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16. Abstract

Vessel collisions with bridges are increasing at an alarming rate, as heavy vessels are making more frequent trips under more bridges. In the US, rigorous design of bridges for vessel collision was first incorporated by *AASHTO Guide Specification and Commentary for Vessel Collision Design of Highway Bridges*[1], in which a model to determine vessel collision forces required for designing bridge elements was introduced. The guide, of which portions have been adopted into the *AASHTO LRFD Bridge Specifications*, does not provide specific guidance for the design of pier protection systems. Given the high number of bridge structures in navigable waterways in the state of Louisiana, bridge pier protection is of concern to the LADOTD. It is desired that bridge fender systems that provide acceptable collision performance be identified. The goal of this project is to identify existing protective systems and propose new systems that can be used to mitigate the effects of bridge/vessel collisions. The focus of the effort is to identify or propose fender systems that are: 1) modular; 2) easily installed or replaced; 3) suitable for retrofitting existing bridges or for use in new construction; 4) crashworthy, i.e. highly damage tolerant with good energy absorption and stiffness characteristics; and 5) durable, with low life-cycle costs. Using a newly proposed multi-tiered performance-based design methodology, the performance of a number of alternative fender systems is evaluated and their suitability for bridge protection examined. The study found that fiber reinforced polymer (FRP) piles arranged in clusters of two piles were shown to provide adequate sideways protection for the low and medium energy performance levels. However, they cannot provide protection for head on collisions for any of the performance levels. For such an application, pier-mounted, energy-absorbing plastic fenders were shown to be suitable for absorbing crash energy and reducing impact forces to acceptable levels. As with vehicle crash cushions that are commercially available and commonly used, the proposed fender systems can be tailored to achieve a wide range of applicability. Additional research is, however, needed to provide proof-of-concept and to engineer a viable and marketable product. It is envisioned that both experimental and computational research will be needed to develop and optimize a system that could be widely adopted in the state of Louisiana and across the country.

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Feasibility of Tubular Fender Units for Pier Protection Against Vessel Collision

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ABSTRACT

Vessel collisions with bridges are increasing at an alarming rate, as more heavy vessels are making more frequent trips under more bridges. In the US, rigorous design of bridges for vessel collision was first incorporated by *AASHTO Guide Specification and Commentary for Vessel Collision Design of Highway Bridges*(1), in which a model to determine vessel collision forces required for designing bridge elements was introduced. The guide, of which portions have been adopted into the *AASHTO LRFD Bridge Specifications*, does not provide specific guidance for the design of pier protection systems. Given the high number of bridge structures in navigable waterways in the state of Louisiana, bridge pier protection is of concern to the LADOTD. It is desired that bridge fender systems that provide acceptable collision performance be identified.

The goal of this project is to identify existing protective systems and propose new systems that can be used to mitigate the effects of bridge/vessel collisions. The focus of the effort is to identify or propose fender systems that are: 1) modular; 2) easily installed or replaced; 3) suitable for retrofitting existing bridges or for use in new construction; 4) crashworthy, i.e. highly damage tolerant with good energy absorption and stiffness characteristics; and 5) durable, with low life-cycle costs.

Using a newly proposed multi-tiered performance-based design methodology, the performance of a number of alternative fender systems is evaluated and their suitability for bridge protection examined. The study found that fiber reinforced polymer (FRP) piles arranged in clusters of two piles were shown to provide adequate sideways protection for the low and medium energy performance levels. However, they cannot provide protection for head on collisions for any of the performance levels. For such an application, pier mounted, energy absorbing plastic fenders were shown to be suitable for absorbing crash energy and reducing impact forces to acceptable levels. As with vehicle crash cushions that are commercially available and commonly used, the proposed fender systems can be tailored to achieve a wide range of applicability. Additional research is, however, needed to provide proof-of-concept and to engineer a viable and marketable product. It is envisioned that both experimental and computational research will be needed to develop and optimize a system that could be widely adopted in the state of Louisiana and across the country.

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IMPLEMENTATION STATEMENT

A comprehensive literature review has been conducted. The survey identified existing systems in other states and countries and categorized them into six main types. A historical survey of various vessel/bridge collisions was also compiled. Based on the results of the survey conducted, a number of alternative fender systems was identified. A new performance-based design philosophy was proposed to evaluate their protective ability.

Assuming a Class IV, standard hopper barge as the specified design vessel, three performance levels were considered in the developed design methodology: low energy, medium energy, and high energy collisions. In the first performance level, both fender system and barge are expected to behave elastically during impact. A low energy collision is expected to occur frequently during the operating life of the fender. The fender and barge should not require any repairs after such an event. The velocity for the design barge for this performance condition is specified to be 1 knot. In the second performance level, the fender system is expected to behave elastically and does not suffer permanent damage. However, the vessel may undergo some limited inelastic deformation. A medium energy collision is expected to occur infrequently during the operating life of the fender. The fender should not require any repairs after such an event, but the vessel may require some repairs. The velocity for the design barge for this performance condition is specified to be 3 knots. In the third and most severe performance level, both fender and barge will suffer extensive damage after such a collision. The barge will not sink and at the same time will have such diminished kinetic energy that it will not deliver a significant impact force to the bridge pier after penetrating through the protection system. A high energy collision is expected to occur rarely during the operating life of the fender. The velocity for the design barge for this performance condition is specified to be 5 knots.

Using the developed performance-based framework, fiber reinforced polymer (FRP) piles arranged in clusters of two piles were shown to provide adequate sideways protection for the low and medium energy performance levels. However, they cannot provide protection for head on collisions for any of the performance levels. For such an application, pier-mounted, energy-absorbing plastic fenders were shown to be suitable for absorbing crash energy and reducing impact forces to acceptable levels. As with vehicle crash cushions that are commercially available and commonly used, the proposed fender systems can be tailored to achieve a wide range of applicability. Additional analytical and experimental research is needed to develop optimized designs that can be installed in the field.

The following conclusions can be drawn from research results obtained in this project:

- Clusters of two or more FRP piles are capable of providing adequate sideways protection for the low and medium energy performance levels. However, they cannot provide protection for head on collisions for any of the performance levels.

- Pier mounted elastic spring fenders are not practical for high energy head-on impact. Springs with low enough stiffness must be used to reduce the impact force to acceptable levels. However, using such soft springs necessitates large deformations that are difficult to accommodate in practice. Therefore, the advantage of elastic spring fenders is best for medium and low energy collisions.

