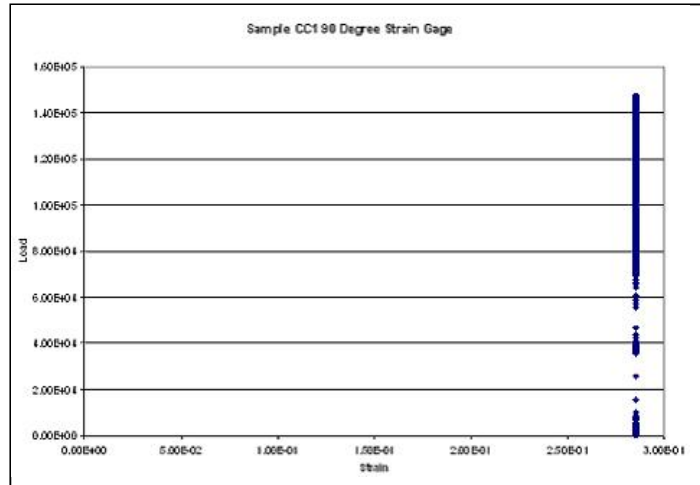
Figure 4-9. Result for sample CC1, 90° strain gage
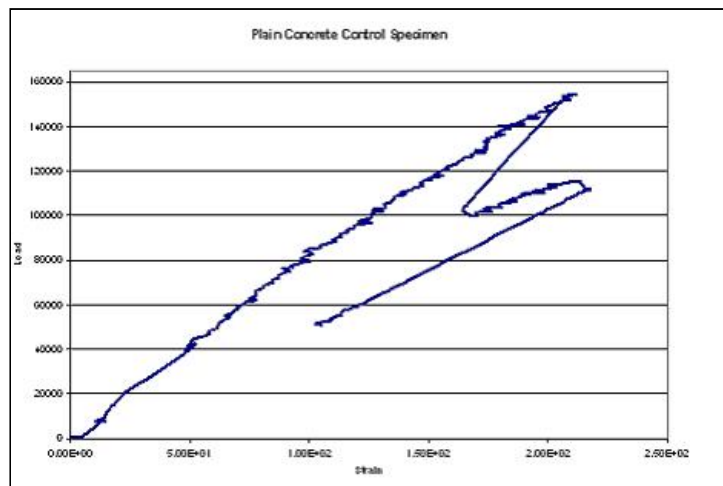
Figure 4-10. Result for sample PC, 0° strain gage, control sample

Intact Overlap

Figure 4-11. Sample CC1 after compression testing showing intact overlap

Plain Concrete
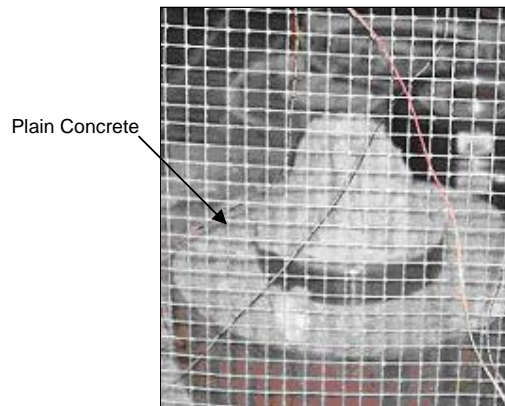
Figure 4-12. Plain 6"x12" cylinder after compression testing

Sample CC1, 0 Degree Strain Gage vs. Control Sample

Figure 4-13. Result for sample CC1, 0° strain gage compared with result for control sample
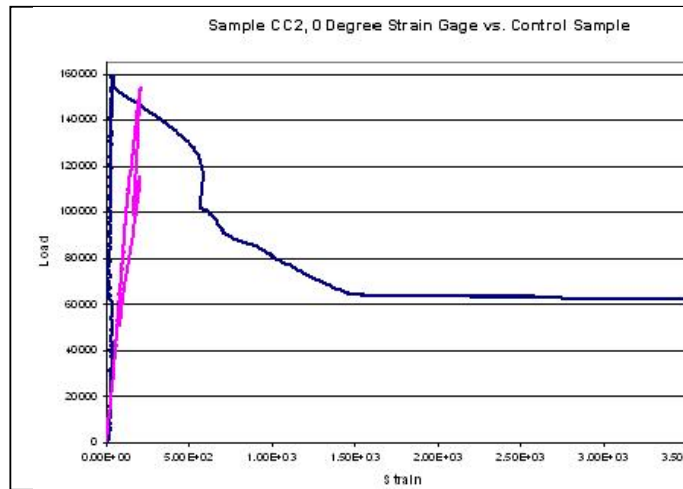
Figure 4-14. Result for sample CC2, 0° strain gage, compared with result for control sample

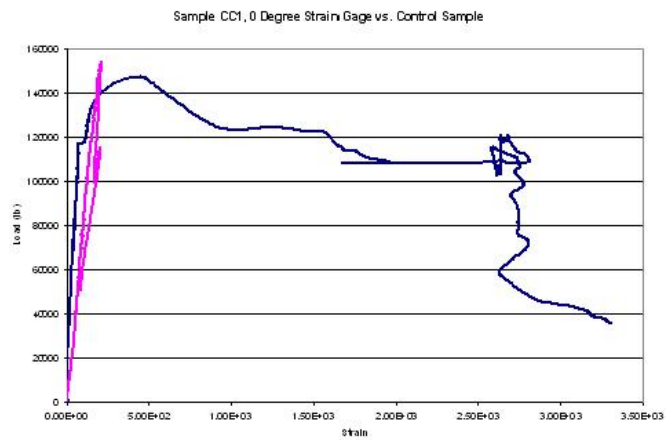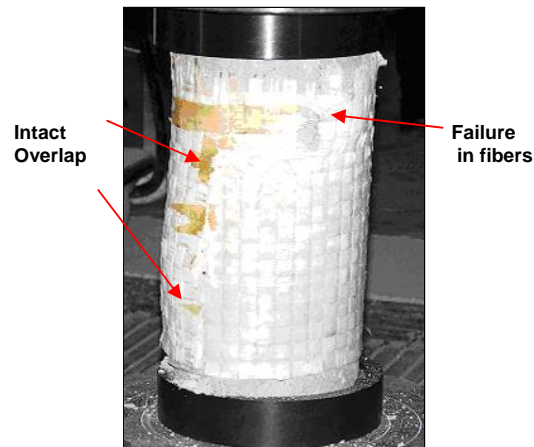**Figure 4-15. Sample CC2 after compression testing showing intact overlap**