- Inelastic energy absorbing fenders are well suited for use as pier mounted crash cushions. Such fenders would be similar to existing vehicle crash cushions that absorb vehicular impact energy through inelastic deformations. The advantage of using inelastic energy absorbing fenders over purely elastic fenders is that the level of force can be more easily controlled. The disadvantage, of course, is that the panels will be damaged during collision and must therefore be replaced after an accident. However, inelastic crash cushions could be designed to be undamaged for low energy collisions and fully damaged and in need of immediate replacement after a high energy collision. For medium energy collisions, the panels could be repaired or replaced, although not immediately. Such a multi-tiered design philosophy will ensure the economy of the energy absorbing panels. Additional research is needed to develop suitable inelastic fender systems.

Timber piles are key components in the majority of bridge fender protection systems in the state of Louisiana. Timber piles, however, suffer from a number of drawbacks: 1) they are inadequate for medium and high energy collisions and can easily be damaged in low energy collisions; 2) they are susceptible to attacks by marine borers and have a relatively short service life; and 3) damaged piles pose disposal problems when being replaced.

The proposed vessel collision protection system comprised of fiber-reinforced polymer (FRP) composites for sideways protection combined with metal crash cushions for head on protection is a cost effective alternative to traditional timber piles. A successful implementation of this project will have far reaching safety benefits to the state of Louisiana and other states. In particular, the use of high performance FRP piles and metallic crash cushions will reduce the hazard associated with vessel collision with bridge piers and therefore improve the safety of bridges that cross navigable waterways.

The research conducted in this project has shown that pier mounted, inelastic crash cushions are well suited for protecting bridge piers against head on collisions caused by barge traffic in shallow waterways. Additional research is needed to provide proof-of-concept and to engineer a viable and marketable product. Experimental and computational research will likely be needed in the development and optimization of a system that could be widely adopted in the state of Louisiana and across the country.

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INTRODUCTION

The potential for vessel collisions with bridges is increasing at an alarming rate, as more heavy vessels are making more frequent trips under more bridges. In the US, rigorous design of bridges for vessel collision was first incorporated by *AASHTO Guide Specification and Commentary for Vessel Collision Design of Highway Bridges*[1], in which a model to determine vessel collision forces required for designing bridge elements was introduced. The guide, of which portions have been adopted into the *AASHTO LRFD Bridge Specifications,* does not provide specific guidance for the design of pier protection systems. Given the high number of bridge structures in navigable waterways in the state of Louisiana, bridge pier protection is of concern to the LADOTD. Bridge fender systems that provide acceptable collision performance should be identified.

According to the *AASHTO Guide Specifications,* the expected impact force depends on the type of vessels traveling in a water channel and the vessel deadweight, size, and speed of travel. The final design should also take into consideration the risk of collision, which depends on the geometry of the channel and the size and number of vessels. The probability of vessel collision and the expected collision forces resulting from the collision and the expected type of damage given on impact are important parameters for a risk-benefit analysis used to choose an appropriate pier fender system design for a particular water channel. This study required an extensive literature search into state-of-the-art protection systems used by other states and any commercially available systems that are in use throughout the world.

One of the conclusions reached from the literature survey conducted in this project is that bridge fender technology is not as advanced as the roadway safety devices used for vehicles. Fender technology has changed little in the past several decades, with the main advances made being in the use of fiber reinforced polymers (FRP) for tubular piles. In spite of some research that was conducted over the last decade, FRP piles are still considered experimental by the majority of bridge engineers. For example, many states are still trying them out under the FHWA's IBRD program that allows states to evaluate experimental technology on pilot projects prior to wide scale deployment. Vehicle protection devices are, however, far from experimental. Hundreds of innovative products are available on the market, and most of these products are protected by active patents. In fact, so many different types of products exist that NCHRP has developed the NCHRP-350 (2000) specifications to ensure that these products can provide the required level of protection.

Significant differences in the philosophies used to design both types of protection devices are evident. Roadway safety devices are primarily used to protect vehicle occupants during a crash, although they are sometimes deployed to also protect bridge piers against excessive vehicle collision forces (El-Tawil et al 2004). Bridge fender systems, on the other hand, protect a bridge against excessive collision forces and, at the same time, are supposed to prevent an errant vessel from sinking or from being damaged to the point at which it releases its cargo into the environment. This latter point is important, because barges and vessel frequently carry cargo that could be polluting or damaging to the environment. Another key difference is in the type of loading that is generated. Vehicle protection devices are subjected to high speed impact loads generated from relatively light vehicles, while fenders see low speed impact loads generated from heavily loaded vessels.

In spite of the differences in the demands seen by vehicle and vessel protection devices, their basic function remains the same, i.e. that they must handle and safely deal with the imparted collision energy. This report is concerned with this particular topic, which has led to the formulation of a new, performance-based design philosophy for bridge fenders. The new method defines three levels of performance for which a bridge fender could be evaluated, namely, low energy collisions, medium energy collisions and high energy collisions. The various types of commercially available fenders are evaluated within this framework, and conclusions are drawn regarding their suitability. In addition, new types of fenders are proposed and evaluated within the newly proposed performance-based design framework.

PROBLEM STATEMENT AND OBJECTIVES

A protection system can be specified to prevent, redirect, or reduce the impact of loads on the bridge piers and abutments. If the force resistance of the protective system is higher than the vessel crushing force, the bow of the vessel will be crushed and the vessel will primarily absorb the impact energy. If the vessel crushing force is higher than the resistance of the protective system, the impact energy will be primarily absorbed by inelastic deformation of the protective system. Damage to the vessel may result in serious environmental consequences, such as spilling of oils and other chemicals. Therefore, an efficient protection system should be designed not only to protect the bridge structure but also to protect the vessel and the environment. The current practice in the design of protective systems is based on energy considerations. Thus, the kinetic energy of the vessel just before impact is transformed into an equal amount of energy that must be absorbed by the protective system through deformation. Fender systems that are currently installed around bridge piers are generally rigid but relatively brittle barriers. These barriers often exhibit high levels of damage or even total destruction, requiring major repairs after a collision.

The requirements for vessel collision design are a significant factor in the design of bridges over navigable waterways and can affect the bridge configuration and layout, the type and size of the bridge piers, and/or the type and size of the pier protection system. As collisions, whether minor or major, do occur, and fenders are first to get damaged, developing fender systems is important to develop fender systems that protect the bridge with a specific performance. For example, a fender design philosophy could involve a variety of performance limits, e.g. in the case of minor collisions or bumps, no damage should occur to the fender; or, for severe collision, the fenders could be damaged, but should be capable of absorbing sufficient energy to prevent the errant vessel from damaging the bridge.

The cost of incorporating vessel collision loads in the planning stages of a new bridge can range from 5% to 50% of the basic structure cost without protection, and the cost of retrofitting or adding protection to an existing bridge can range from 25% to over 100% of the cost of the existing bridge. Energy absorbing fenders have been identified as systems with the potential to provide protection for bridges with acceptable performance and life cycle costs.