Figure 4-16. Sample CC3
after compression testing showing intact overlap

Sample CC3, 0 Degree Strain Gage vs. Control Sample
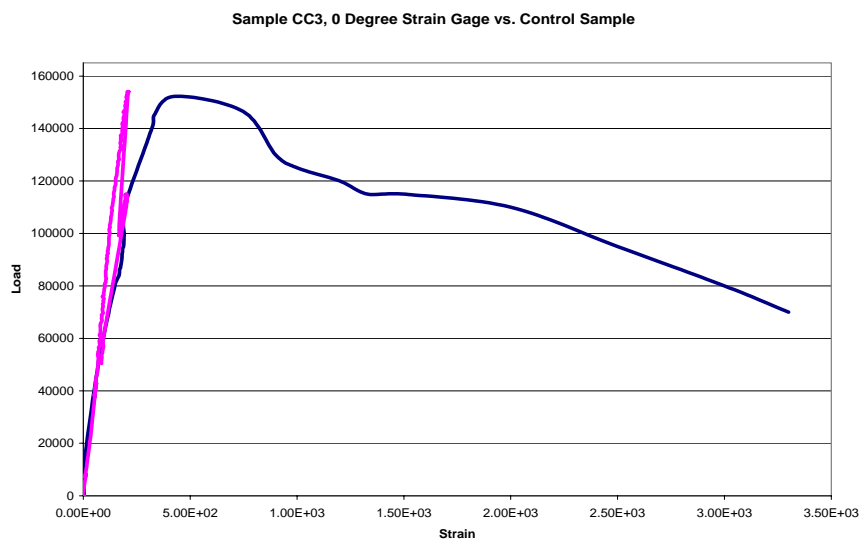
Figure 4-17. Result for sample CC3, 0° strain gage, compared with result for control sample

several significant observations can be made from the compression testing phase of the research. First, the failure occurred in the confining jacket and not in the overlap, which allows a passive type of failure of the composite column, thus eliminating the chance of catastrophic and sudden failure. In addition, the columns were able to maintain their integrity after failure and to continue to support compressive loads for a considerable period. From the load-strain graphs, it can be concluded that the ultimate strain of the composite samples was on the average about 0.033 in/in, almost 15 times the ultimate strain of the plain concrete sample which was about 0.0022 in/in.

The initial portion of the load versus strain curve shows a similar behavior in the plain sample versus the confined concrete, as expected, an increase in load occurred with an increase in strain. This increased load is then followed by a drop in load due to the initial failure of the concrete; after that point, the load continues to drop with an increase in strain, indicating the progressive

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nature of the failure of the glass/PP due to the dilation of the concrete. In the end, there is a drop in the load readings due to the failure of the fibers in the confining jacket.

Sample CC2 did not show a considerable strain reading for the first part of the loading phase because the glass/PP did not provide any initial confinement; thus, strain readings did not occur until the dilation of the concrete. As can be seen in Figures 4-11, 4-15, and 4-16, the wrapped columns were virtually intact when compared with the plain concrete column (Figure 4-12), which showed complete failure. The composite columns did not experience any significant increase in compressive strength capacity. Table 4-2 summarizes the results.

Table 4-2. Results of axial compressive testing for 6"x12" cylinders

Sample	Compressive Strength (lb)	Maximum Strain
PC	152000	0.00217
CC1	147000	0.0331
CC2	159000	0.0354
CC3	145000	0.0330

The results of the compressive axial tests were compared with the results from other studies to determine the effectiveness of the use of thermoplastic glass/PP confining jackets when compared with conventional carbon/epoxy or glass/epoxy composite columns. Several studies were considered, and the data obtained were tabulated with the results obtained from the axial compression tests performed in the present study. The values in Table 4-3 are the ratio of the strain at failure of the composite cylinder divided by the strain of the plain concrete specimen at failure $\varepsilon_{tu} / \varepsilon_{to}$, as shown in Figure 4-18. This is done to obtain normalized response parameters for the lateral strain. The results obtained are compared with the results of epoxy composite tests conducted by Kestner et al. (1997), since in that study tests were conducted on a variety of thermoset confining jackets utilizing singe and double layers of reinforcement.

Table 4-3. Comparison of normalized strain parameters

	CC1	CC2	CC3	E-glass Epoxy	E-glass Epoxy	Carbon Epoxy	Carbon Epoxy
Number of plies	1	1	1	1	2	1	2
Normalized strain	15.3	16.3	15.2	11.5	12.4	8.1	7.2

The results in Table 4-3 clearly show that the glass/PP confining jackets provide excellent confinement when compared with the thermoset confining jackets, which means that composite columns reinforced with glass/PP provide better ductility than those reinforced with thermoset jackets. The ductility is almost twofold that of carbon/epoxy and is even better when compared with E-glass/epoxy systems.

After successful testing of the 6"x12" cylinders, the researchers tested 6"x24" samples to study the effect of scale on the reinforcing jackets. One sample was prepared by the same method used for wrapping the 6"x12" cylinders (Figure 4-19). The sample was then placed in the RAYMAX

1220 heater for the same profile used at the smaller specimens. After removing the sample from the heater, it was noticed that differential heating had occurred over the length of the sample; the upper parts of the sample seemed to have been exposed to more heat because hot air expands and rises to the top of the heater. It was decided that before preparation of more samples, the existing specimen should be tested under axial compression. It was noticed that the sample experienced a failure in the reinforcing jacket overlap (Figure 4-20). This method of failure of the 6"x24" sample was undesirable since the confining jacket failed in the overlap due to a lack of bonding between the concrete column and the confining jacket causing catastrophic failure.
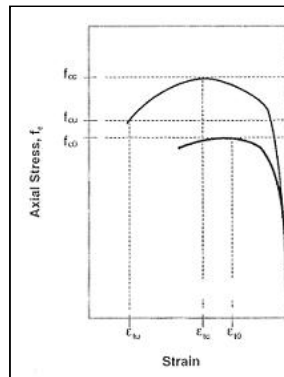
Figure 4-18. Normalized response parameters for strain Kestner et al. (1997)

Figure 4-19. Sample measuring 6"x24" before

Fig 4-20. Sample measuring 6"x24" showing overlap failure

In an effort to pr_____ 16-gauge PP s_____ _____rlap and around the confining jacket to increase the amount of PF _____ _____ditional confinement and strengthen the overlap bond. The samples were prepared and placed in the heater at the same profile used for the shorter specimens. It was observed that when the samples were heated, the additional PP caused the matrix containing the glass fibers to weaken. As a result of the weakened matrix the glass fibers started to bubble outward by sliding under their

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own weight (Figure 4-21). Figure 4-22 depicts the failure in the overlap that occurred as a result of compressive testing.

Glass fibers bending under their own weight.
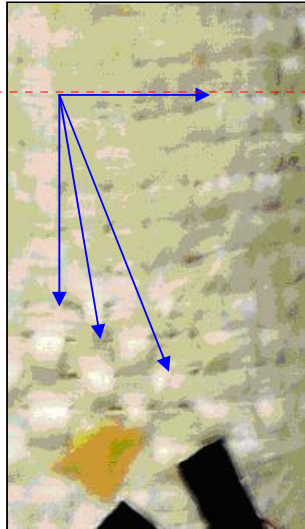
Figure 4-21. Effect of adding PP to the thermoplastic

Overlap Failure
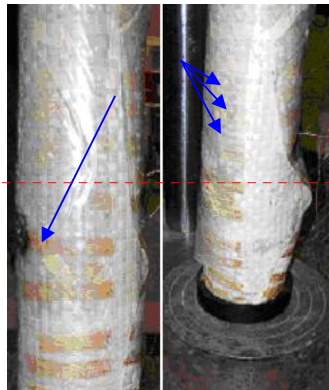
Figure 4-22. Sample wrapped with PP sheet showing overlap failure

It was therefore, concluded that the RAYMAX 1220 heater was efficient and showed great performance when dealing with the smaller specimens, and that some modifications were needed for larger specimens and field applications. Personnel at Watlow, Inc., the company that supplied the heater, are working on correcting the problem with the RAYMAX 1220 heater by either adding fans or implementing different types of heating panels to provide a consistent heat source over the length of the specimen. With the modification, the heater can be used for future field implementation.

4.5.4 Practical Considerations in Wrapping Applications

The laboratory studies showed that significant difficulty was encountered when the thermoplastic tape was applied to larger specimens. The results from the bond characterization tests, along with those from the axial compression tests showed that the bond between the thermoplastic tape and the concrete was minimal and was not required to achieve enhancement in ductility. This finding leads to the conclusion that the heat source application of the thermoplastic tape was not optimal, and the use of fabricated thermoplastic split rings joined to create a confining jacket should be considered in future research.

Section 5.0
Ballistic Performance

5.1 Introduction

Most research on composite applications to infrastructure concentrates on static loading, neglecting situations in which structures undergo impact or dynamic loading, such as during explosions or impact due to causes like moving vehicles or tornado projectiles. In impact scenarios, the loading duration is extremely short. In addition, the strain rate of the material is significantly higher than that under static or seismic loading.

Because of the size of motor vehicles and the rising threat of terrorisms, evaluating new bridge pier retrofitting materials against impact has become important. In an effort to evaluate the feasibility of glass/PP wrap for impact loading, ballistic impact testing was performed on five 8"x11" plates with a thickness of 1/2".

5.2 Previous Studies

Almost all of the reviewed research related to impact focused on pure composite structures. Only one study was found that determined the resistance of RC to hard projectiles. Another study determined the behavior of concrete beams strengthened with FRP laminates under impact loading.

Dancygier and Yankelevsky (1999) conducted tests on 40-cm x 40-cm (15.6"x 15.6") plates that were 5 cm (1.95") thick and had varying steel reinforcement and concrete strengths to determine the resistance of the plates to hard projectiles. The results of their study indicated that increased reinforcement dramatically increased the concrete plates' performance and perforation resistance under impact testing, and considerably reduced the damaged area in the front and rear of the plates.

Erki and Meier (1999) conducted tests on 8-m-long concrete beams strengthened for flexure with steel plates and carbon-fiber-reinforced polymer. Impact loading was induced by lifting one end of a simply supported beam and dropping it. The study showed that FRP laminates performed well under impact loading, although they did not provide the same energy absorption that was found when the beams were strengthened with steel plates.

Caprino et al. (1999) investigated the effect of material thickness on the response of carbon fabric/epoxy panels to low velocity-impact. The force and absorbed energy at the point of delamination initiation, the maximum force and related energy, and the penetration energy were evaluated. The researchers concluded that except for the energy for delamination initiation, all parameters examined followed the same trend of increasing 1.5 fold with increasing plate thickness. The study showed that the energy at the start of the delamination was composed of two parts, one that pertained to the flexural deformation of the specimen and one that related to local deformation at the contact point. Caprino et al. (1999) also pointed out that the local

deformation at the contact point became more and more important as the plate thickness increased.

5.3 Specimen Description

Low-strength commercial concrete blocks were used in this part of the research since they allowed easier cutting to the required ½" thickness. Three 3.75" x 3.75" x 3.75" concrete cubes were cut from the concrete blocks to determine the compressive strength of the concrete and were labeled B1, B2, and B3, respectively. The results are reported in Table 5-1. Commercial adhesive manufactured by 3M was used to bond the thermoplastic tape to the 0.5" concrete plate. Four plates measuring 8"x11" were reinforced with glass-infused PP thermo-plastic tape and exposed to various impact velocities. No tests were conducted on a control specimen due to the explosive nature of spalling concrete when subjected to impact loads, since the laboratory was not adequately prepared with safety measures to prevent injury from the spall, and because the minimum velocity required for the projectile to travel through the barrel would exceed the perforation limit of the concrete specimen.

Table 5-1. Compressive strength of concrete blocks

Specimen	B1	B2	B3	Average
Compressive strength (psi)	2813	2800	2309	2641

It is important to note that the average compression strength from Table 5-1 should be reduced for the concrete panels. The reason is that some damage was bound to have occurred to the concrete due to the vibrations of the saw during cutting.

5.4 Experimental Set

The impact tests were performed using a gas gun capable of high-speed impact testing. Figures 5-1 and 5-2 show the gas gun setup in the Materials Science and Engineering laboratory. A sabot stripper plate is mounted in front of the gun muzzle to separate the projectile from the launching sabot before impact with the target. A fixture restrained the samples during testing, and the performances of reinforced and control specimens were compared (Vaidya 2003).

5.4.1 Test Results of Glass/PP Panels

Preliminary work was conducted to help in understanding damage resistance of glass/PP composite panels to high-speed dynamic impacts was conducted (Vaidya et al. 2003). The composite material tested consists of one inch randomly oriented fibers. The material was not the exact replicate of the thermoplastic tape used for the confining jackets since the compression molding process used to create thermoplastic tape of a desired thickness was not available at SRI, but the test provided a means of understanding the behavior of the composite material under impact. The high-speed blunt object impacts involved speeds ranging from 10-100 m/s. The gas gun consists of a 3m barrel, a firing valve, and a capture chamber which holds the specimen. An aluminum sabot of 38.1 mm diameter and a mass of 100 grams was used as the blunt object projectile. High-speed photography was adopted to observe the deformation mechanisms of the glass/PP plate. A significant amount of energy absorption in flexure was shown in Figure 5-3.

About 38 mm of dynamic deflection was observed in conjunction with torsional oscillations of the panel during the impact. The energy absorbing mechanisms were fiber pull-out; strain/crazing of PP matrix, flexure, torsion, and fiber breakage. The maximum energy absorbed by the 4 mm plates was approximately 145 J before perforation. This energy absorption capability can potentially contain the concrete damage if used for retrofit. The results of the testing led to the conclusion that the glass/PP material can be considered a suitable candidate for absorbing the energy of an impact (Vaidya et al. 2003).