The goal of this proposed research is to identify existing protective systems and propose new systems that can be used to mitigate the effects of bridge/vessel collisions. The focus of the effort is to identify or propose fender systems that are: 1) modular; 2) easily installed or replaced; 3) suitable for retrofitting existing bridge or for use in new construction; 4) crashworthy, i.e. highly damage tolerant with good energy absorption and stiffness characteristics; and 5) durable, with low life cycle costs. As part of this effort, a comprehensive literature review has been conducted, considering many existing systems in other states and countries. The results obtained help in determining the proper fender system to be used.

LITERATURE SURVEY

Pier fender systems can be made of timber, steel, concrete, or rubber and are located directly on bridge piers (see figures 1-4). While timber, steel and concrete fenders are usually crushable and can be damaged irreparably at high impacting forces, the high elasticity inherent in rubber results in relatively high energy absorption characteristics. Timber fenders are composed of vertical and horizontal wood beams that can be attached to a pier or erected adjacent to the pier. Timber is commonly used because of its low cost. However, timber fenders are most effective against minor collisions and are generally not created in sizes that would protect against a major vessel.

Figure 1
Timber fender systems used in some small bridges in Louisiana

Concrete fenders are hollow, thin-walled concrete box structures that diffuse impact energy through buckling and crushing of the concrete walls. Steel fenders offer the same kind of energy diffusion as a concrete fender; however, with this application, timber fenders should be attached to prevent sparks when steel-hulled vessels meet steel fenders.

Figure 2
UHMW marine plastic material panel facing (Maritime International, Inc.)

Rubber fenders are available in a variety of shapes and can be purchased commercially. They absorb impact through compression, bending, and shear deformations or a combination of all three. Rubber fender systems also have the advantage of low maintenance costs and high durability. Pier mounted rubber fenders have successfully served to absorb some of the impact forces during collisions, reducing the final force on the pier and avoiding permanent damage. These improved rubber products have helped improve the efficiency of rubber-based fenders for pier protection. For example, the load deflection, energy absorption, and chemical properties of laminated rubber have made them a preferred choice over virgin extruded and molded rubber for marine vessels and structures [2].

Figure 3
Laminated rubber fenders (Schuyler Rubber Company, Inc.)

Figure 4
Seapile and SeaTimber Marine Composite (SEAWORD, Trelleborg Group)

Bridge Pier Collisions

A brief survey of literature, as shown in Table 1, is illustrative of the consequences of poor protective systems. Properly designed fender systems help protect the bridges against catastrophic failures, such as the 1993 vessel collision with an Amtrak bridge in Alabama, which cost 47 lives and millions of dollars. Fourteen motorists were killed in May of 2002 when the 99-foot-long towboat Robert Y. Love, pushing two empty 298-foot-long barges on the Arkansas River, veered off course and struck the Interstate 40 Bridge in Webbers Falls, Oklahoma. Whitney et al.[3] describe the application of the AASHTO vessel collision model for barge traffic over the Ohio River.

Figure 5
I-40 Bridge, Arkansas River

Figure 5 shows a picture of the I-40 Bridge collision in which a section of roadway rests on the barge that knocked out the supports of the I-40 Bridge across the Arkansas River. The piers that collapsed were about 200 feet from the channel. This collision renewed concerns about the protection of highway and railroad bridges from collisions with vessels. The I-40 Bridge was built in 1967 and was rated satisfactory by the Oklahoma DOT. The state's DOT had done a ship-bridge collision survey of its bridges across the Arkansas River but concluded that the probability of a ship striking the outer pier of the I-40 Bridge was small. Fenders were, therefore, provided on the upstream side of the two bridge piers next to the navigation channel, with none on the downstream side[4].

Table 1
Major ship collisions with bridges[2]

Location	Year	Lives Lost	Others
CSX/Amtrak Railroad Bridge, USA	1993	47	
Claiborn Avenue Bridge, USA	1993	1	
Hamburg Harbor Bridge, USA	1991	0	
Volga River Railroad Bridge, Russia	1983	176	
Tjorn Bridge, Sweden	1980	8	
Sunshine Skyway Bridge, USA	1980	35	
Pass Manchaca Bridge, USA	1976	1	
Tasman Bridge, Australia	1975	15	
Sidney Lanier Bridge, USA	1972	10	Bridge/pier destroyed
Old bridge in Portland Maine 1-40 Bridge Arkansas river Oklahoma	1996 2002	 14	$46 million to clean oil spillage Bridge/pier destroyed
Casco Bay Bridge US Virginia	2002	0	No major Damage.

Pier Protection: History and Experimentation

The development of standards for impact-resistant bridge structures in the United States began after an ocean freighter struck a bridge support of the Sunshine Skyway Bridge in Tampa, Florida, on May 8, 1980, resulting in the collapse of a long-span, high-level bridge. In 1988, 11 states and the FHWA sponsored a pool-funded research project to establish design specifications for ship impact with bridges. In 1991, the findings of this project were adopted by AASHTO and were presented as the *Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges*[1]. The *Guide Specifications* provide three vessel impact design methods, called Methods I, II and III. The first is a semi-deterministic method that allows the designer to select a design vessel for collision impact. The second involves selection of the design vessel based on a probabilistic analysis of actual traffic data. The third employs a cost-effective analysis procedure to select the design vessel and resembles Method II. Method II of the *Guide Specifications* has been adopted into the *LRFD Bridge Specifications*.

The U.S. Army Corps of Engineers (USACE) recently conducted full-scale barge impact experiments(6). The experiments were conducted at the Waterways Experiment Station to assist in the verification of the current barge impact methodologies being utilized in the design of energy absorbing fender systems. These full-scale experiments utilized four- and fifteen-barge tow configurations. The flotillas were fully ballasted to approximately 9 ft (3 m) of draft and laid out with state-of-the-art instrumentation to record the actual impact force and the behavior of the system during impact. The angles and speeds of the tow at impact during these experiments ranged from 0.5 to 4.1 ft (0.2 to 1.2 m) per second, at angles of impact from 5 to 30 deg. The results from these experiments will be used to further define and develop the barge impact numerical models and assist with design procedures to be used in USACE projects.

In a joint effort with the University of Florida, the Florida Department of Transportation recently conducted a series of barge impact experiments similar to the USACE experiments. The Florida experiments were aimed at evaluating the AASHTO provisions and calibrating existing design guidelines(7). The experiments were recently concluded, but their results have not yet been published.