Figure 5-1. Gas gun pressure chamber

Figure 5-2. Gas gun barrel and velocity screens
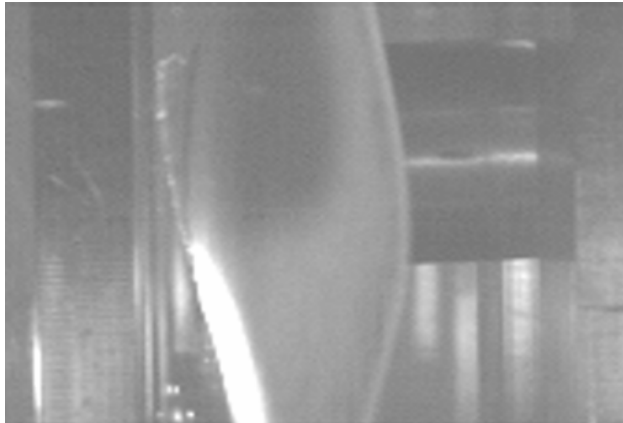
Figure 5-3. High-speed imaging showing dynamic deflection and energy absorption of glass/pp plate under dynamic impact

5.4.2 Test Results of Concrete Panels Reinforced With Glass/PP

The panels were impacted with different velocities to determine the behavior and performance of the plates to different projectile velocities using the same sabot. Impact velocities ranged from 59.50 m/s to 121.19 m/s, and perforation occurred at the latter speed.

The results were evaluated by comparing the target resistance to impact at different velocities. For a certain sample, the resistance was determined by the perforation velocity; performance was determined according to the level of front and rear face damage. The crater's diameter was also measured. The resulting values along with the thicknesses of the plates were used to determine the volume of the crater's. The resistance was evaluated according to the following five levels of response:

1. No damage or fine cracks at the plate's rear face (ND)

2. Rear face scabbing without perforation (S).

3. Rear face scabbing limit (SL).

4. Perforation without penetration; that is the projectile punched through the surface of the plate but bounced and did not fully penetrate the plate (UP).

5. Perforation accompanied by penetration [either penetration limit (PL) or full penetration (P)]; that is, the projectile caused punching of the plate and was either stuck in it (perforation limit) or exited the rear face.

Scabbing refers to the spalling of the concrete at the backside of the plate due to impact. The scabbing limit represents the impact velocity that leads to spalling of the concrete all the way to the reinforcement.

Tables 5-2 and 5-3 summarize the results, and Figures 5-4 through 5-7 show tested specimens. It is obvious during the testing and from the figures that the energy absorption was composed of two parts. One pertains to the flexure deformation of the concrete plates, and the other to the local deformation at the contact point of the glass/PP face. The failure of glass/pp facing was in the form of perforation and plastic flow in the direction of the projectile. Shear plugging of laminates led to circumferential damage in concrete backing. As the concrete did not undergo shear plugging, the damage in the concrete plate was in the form of radial cracks, in addition to the perforation.

On the other hand, the interface between the concrete and the laminate remained intact showing a continuous crack almost in the middle of the concrete plate. Visual inspection of the post-mortem sample showed that the concrete plate ruptured in a progressive conical way and that the damage area in the bottom laminate was significantly larger than the damage area in the glass/PP laminate.

In summary, typical failure of glass/pp laminated concrete subjected to impact, progressive conical failure, also known as pine tree damage (Abrate, 1998) seems to be the typical failure mode. This failure mode is successful in applications that require energy absorption since the damage is spread around a larger area on the backside of the concrete plate. It is to be noted that the energy absorbed by the glass/pp laminate is 145 J and the energy absorbed by the glass/pp laminated concrete plate with perforation is about 711 J.

Table 5-2: Visual analysis of results from ballistic testing

Low Strength Concrete			Rear Crater	
Specimen	Impact Velocity (m/s)	Response	Gross Dimensions (in x in)	Volume (cubic-in)
PP-Con 1	121.19	UP	3.00 x 4.00	6.00
PP-Con 2	82.84	S	4.00 x 5.50	11.00
PP-Con 3	59.50	S	3.75 x 4.00	7.50
PP-Con 4	99.00	SL	5.25 x 5.75	15.09

Table 5-3: Impact results from ballistic testing

	Impactor	Impactor Mass (g)	Impact Velocity (m/s)	Impact Energy (J)	Perforation (Y/N)
PP-Con 1	38mm flat AL sabot	96.80	121.19	710.85	Y
PP-Con 2	38mm flat AL sabot	96.80	82.84	332.14	N
PP-Con 3	38mm flat AL sabot	96.80	59.50	171.35	N
PP-Con 4	38mm flat AL sabot	96.80	99.00	474.37	N
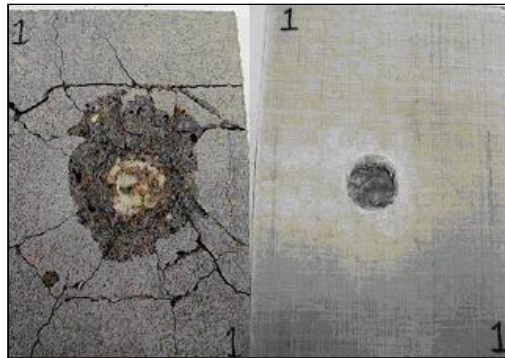
Figure 5-4. Back and front of PP-Con 1
(impact velocity=121.19, impact energy=710.85, response=UP)
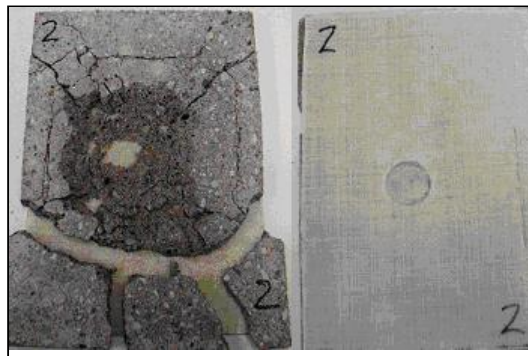
Figure 5-5. Back and front of PP-Con 2
(impact velocity=82.84, impact energy=332.14, response=S)
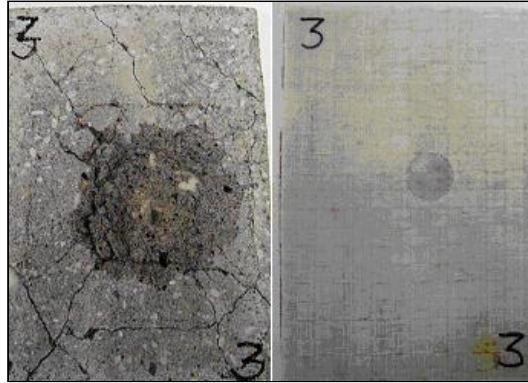
Figure 5-6. Back and front of PP-Con 3
(impact velocity=59.50, impact energy=171.35, response=S)