Existing Fender Protective Systems

Review of literature indicates existence of only a modest number of systems exhibiting energy absorbing characteristics. For instance, a new wide-flange beam system that incorporates energy-absorbing technology has been developed and crash tested as guard rails and has potential for use as an energy absorbing fender(8). It incorporates an impact head designed to dissipate impact energy by producing a series of plastic hinges in the W-beam as the impact head is compressed. The energy-absorption mechanism allows the W-beam to absorb large amounts of kinetic energy. Another new biaxial elasto-plastic energy absorbing device has been developed and tested for application in bridge fenders(9). This device is promising and is made up of bent U-shaped steel elements arranged in a radial pattern. Each element can deform along any direction. The radial arrangement allows for a full exploitation of the energy dissipating capability of each element as well as for the possibility of calibrating the resisting forces in the horizontal directions. The experimental and the numerical results show a good non-linear behavior of the U-elements as well as of the complete device, with high-energy dissipation capacity and allowance for large displacements.

Rubber fender systems are capable of absorbing high levels of energy during impact. However, fiber reinforced composites provide attractive alternatives to conventional fender materials. The use of composite plastic materials eliminates the problem of attack by marine organisms and the environmental consequences of creosote treatment of timber piles[10,11]. The pilings are made from molded hollow tubes of advanced composite materials including glass fiber and vinyl ester resin. Recycled plastic sheaths around the tubes provide an abrasion-resistant outer surface. The structural composite materials are strong, lightweight, highly corrosion resistant, and immune from sea worm attack. Although the materials for the composite pilings are more expensive than wood or concrete, Parker and Ansari (2003) showed that piling and fender systems made from such materials are more durable and cost effective over the life of the system than traditional alternatives.

This proposal intends to present a summary of existing fender systems, along with their cost, advantages, and disadvantages. This, however, requires a thorough investigation of the guides and standards developed by various agencies, associations, and manufacturers in order to acquire insight into the attributes of the various systems. In this regard, the standards established by the Permanent International Association of Navigation Congresses (PIANC)[12] for the design of fender systems and the *Advanced Pier Concepts Users Guide* (1985)[13] will be utilized to provide some guidelines for systems selection[14,15]. Existing technologies used for bridge fender protective systems by other states or countries were identified and grouped into six main categories as follows:

- Pile fender systems
    - Timber piles
    - Steel piles
    - Pre-stressed concrete piles
    - Composites piles
- Rubber fender systems
    - Rubber-in-compression
    - Rubber-in-shear
    - Rubber-in-torsion
    - Lord flexible
    - Pneumatic
- Hydraulic/pneumatic fender systems
    - Dashpot hydraulic
    - Hydro-pneumatic floating fender
- Retractable fender systems
- Gravity-type fender systems
- Floating fender systems

Pile Fender Systems

This type of fender system employs piles driven below the mud line such that the energy is mainly absorbed by deflection of the pile. The energy absorption capacity depends on the pile and is determined on the basis of internal strain-energy characteristics. Piles used in this type of fender system are usually made of different types of materials such as timber, steel, concrete and composites:

a. **Timber piles:** Consist of timber members with a contact frame that is formed to distribute impact loads. This type of pile has a low initial cost as an advantage and limited energy absorption as a disadvantage. Moreover, it is highly susceptible to both mechanical and biological damage.

b. **Steel piles:** Normally used at a water depth greater than 40 feet, in which they show strength and feasibility for difficult seafloor condition. Vulnerability to corrosion and the high initial cost are considered disadvantages for this type of pile fender system.

c. **Pre-stressed concrete piles:** usually used with rubber buffers at deck level. They are able to resist natural and biological deterioration. They have limited strain energy capacity and show corrosion of steel through cracks.

d. **Composites Piles:** cylindrical shells fabricated of high-strength fiber reinforced composite materials and filled with concrete. Another variation is plastic piling reinforced with fiber reinforced polymer bars. Both types of piles exhibit high-energy absorption and resist natural and biological deterioration. However, their high initial cost is considered a disadvantage.

Rubber Fender Systems

The rubber fender systems consist mainly of two major types, rubber-in-compression and rubber-in-shear. However, there exist some other types of rubber fender systems, such as rubber-in-torsion, lord flexible, and pneumatic.

a. **Rubber-in-compression:** Consists of a series of cylindrical rubber or rectangular tubes installed behind standard fender piles. Energy absorption is achieved by compression of the rubber. Absorption capacity depends on the size of the buffer and on maximum deflection. The energy-absorption capacity can be varied by using the tubes in single or double layers or by varying tube size. Simplicity and adaptability plus effectiveness at a reasonable cost are considered as advantages, whereas their initial cost is higher than a standard pile system without resilient units.

b. **Rubber-in-shear**: Consists of a series of rubber pads bonded between steel plates to form a series of rubber sandwiches mounted firmly as buffers between a pile-fender system and a pier. Two types of mounting units are available: standard unit or overload unit, which are capable of absorbing 100% more energy than the timber systems. Capable of cushioning impact from lateral and vertical directions with high energy absorption capacity and favorable initial cost. They are too stiff for small vessels with steel plates subject to corrosion. They show some problems with bonding between steel plates and rubber.

c. **Rubber-in-torsion:** A combination of rubber and steel fabricated in cone-shaped compact bumper form, molded into a specially cast steel frame and bonded to the steel. It absorbs energy by torsion, compression, shear and tension, but most energy is absorbed by compression. Capable of resisting impact from all directions. Besides fatigue, it also shows some bond problems between steel casting and rubber.

d. **Lord flexible:** Consists of an arch-shaped rubber block bonded between two end steel plates. It can be installed on open or bulk head-type piers or dolphins, or incorporated with standard pile or hung fender systems. Impact energy is absorbed by bending (buckling) and compression of the arch-shaped column. The Lord flexible system maintains high energy absorption and low terminal-load characteristics. Possible fatigue and bond problems between steel plates and rubber are also observed.

e. **Pneumatic:** Pneumatic fenders are pressurized, airtight rubber devices designed to absorb impact energy through the compression of air inside a rubber envelope. Energy-absorption capacity and resistance load depend on the size and number of tires used and on the initial air pressure when inflated. The pneumatic system is berthed and moored ships and requires high maintenance cost.

Hydraulic/Pneumatic Fender Systems

Consist of the following two main types:

a. **Dashpot hydraulic:** Consists of a cylinder full of oil or other fluid so arranged that when a plunger is depressed by impact, the fluid is displaced through a non-variable or variable orifice into a reservoir at higher elevation. Suitable where severe wind, wave, swell, and current conditions exist. It has a favorable energy absorption characteristic but requires high initial and maintenance costs.

b. **Hydro-pneumatic floating fender:** This is a system of floating rubber envelopes filled with water and air that absorbs energy through viscous resistance or air compression. It has a favorable energy absorption characteristic but requires high initial and maintenance costs.

Retractable Fender Systems

The retractable fender systems consist of vertical-contact posts connected by rows of wales and chocks. The fender retracts under impact, thus absorbing energy by action of gravity and friction. Energy-absorption capacity depends directly on the effective weights, the angle of inclination of the supporting brackets and the maximum amount of retraction of the system. Besides their low maintenance cost, they have negligible effects of bio-deterioration on energy absorption capacity. However, their vulnerability to corrosion of the supporting brackets as well as high initial cost if used on open type piers are considered as disadvantages.