Figure 5-7. Back and front of PP-Con 4
(impact velocity=99.00, impact energy=474.37, Response=SL)

5.4.3 FE Analysis

The composite panels tested were not sufficient to acquire all of the data since the exact perforation limit of the composite panels was not determined and verified with additional replication of the results; further experimentation is required so that the concept can be implemented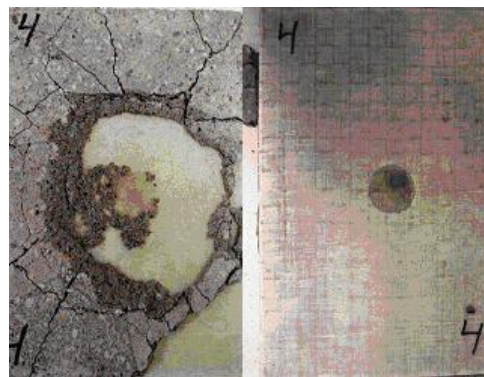 in practical design. On the other hand, the information from the ballistic testing is adequate and sufficient for creating a LS-DYNA finite-element model that can be used to replicate laboratory experimentations and (once perfected) to run multiple scenarios to help understand the behavior of the composite panels and bridge piers under various types of loading.

Finite-element models provide an exceptional advantage since, when verified, they can reduce the number of costly and time consuming laboratory experiments. These models can be used to replicate various scenarios that in some cases cannot be replicated in a laboratory environment.

The first challenge in creating an LS-DYNA model is selecting a constitutive model for the material being analyzed that will respond in the same manner as the actual material and provide accurate data. Unlike aluminum and steel, which have proven material cards that provide accurate data when modeled, concrete is especially difficult to model due to its brittle nature and the variability of its properties.

The basic goal of computer modeling in this project was to produce a model that could satisfactorily replicate the laboratory testing results of the composite panels. When the goal is accomplished, we can use the data to determine the thickness of reinforcing jackets for bridge piers to prevent failure from impact of a known velocity. The steps used in this process are summarized as follows:

1. The accuracy and applicability of the model are verified with the composite panels tested in the lab.

2. Small-scale tests replicating impact can be conducted on bridge piers when the appropriate material properties are determined.

3. These results can then be used to determine the accuracy of a modeled bridge pier under impact using the same material properties verified in the composite panel testing.

4. The results can then be used to determine the thickness of the confining jackets needed to prevent bridge pier failure under a certain impact load that can be easily calculated from the trailer mass and velocity.

5.4.4 Selecting LS-DYNA Material Models

LS-DYNA provides a variety of material cards for modeling different materials and also provides several material cards that can be used to model a material. An extensive review was conducted on the manuals provided by LS-DYNA and the work of previous researchers to determine the best or most practical material cards for providing satisfactory models.

5.4.4.1 Modeling the Concrete Back Plate

The first task was creating the model for the concrete plate; concrete is considered a geomaterial, which also includes similar materials such as soil and rock which are common building materials. The strength characteristics of geomaterials range from sand which is relatively weak, to granite which is one of nature's strongest materials. Although spanning a wide range of strength properties, geomaterials have very similar constitutive response characteristics, which differ greatly from the more familiar common metal constitutive responses.

Constitutive models used for geomaterials are usually based on the same mathematical plasticity theory used to model common metals like steel or aluminum. However, the behavior of geomaterials differs from that of metals in four important aspects:

1. Geomaterials have relatively high compression strength, i.e., pressure volume response.

2. The yield strength depends on the mean stress; i.e., frictional response.

3. The yield strength depends on the relative magnitude of the principle stresses.

4. Geomaterials have relatively low tensile strengths when compared with their compressive strength.

These basic differences between geomaterials and metals give rise to interesting aspects of constitutive modeling that may not be familiar to engineers trained in classical metal plasticity. Geomaterials are unlike metals since the entire response of geomaterials cannot be described by one characterization test such as the uniaxial stress test. Geomaterials require a suite of material characterization tests due to the various parameter inputs required for simulation, and due to the fact that they are not frequently modeled and verified, as is the case with metals. Knowledge of the tests, the correct manner of conducting them and interpreting their data is essential for creating a successful geomaterial model. In brief, the following laboratory tests are required to calibrate the material model parameters required for modeling a geomaterial:

- Hydrostatic compression
- Triaxial compression/extension
- Uniaxial strain

The hydrostatic compression test determines the bulk modulus of the material when the axial and lateral stresses are equal. In the triaxial test the lateral and axial stresses are not equal; this test provides the most data for characterizing the strength of geomaterials. The unconfined compression test provides the value for the elastic shear modulus. Before choosing the tests to ascertain the material properties, it is first necessary to select an appropriate material model. There are several material models available that have been successful in modeling concrete. Material models 5, 14, 16, 72, 84, and 96 can be used for this purpose. Material cards 5 and 16 have been successfully used for simulating penetration into concrete, and one of these material models was selected for the analysis. The Soil and Foam Model (Mat_5) is the oldest and most basic material model available for concrete in LS-DYNA; therefore, this model has the most user experience and feedback and is considered a robust model that provides good results. The Pseudo Tensor Model (Mat_16) is convenient if only the unconfined compressive strength of the concrete is known. Mat_5 requires a minimum amount of input data and material characterization, and is recommended for the preliminary analysis of geomaterials and for users who are new to geomaterials.

The material Soil and Foam Model requires the input of the material unit weight, the shear modulus, and the bulk modulus. The unit weight was measured in the laboratory and the shear modulus and the bulk modulus were calculated using ACI 318 with values obtained from the unconfined compression test. The calculations used an assumed value of Poisson's ratio of 0.2, because Poisson's ratio varies from 0.15 to 0.2 for the material.

Livermore Software Technology Corporation provides examples of Material constants for Material Model Cards 5 and 16. These models (in English units) were used as a starting point for

modeling, and were corrected for the concrete properties determined along with the LS-DYNA card variables and definitions of Mat Soil and Foam.