Gravity-Type Fender Systems

Gravity fenders are normally made of concrete blocks and are suspended from heavily constructed wharf decks. Impact energy is absorbed by moving and lifting the heavy concrete blocks. Capable of absorbing high energy. However, they require heavy equipment with high initial and maintenance costs.

Floating Fender Systems

Consist of floating logs that ride up and down against the timber breasting face. Easily applicable and can be used at high water depths. They have low energy absorption.

Commercially Available Fender Piles and Systems

Energy absorbing fender piles and systems that are commercially available are identified as explained below:

a. **SEAPILE® & SEATIMBER® Composite Marine Products:** SEAPILE and SEATIMBER composite marine products are plastic piling and timbers made from 100% recycled plastic that provide alternatives to traditional chemically treated wooden piling and timbers. SEAPILE and SEATIMBER Composite Marine Piling and Timbers have been used in Washington, Algeria, Hong Kong, Korea, Barbados, and Sweden.

b. **Hardcore Composites:** Hardcore Fender and Dolphin Systems are custom designed for each situation. Fenders are secured to the outside of the composite piles to protect the dock or pier. They have been used in Delaware.

c. **Foam Filled Marine Fenders:** ProMar foam filled marine fenders are high-energy absorption, elastomeric marine systems used to provide protection to ships, wharves, and piers in vessel-to-vessel or vessel-to-facility operations.

d. **Donut Type Monopile Fenders:** ProMar Donut-Type Monopile Fenders are special purpose foam filled fenders that are installed on a fixed monopole. The fender and the pile act as an integrated system to absorb energy and resist reaction forces imparted by vessel impact or other external forces.

e. **Maritime International, Inc.:** Maritime International, Inc. markets a line of UHMW-PE marine plastic material utilized for fender applications for docks, piers, and bridge applications. A wide range of sizes, thicknesses, and colors of virgin material as well as reprocessed material is offered.

f. **Urethane Technologies, Inc.:** Urethane Technologies, Inc. manufactures collision survivable products that are available in a wide array of designs, shapes, configurations, and colors. Fenders or other floatation devices can be custom designed and manufactured for customers' particular needs.

g. **Viking Fender:** Viking "Softlite" Foam Ship and Pier Fenders are reputed to be the longest-lived, lightest heavy-duty ship and pier fenders available. They are easy to use, safe to handle, and require few personnel and light equipment to deploy and retrieve. They have been used in New Jersey.

h. **Svedala/Trellex:** Svedala/Trellex is a subsidiary of J. H. Menge & Company, Inc., a producer of specially engineered marine fendering and machinery. It is presently in its fourth generation of engineering sales to Gulf Coast shipyards, refineries, and terminals as well as the dock building industry and the offshore oil industry. From their office in New Orleans, they cover the Gulf Coast and up-river to Memphis.

i. **Ultra Poly, Inc.:** Ultra Poly, Inc. is a service-oriented company with a wide offering of UHMW products from compression-molded sheets to ram extrusion profiles and custom fabricated parts. Ultra high molecular weight (UHMW) polyethylene is often referred to as the world's toughest polymer. UHMW is a linear high-density polyethylene that has high abrasion resistance as well as high impact strength.

Besides being used in New York and Washington, UHMW have been used in Canada, Central and South Africa.

j. **Schrader Co.:** The Schrader Company's Plastic Pilings, Inc. offers recycled plastic pilings to meet design engineers' requirements for bending loads, axial loads, or a combination of both. Fender and vertical load bearing pilings with a steel pipe core (and fender pilings with fiberglass reinforcing) are available upon request. PPI pilings are immune to all marine borer attacks, so no further protection (such as creosote or plastic sheathing) is required. PPI pilings are essentially maintenance free. They have been tested in the Los Angeles Harbor since April 1987.

k. **Schuyler Rubber Company:** Schuyler Rubber Co., Inc. has designed, tested; and manufactured laminated rubber fenders since 1950. Laminated rubber's proven track record of economy, protection, durability, and reliability make it the preferred choice over virgin extruded and molded rubber for tugs, push boats, barges, ferries, piers, docks, dolphins, trawlers, and other marine vessels and structures.

Structural Characteristics of Commercially Available Tubular Piles Used in Fender Systems

Two types of tests are commonly used for fender piles: cold radial compression and flexure tests. The radial test is conducted at -40^{o} F, while the flexural tests are usually conducted at room temperature (70^{o} F) and at sub-ambient temperature (-20^{o} F). Following is a synthesis of pertinent tests conducted by ACE-CERL in 1998 (Lampo et al. 1998).

Cold Radial Test (13" Diameter Piles)

The pile specimens are tested at a radial compression rate of 100 percent per minute. Table 2 is a compilation of test results for various types of piles from Lampo et al. (1998).

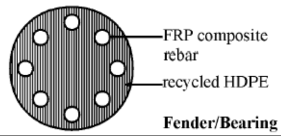
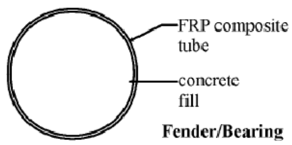
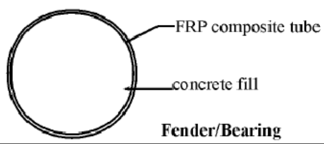
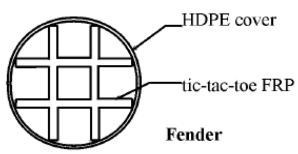
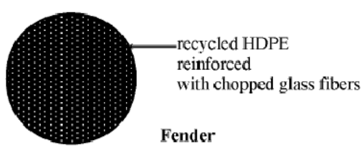
Room Temperature Flexural Test (13" Diameter Piles)

The specimens are tested in flexure at room temperature. Long specimens are usually preferred (L/D > 16), however, to reduce costs, tests on specimens with L/D = 9 were performed. Table 3 is a compilation of test results for various types of piles from Lampo et al. (1998).

Sub-Ambient Temperature Flexural Test (13" Diameter Piles)

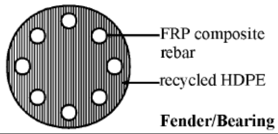
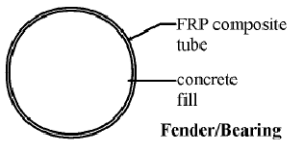
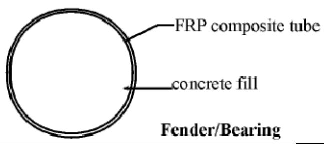
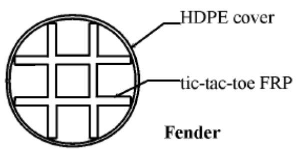
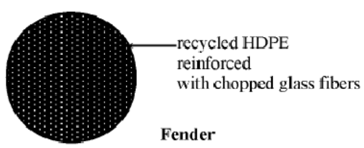
The specimens are tested in flexure at -70^{o} F. Table 4 is a compilation of test results for various types of piles (Lampo et al 1998).

Table 2
Characteristics of various tubular piles in cold radial test

Fender Pile Type	Stiffness (kips/in)	Force at Failure (kips)	Δ at Failure (in)	Energy (ft-lb)	Failure Warning
Seaward International, Inc.  	317	18.24	0.18	26	Yes
Hardcore Dupont Composites, LLC  	4.9*	2.9	2.23	71	Yes
Lancaster Composite, Inc.  	121	9.4	0.29	23	Yes
Creative Pultrusions, Inc.  	6.5**	20.75	1.34	595	Yes
Trimax of Long Island, Inc.  	347	22.7	0.28	44	Yes
Timber (new, chemically treated)	1503	80.4	0.39	42	Yes

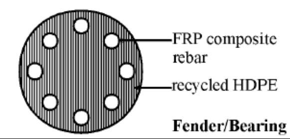
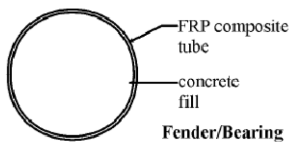
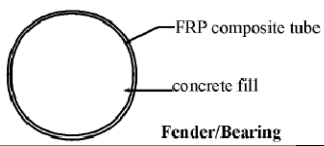
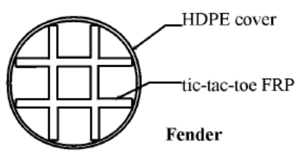
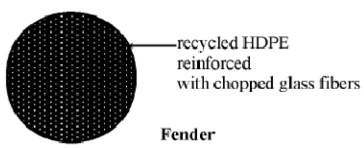
*The Hardcore DuPont piles were tested hollow (i.e. without the concrete core), which is the reason for the very low structural characteristics listed in the table.
**Creative Pultrusion pile was foam filled and tested with the tic-tac-toe profile vertically/horizontally aligned.

Table 3
Characteristics of various tubular piles in room temperature flexural tests

Fender Pile Type	EI x 10^3 Kip-in^2	Force at Failure (kips)
Seaward International, Inc. 	580	89
Hardcore Dupont Composites, LLC 	1575*	83
Lancaster Composite, Inc. 	1151	84
Creative Pultrusions, Inc. 	516	30.5
Trimax of Long Island, Inc. 	132**	9.2
Timber	1019***	
Concrete	3124***	

*The Hardcore DuPont piles were tested filed with concrete.
**Unlike other piles which are 13” (nominally) in diameter, Trimax piles are 8.75” in diameter.
***Adjusted from long-span test data based on data for the Seaward piles, which were tested in both long span and short span configurations.

Table 4
Characteristics of various tubular piles in sub-ambient temperature flexural tests

Fender Pile Type	EI x 10^3 Kip-in^2	Force at Failure (kips)
Seaward International, Inc. 	621	55
Hardcore Dupont Composites, LLC 	1993*	105
Lancaster Composite, Inc. 	1056	105
Creative Pultrusions, Inc. 	583	42
Trimax of Long Island, Inc. 	236**	15

*The Hardcore DuPont piles were tested filed with concrete.
**Unlike other piles which are 13” (nominally) in diameter, Trimax piles are 8.75” in diameter. They failed catastrophically in the low temperature tests.

Discussion of Existing Test Results

Based on the test data, all of the listed commercially available piles appear to have reasonably good structural characteristics. There are other factors, however, that limit the choice of an appropriate pile. For example, Creative Pultrusions piles suffered severe damage during a fire (Lampo et al. 1998), and may thus be vulnerable to accidental fires that may occur during collision.

Another consideration is pile driveability. Composite materials, in general, have higher damping and lower stiffness than traditional materials. This hinders the driving process, due to the difficulty of transferring energy to the pile. Lampo et al. (1998) reported that they had difficulty driving the Trimax piles. They resorted to tapering the pile ends to eliminate wandering of the pile tip during driving. Baxter et al. (2005) also reported difficulties driving Seaward piles. At the end of a driving test: 1) the pile tops were bent out of alignment by more than three degrees, 2) the diameter of the top portion grew substantially, and 3) the pile tip was severely damaged. Baxter et al. (2005) reported driving problems with Lancaster piles, including damage to the pile top during driving.

From the test results summarized above, the Hardcore DuPont (HD) piles have the best structural characteristics. The cold radial tests data appears to show that these piles have low resistance for this type of loading, but one should bear in mind that the test was performed while the tubes were hollow (i.e. not filled with concrete). It is expected that the cold radial resistance of these types of piles would be of the same order of magnitude as that of the Lancaster piles, which have a similar composition.

At this time, it is not clear if HD piles would have good fire resistance, as test data about the fire behavior of FRP is limited. In terms of driveability, HD piles would have the same driveability characteristics of concrete piles, as a large portion of the cross-section is concrete. HD piles are likely substantially more durable than concrete piles because the FRP cover protects the concrete and there is no steel to rust or deteriorate. However, there are no tests to document this assertion.

Commercially Available Diameters for Hardcore DuPont Piles

The previous section identified Hardcore DuPont piles as having the best structural characteristics of the commercially available piles tests reported in Lampo et al. (1998). This product comes in several diameters, as shown in Table 5 (adapted from Parker and Ansari 2003), in which the first number in the product identification is the nominal outer diameter. In the table, the bending stiffness is calculated at 20% of the ultimate bending moment. In addition, data for the 24 inch diameter pile flexural data is based on extrapolation of experimental data.

Table 5
Flexural data for Hardcore DuPont piles

Product Identification	Bending Stiffness , EI (lb-in ^{2})	Ultimate Bending Moment (in-lb)
10-2	4.49×10^8	1.15×10^6
12-2	9.78×10^8	2.04×10^6
12-3	1.38×10^9	2.80×10^6
14-3	1.76×10^9	3.43×10^6
18-3	4.59×10^9	5.66×10^6
18-4	5.78×10^9	7.60×10^6
24-3*	1.05×10^{10}	1.01×10^7
24-4*	1.34×10^{10}	1.29×10^7

Example Application: Protection of East Pearl River Bridge

According to the Modjeski and Masters report (1985) provided by LADOTD, the longitudinal impact design force is 1800 kips. Assuming that fender piles are fixed at a depth of -42.4’ and that the load is applied at the high water point at +2.6’, the total pile length is 45’. In the following calculations, it is that 24-4 piles (Table 5) are used and that the piles are fully restrained at the top by the dolphin cap, i.e. the pile is in double bending.