5.4.4.2 Modeling the Glass/PP Tape

For modeling the glass/PP tape, there are different composite material models that are standard with LS-DYNA, as follows:

1. Mat Composite Failure Shell (Mat_59).
2. Mat Composite Damage (Mat_22).
3. Mat Enhanced Composite Damage (Mat_54).

These material models can be used as arbitrary orthotropic materials. Mat_54 is an enhanced version of Mat_22. Mat_22 was used to model the thermoplastic tape in the LS-DYNA model, again due to the fact that it is an older model that has been previously tested and found to provide satisfactory models. The input variables used for the glass/PP in the finite-element model were the values supplied by SRI; for values that were not available, generalized material properties were used. Further study is needed to perfect those material properties. A more accurate modeling of the glass/PP is obtaining by using Mat_Laminated_Composite _Fabric (Mat_58), which is highly accurate due to the large number of input variables it requires. A vast knowledge in computer modeling is necessary to use this model, as it uses an extensive matrix of lab tests to determine all the material variables.

5.4.4.3 Modeling the Sabot

The sabot was considered a rigid body (Mat_20) and was given the correct aluminum properties, mass density, Young's modulus, and Poisson's ratio. The reason for choosing the rigid body model for the aluminum sabot was that the effect of the impact on the sabot was not of concern to the researcher. The most important value when modeling the sabot was the correct density value that would result in the correct mass that is essential for calculating the correct impact energy.

5.5.5 Modeling in LS-DYNA

After selection of the desired material models that would be used in the model, the next step was to create the geometrical model of the impact scenario. The geometrical model is the exact replication of the actual dimensions of the tested composite panels. The units used for the model were metric.

The glass/PP was modeled as a shell element with 279 mm x 203 mm x 2mm dimensions. The concrete dimensions were 279 mm x 203 mm x 13 mm. The sabot was modeled as a cylinder with a diameter of 38 mm and length of 50.8 mm. The material was then meshed with 30 elements along each edge, thus satisfying the aspect ratio of less than five. After the geometry was created, the next step was to input the selected material models. The third step of the finite-element modeling was to input the material properties, followed by defining the contact surfaces. The last step was to input the boundary conditions; in this step all of the nodes along the outer

edges were fixed against rotation and translation in all directions. Figure 5-8 shows the numerical model created in LS-DYNA.

The next step was to run the numerical model giving the variable velocities of the sabot and compare the results from the numerical model with the data obtained from the ballistic impact tests performed in the laboratory. The first model used the material properties suggested by Livermore Software Technology Corporation for the Mat_Soil_And_Loam. The results showed that the suggested numerical input for the material variables was not satisfactory for the model. The suggested unconfined compression test was then conducted, and the appropriate values were calculated in accordance with ACI 318.
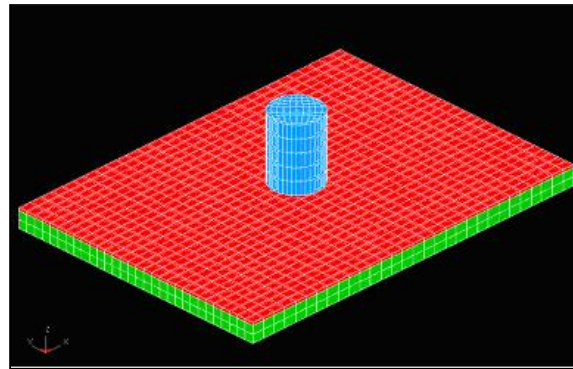

Figure 5-8. Computer model of the composite panels subjected to impact

5.6 Results of LS-DYNA Analysis

The finalized model was run and compared with the results of the ballistic impact tests performed in the laboratory. Figures 5-9 though 5-14 and Table 5-4 illustrate the findings. An analysis was conducted for each tested case, with the only difference being the impact energy varied case to case. For each case, the impact energy curve from LS-DYNA was plotted; these graphs verified the high energy absorption capacity of the composite panels. The mode of failure from the computer model showed satisfactory resemblance to the visual observations from the lab results. Scabbing in the concrete was observed, along with radial cracks. The cracks in the concrete did not propagate to the required lengths because mesh was not reduced to the desired size due to modeling limitations. It was also noticed that perforation occurred only in the model exposed to an impactor velocity of 121.2 m/s, which agreed with the laboratory results. This finite-element model can be considered a satisfactory model despite the fact that some laboratory tests are required to verify the mechanical properties and values of the material input that are required by the material cards.
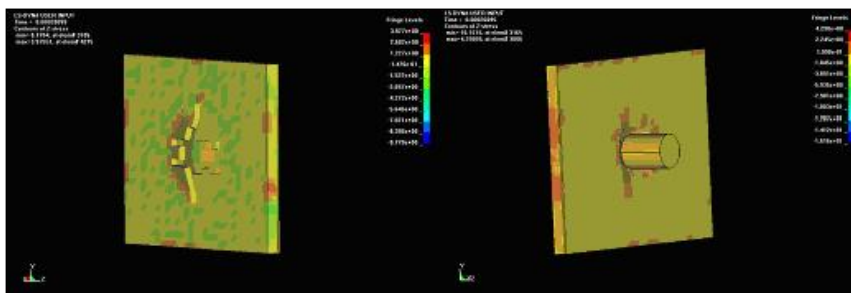
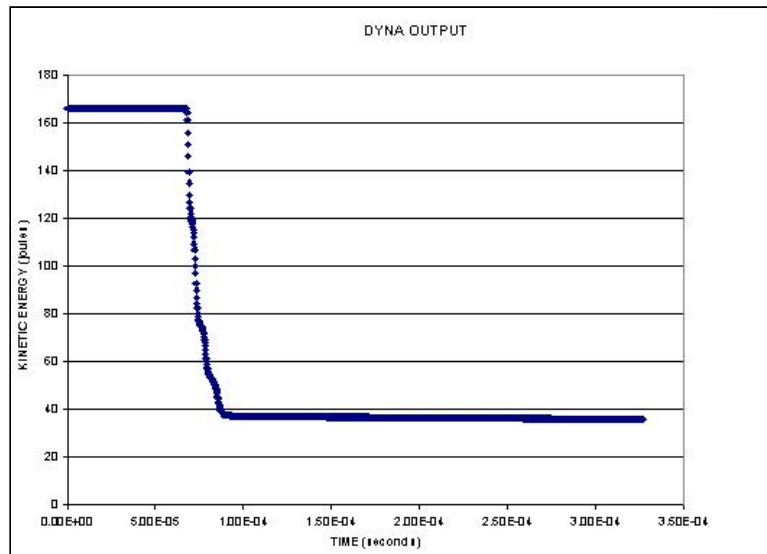**Figure 5-10. Impact energy=166 joules**
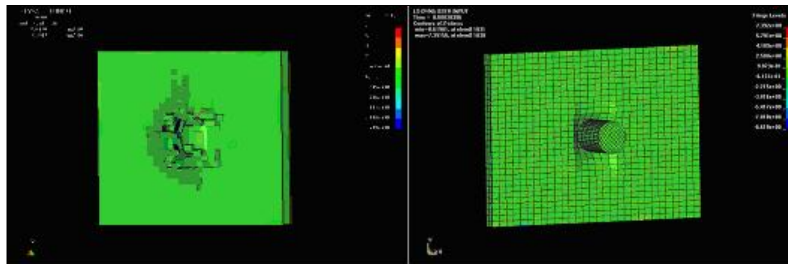
Figure 5-11. Back and front of concrete plate (impact velocity=82.84 m/s)