Force resisted by one pile = 2 x moment capacity / pile length = 2 x 1.29E7 / (45x12) / 1000
= 47.8 kips

Number of piles needed = 1800 / 47.8
= 38 piles

The number of piles in the fender system can be reduced if the pier is designed to resist some of the impact demands. In this case, however, extensive damage to the fender system will likely occur during the collision event.

Structural Characteristics of Commercially Available Sheet Piles used in Fender Systems

A number of sheet piles was tested by Lampo et al. (1998) (Figure 6). This product was tested as a stand-alone product. Variations of the product which two sheet piles were attached to form a honeycomb configuration (Figure 7) and a third case in which the honeycomb voids were filled with concrete were tested. The flexural properties are shown in Table 6 (adapted from Lampo et al. 1998).

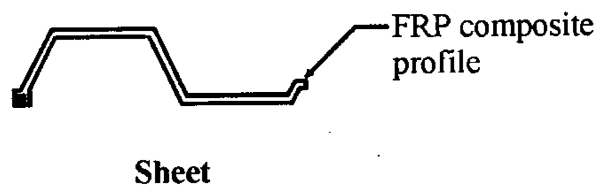


Figure 6
Sheet pile product from International Grating

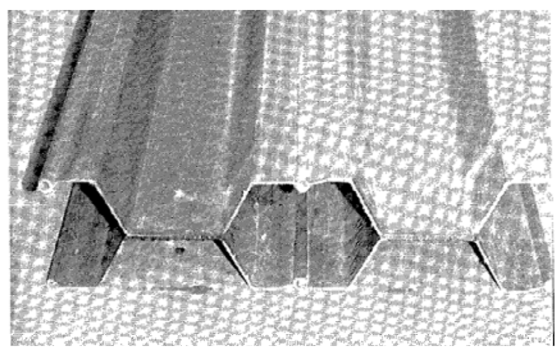


Figure 7
Honeycomb configuration of sheet pile product

Table 6
Structural properties for International Grating sheet pile product

	As Is	Honeycomb	With Concrete
Span (in)	108	108	107
Maximum Load (lb)	1,092	1,300	11,600
Maximum Moment (in-lb)	39,312	46,800	620,600
EI (kip-sq in./ft)	4.22×10^3	9.97×10^3	3.62×10^4

Light Duty Composite Sheet Piles

Assuming that tubular piles are spaced at 6 ft, comparing the stiffness properties of 6 ft of stand-alone sheet piles with the stiffness of one 12-3 pile (Table 5) shows that the sheet piles are much softer. For example, the ratio in EI is 1.38E9/(4.22E3 x 1000 x 6) = 55, i.e. a 12-3 pile is 55 times stiffer than 6 ft of standalone sheet pile. *Therefore, composite sheet piles tested by Lampo et al. (1998) are essentially light duty sheet piles and are therefore not suitable for fendering applications.*

Heavy Duty Steel Sheet Piles Versus Composite Piles

Heavy duty steel sheet piling (e.g. PZ–27 sheet piles, Appendix I) has an EI of 5.5E6 kip-in^2/ft. In this case, the ratio in EI between 6 feet of PZ-27 sheet pile and one 12-3 (Table 5) is 1.38E9/(5.5E6 x 1000 x 6) = 0.042, i.e. the 12-3 pile is 25 times softer than 6 feet of heavy duty steel sheet pile. Conducting a similar comparison with a 24-4 pile (Table 5), the new ratio is 1.34E10/(5.5E6 x 1000 x 6) = 0.41, i.e. the stiffness is about half. *When used in a parallel configuration with sand or concrete between both piles, heavy duty steel sheet piles could serve as effective retaining walls and/or fender systems for bridge piers that are close to shore.*

Newly Available Composite Sheet Piles versus Composite Piles

Lee Composites Inc. (*http://www.leecomposites.com/sheetpile.html*) produces sheet piles (Appendix I) that are heavier than those tested by Lampo et al. (1998). Heavy duty composite sheet piling (e.g. 1610 sheet piles) has an EI of 3.85E5 kip-in^2/ft. In this case, the ratio in EI between 6 feet of 1601 sheet piles and one 12-3 is 1.38E9/(3.85E5 x 1000 x 6) = 0.6, i.e. the 12-3 pile (Table 5) is about 60% as stiff as 6 feet of heavy duty composite sheet pile. Conducting a similar comparison with a 24-4 pile (Table 5), the new ratio is 1.34E10/(3.85E5 x 1000 x 6) = 5.8, i.e. the stiffness of a 24-4 pile is about 6 times that of the sheet pile. *Therefore, when used in a parallel configuration with sand or concrete between both piles, heavy duty composite sheet piles could serve as effective retaining walls and/or fender systems for bridge piers that are close to shore.*

Fenders used by the Florida Department of Transportation

According to the *Florida Department of Transportation (FDOT) Structures Design Guidelines*, fender systems serve primarily as navigation aids to vessel traffic passing through shipping channels underneath bridges. Their design philosophy is as follows: “Fenders should be robust enough to survive the inevitable bumps and scrapes from barge traffic with little or no maintenance. The fender system must also be capable of redirecting errant barges or vessels without sustaining too much damage or inflicting too much damage on these vessels." This is consistent with the AASHTO philosophy.

Classification of Fender Systems According to Rigidity

Depending on their structural characteristics, fender systems can be classified as either rigid or flexible. Dolphins and islands fall in the former category. These systems can be used to protect new or existing bridge piers that were not designed to resist vessel collision loads. They have also been used to protect the substructure of bridges located at port facilities. FDOT discourages the use of such systems, as even though they protect bridge piers effectively, they represent a hazard to vessels. They also aggravate scour and increase water flow velocities. Nevertheless, such systems may be necessary when the pier must be completely protected against collision.

Flexible fender systems form the basis of most existing bridge pier protection systems. These systems are comprised of energy absorbing components and are designed to minimize the potential for damage to vessels and fenders during minor collisions. During a severe design collision event, flexible fender systems are proportioned to absorb a predetermined amount of the errant vessel's kinetic energy, thereby allowing the bridge pier to be subjected to a reduced collision force.

Design Process Adopted by FDOT

According to AASHTO, bridge protection systems generally follow three approaches:

1. Reduce the annual frequency of collision events, e.g. by improving navigation aids near a bridge.
2. Reduce the probability of collapse, e.g. by imposing vessel speed restrictions in the waterway.
3. Reducing disruption costs of a collision, e.g. by physical protection as in fender system.