55
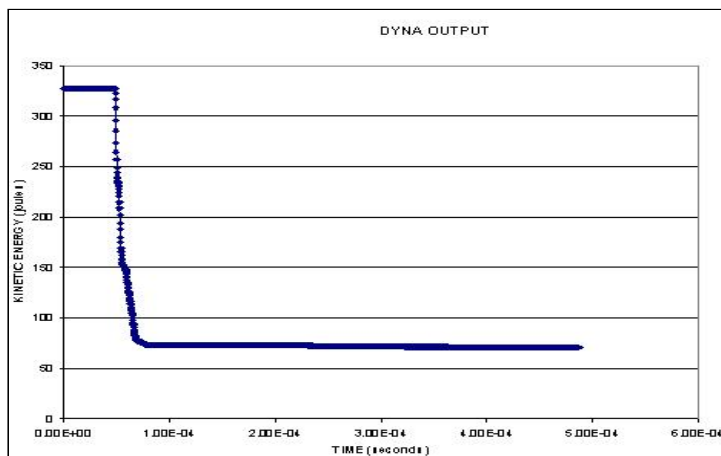
Figure 5-12. Impact energy=327 joules
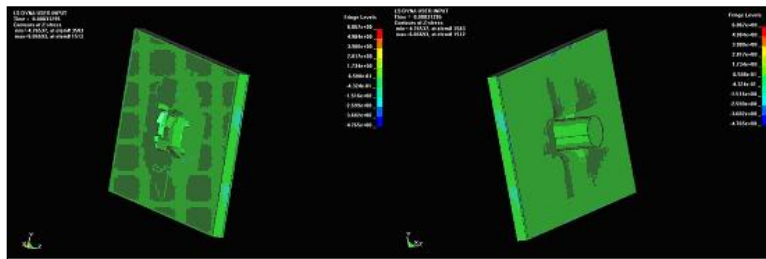
Figure 5-13. Back and front of concrete plate (impact velocity=99.00 m/s)
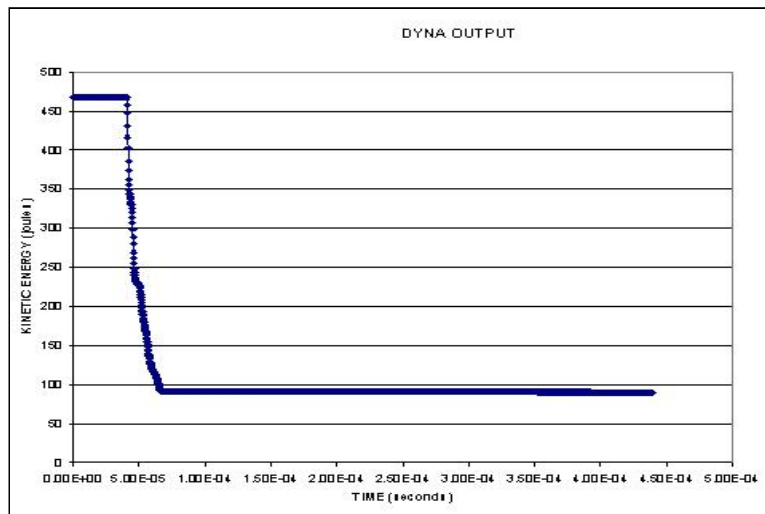
Figure 5-14. Impact energy = 468 joules
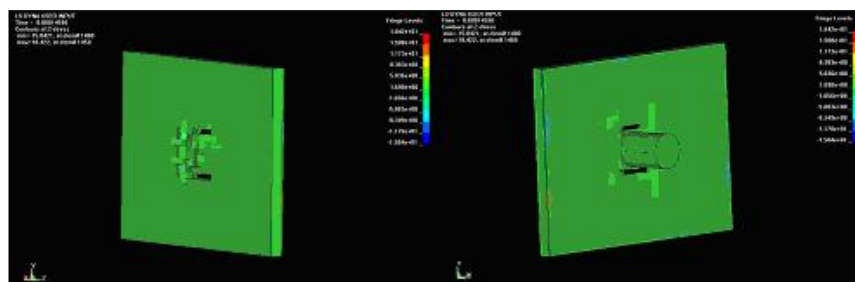
Figure 5-15. Back and front of concrete plate (impact velocity=121.19 m/s, note: perforation)
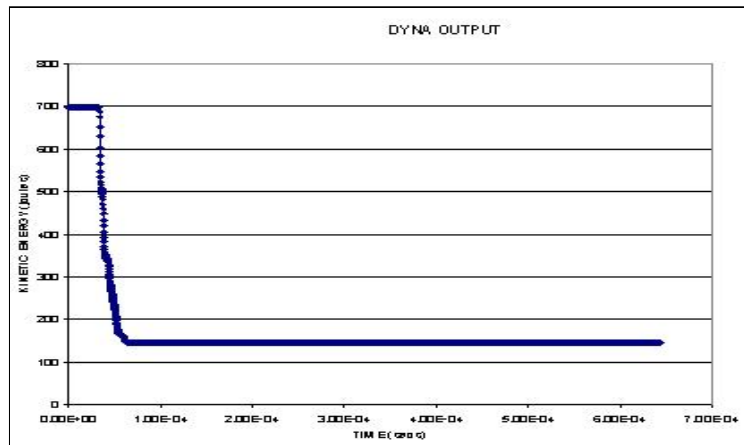
Figure 5-16. Impact energy = 699 joules

Table 5-4: Comparison of results between lab results and computer analysis

Laboratory Results		Computer Analysis	
Impact Energy	**Perforation**	**Impact Energy**	**Perforation**
(Joules)	**(Y/N)**	**(Joules)**	**(Y/N)**
710.85	Y	699	Y
332.14	N	327	N
171.35	N	166	N
474.37	N	468	N

Section 6.0
Summary and Discussion

6.1 List of Completed Tasks

Novel processing systems have made it feasible to use thermoplastic composites in the field of civil engineering. This project examined the suitability of these composites for retrofitting bridge piers and investigated the performance of concrete cylinders fitted with thermoplastic confining jackets. The results of the study have clearly shown the advantages of using glass/PP confining jackets to enhance the ductile behavior of concrete cylinders and the ballistic impact performance of glass/PP reinforced, concrete panels. The tasks performed during the project included the following:

1. An extensive literature review of composites in general and thermoplastics in particular showed that thermoplastic materials have a bright future in civil infrastructure applications.
2. Low-cost thermoplastic composite wraps were manufactured using the novel DRIFT process from SRI.
3. Bond characterization tests conducted on the thermoplastic material showed that there was no significant bond between concrete and PP.
4. A successful method for retrofitting concrete cylinders with glass-reinforced PP confining jackets was developed and implemented
5. A retrofitting method using a heater was found to provide excellent results for the small-scale specimens; however, the retrofitting method could not be replicated for larger scale specimens. The researchers are working to modify the retrofitting method for use with larger scale specimens and to eventually create a retrofitting method that can be implemented in real life applications. Development of the retrofitting method included the following tasks:
   a. Determining a heating profile that allowed maximum bonding without causing deterioration in the confining jacket.
   b. Determining the length of overlap of the confining jackets that allows adequate confinement and passive failure.
   c. Developing a technique that will provides temporary confinement to the confining jacket during placement in the thermoplastic heater.
6. Ballistic impact tests were conducted on composite panels and plain glass/PP panels to determine the energy absorption capacity and ballistic limit.
7. A finite-element numerical model was created to replicate the ballistic impact test results.

6.2 Summary

The various tests conducted during the course of these study involved bond characterization tests between the concrete and thermoplastic glass/PP, compression tests of glass/PP-wrapped

concrete cylinders, and ballistic impact tests of glass/PP reinforced concrete panels, as well as numerical modeling for the impact test. The following sections discuss the results obtained from those tests.

6.2.1 Bond Characterization

Both in-plane shear tests and pull-off tests were conducted to characterize the bond between thermoplastic and concrete substrate. The pull-off test is used to evaluate the fundamental behavior of glass/PP with concrete and is dictated by ASTM standard D 4541-95. The in-plane shear test is designed to determine the properties and behavior of the interface formed between the glass/PP thermoplastic tape and the concrete, and to determine the shear strength of the bond. The results of both the in-plane shear and the pull-off tests showed that there was no significant bond between the glass/PP thermoplastic tape and the concrete. The bond characterization tests, along with the results from the axial compression tests, showed that use of a heat source for applying the material can be abandoned in future applications and that the use of the thermoplastic tape in the form of split rings should be considered, along with an adequate application method.

6.2.2 Axial Compression Testing

This part of the current study investigated the behavior of glass/PP jacketed and plain concrete subjected to uniaxial compression. The results for the confined column were measured and compared with the results for the plain concrete samples and concrete samples reinforced with thermoset composites. The following conclusions were drawn from this part of the research study:

1. A retrofitting method was successfully developed for thermoplastic confining jackets to retrofit concrete cylinders using a heat source.
2. Composite columns confined with glass/PP demonstrated superior deformation capacity when compared with other confinements, including thermoset composites.
3. The confinement provided by the jackets limited the level of concrete dilation, thus preventing catastrophic failures and spalling of the concrete

6.2.3 Ballistic Impact Testing

Ballistic impact tests were conducted on both glass/PP panels and concrete panels reinforced with glass/PP. The main purpose was to evaluate the response of the cost-effective glass/PP design to ballistic impact. An understanding of the response of glass/PP and glass/PP reinforced concrete panels to ballistic impact can lead to increased confidence in and understanding of the application of similar designs for protecting bridge piers against blast or impact type loading. The following conclusions can be drawn from this part of the current study:

1. Thermoplastic glass/PP panels have an excellent energy absorption capacity when subjected to ballistic impact.
2. The glass/PP composite significantly increased the capacity of the concrete plates to resist impact. When glass/PP laminated concrete subjected to impact, a progressive conical failure

was found to be the typical failure mode. This failure mode is successful in applications that require energy absorption since the damage is spread around a larger area on the backside of the concrete plate. It is to be noted that the energy absorbed by a thin concrete plate (280 mm x 200 mm x 13 mm) reinforced with glass/PP laminate with perforation was about 711 J.

6.2.4 Numerical Modeling of Ballistic Impact

A numerical model was created using the LS-DYNA finite-element-analysis software. The finite-element model, once further verified by laboratory testing, provided an excellent tool for determining energy absorption of glass/PP reinforced concrete panels to different reinforcement ratios of glass/PP to concrete. The model will basically allow the researcher to determine the ballistic limit numerically for varying thicknesses of glass/PP. The following conclusions can be drawn from this part of the present study:

1. An extensive literature review on LS-DYNA material modeling was performed; this review allowed researchers to further refine the numerical model to provide more accurate and reliable results. The material models for the concrete have been extensively researched and are considered complete. Although the LS-DYNA model provided good results for the glass/PP composite, the use of a different material model should be further studied.
2. When completed and verified, the numerical model will allow replications of various impact scenarios, including bridge pier situations, and will reduce the number of tests required.

6.3 Conclusions and Future Research

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 of 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 proof-of-concept study demonstrated that thermoplastic composite wrap could 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 essential first step toward developing thermoplastic confining jackets to reduce the vulnerability of bridge piers to dynamic loads that deliver immense energy to the structure in a very short time, such as collisions involving trailer trucks, blasts, or earthquakes. Thermoplastics are a new material for infrastructure applications in the field of civil engineering; for this reason, small-scale testing and material characterization were required to determine the baseline performance of the material and to provide proof of concept.

To the researcher's knowledge this proof-of-concept study was the only study ever attempted to explore the potential superior impact resistant of thermoplastic composites for bridge piers. As expected, this exercise was successful in confirming the feasibility of the proposed retrofitting concept. The results confirm that thermoplastic composites can provide significant impact strength and ductility that can prevent on delay pier failure. This study also demonstrated the

thermoplastic confining concrete have progressive failure potential, instead of catastrophic fracture presently associated with RC columns.

The laboratory studies, however, showed that significant difficulty was encountered when the thermoplastic tape was applied to larger concrete specimens through radiant heating. The results from the bond characterization tests, along with those from the axial compression tests, showed that the bond between the thermoplastic tape and the concrete is minimal even though not required to achieve enhancement in ductility. Nevertheless this finding lead to the conclusion that the current technique of heat application of the thermoplastic tape was not the optimal preparation technique. Either a different heating technique should be investigated or the use of fabricated thermoplastic split rings (which may be joined to create a confining jacket) should be considered in future research.

To implement the results of the study, future works is needed in the following areas:

1. Develop an effective heating technique for glass/PP confining jackets to retrofit large scale specimens. Investigation of prefabricated glass/PP split rings should also be seriously considered.
2. Carry out compression testing of ¼ to ½-scale bridge columns.
3. Perform further impact testing on glass/PP-reinforced panels and ¼ and ½-scale columns to further understand the performance, and to create more data that can be compared with the numerical model.
4. Continue LS-DYNA modeling by further investigating the glass/PP 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 glass/PP-confined columns, and use the data obtained to develop a design methodology.

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