For the last alternative, AASHTO recommends an iterative design process in which a trial configuration of a protective system is initially developed. For each trial, a force versus deflection diagram is developed via analysis or physical testing. The energy under the diagram is the capacity of the fender system to absorb energy, i.e. through work done by flexure, shear, torsion, and displacement of the components of the protective system. The forces and energy capacity of the protective system are then compared with the design vessel impact force and energy to see if the collision loads have been safely resisted. If the fender system is unable to dissipate the collision energy, the remaining kinetic energy of collision is then computed by subtracting the energy absorbed by the fender system from the initial kinetic energy of the vessel. The remaining energy can be used to compute the approach velocity of the vessel, for which the bridge pier must be designed.

Using the reduced approach speed, equivalent static forces parallel and normal to the centerline of the navigable channel can be computed and used to design the bridge pier and substructure. The pier should be designed for 100% of the static force in a direction parallel to the centerline and 50% perpendicular to it. For overall stability, the design impact force should be applied as a concentrated load on the pier at mean high water level of the waterway. For local collision effects, the design impact force should be applied as a vertical line load equally distributed along the depth of the barge's head block.

FDOT Structures Design Guidelines for Fender Systems

FDOT recommends the fender systems shown in Appendix II and described next.

- *Heavy duty fender system*: Comprised of plastic lumber (Appendix II, Figure AII.1), this fender system has an energy capacity of 295 kip-ft and can resist two loaded jumbo hopper barges and a push boat approaching at 15^o and moving at 4.0 knots. Alternatively, it can resist two empty jumbo hopper barges and a push boat approaching at 15^o and moving at 9.8 knots.

- *Medium duty fender system*: Comprised of plastic lumber (Appendix II, Figure AII.2), this fender system has an energy capacity of 132 kip-ft and can resist one loaded jumbo hopper barge and a push boat approaching at 15^o and moving at 3.6 knots. Alternatively, it can resist one empty jumbo hopper barge and a push boat approaching at 15^o and moving at 7.8 knots.

- *Light duty fender system*: Comprised of concrete piles and a plastic wale system (Appendix II, Figure AII.3), this fender system has an energy capacity of 38 kip-ft and can resist one empty jumbo hopper barge and a push boat approaching at 15^o and moving at 3.6 knots. Alternatively, it can resist a push boat approaching at 15^o and moving at 5.6 knots.

ETL Methods for Estimating Barge Impact Demands

ETL 1110-2-563 Method for Rigid Walls

This document provides information for estimating masses, approach velocities, and approach angles for barge impacts. It also contains information on return periods for use in probabilistic design of lock walls for barge impact and provides a method for estimating barge impact loading on rigid navigation devices such as lock walls, approach walls, etc. The method is applicable for approach angles less than 30 degrees. It is not suitable for broadside or head-on impacts and should also not be applied to flexible structures. The method is empirical in nature and is calibrated to full-scale barge impact experiments.

Empirical Barge Impact Model – Deterministic Model

$$F_m = 0.435.M.(V_{0x}.\sin\theta + V_{0y}.\cos\theta)$$

Equation 1 is valid for $F_m < 800$ kips

where, as shown in Figure 8,

F_m = Impact force

V_{0x} = Initial longitudinal velocity of barge in x-direction, ft/sec

V_{0y} = Initial longitudinal velocity of barge in y-direction, ft/sec

M = Mass of barge train, kip-sec^2/ft

= $2W/g$

W = Weight of barge train in short tons, including towboat (but excluding hydrodynamic added mass)

2 = Conversion factor from short tons to kips

g = 32.2 ft/sec^2

For head-on collision, the report recommends that an impact load of 2000-kips be used for design until more research becomes available.

Probabilistic Model

A probabilistic model can be constructed by using Equation 1 and accounting for the variability in its parameters. The method requires that annual distributions be determined for mass, impact angle and approach velocities. These probabilistic variables can be related to variations in the impact load through a Monte Carlo simulation. The method defines three design events for barge impact as follows.

Usual: These are frequent loading conditions that are expected to occur with a return period of 1-10 years. No damage is expected to occur to the barge or the wall.

Unusual: These are infrequent loading conditions that are expected to occur with a return period of 10-300 years. Minor easily repairable damage could occur to the barge or wall.

Extreme: These are rare events that are expected to occur with a return period of more than 300 years. Moderate to extreme damage is expected to occur to the barge and wall, but the wall should not collapse.

Table 7 shows typical ranges for impact velocities, while Table 8 shows typical ranges for impact angles that can be used for preliminary analyses.

Information is provided in the report on statistical parameters for key variables that can be used in the final probabilistic design model.

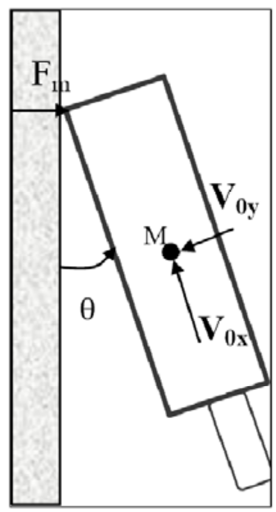


Figure 8
Data requirements for empirical model

Table 7
Typical ranges for impact velocities used in preliminary analyses

Load Condition	V_{0x} (ft/sec)	V_{0y} (ft/sec)
Usual	0.5 – 2	0.01- 0.1
Unusual	3 – 4	0.4 – 0.5
Extreme	4 – 6	0.5 – 1

Table 8
Typical ranges for impact angles used in preliminary analyses

Load Condition	Approach Angles, degrees
Usual	5 – 10
Unusual	10 – 20
Extreme	20 – 35

METHODOLOGIES FOR ABSORBING IMPACT ENERGY

Performance-Based Design Philosophy

A performance-based design philosophy is proposed herein. Three performance levels are considered: low energy, medium energy, and high energy collisions.

Low Energy Collision

In this case, both fender system and barge behave elastically and do not suffer significant permanent damage. The vessel’s energy is delivered to the fender system, stored as potential energy in the fender, and then given back to the vessel, forcing the energy to rebound. Some energy is lost due to friction, minor damage to the barge, etc. The elastic behavior of the fender system may be linear or nonlinear, e.g. in the case of fenders with rubber components. The forces induced during the impact event are important for investigating the ability of the fender to withstand the impact event.

A low energy collision is expected to occur frequently during the operating life of the fender. The fender and barge should not require any repairs after such an event. The velocity for a Class IV, standard hopper barge (displacement = 1900 tons) for this performance condition is assumed to be 1 knot.

Medium Energy Collision

In this case, the fender system behaves elastically and does not suffer permanent damage. However, the vessel may undergo some limited inelastic deformation. The vessel’s energy (in excess of that needed to cause permanent deformation to the vessel) is delivered to the fender system, stored as potential energy in the fender, and then given back to the vessel, forcing the energy to rebound. Some additional energy is lost due to friction, pile soil interaction, etc. The elastic behavior of the fender system may be linear or nonlinear, e.g. in the case of fenders with rubber components. The forces induced during the impact event should be computed and used for investigating the ability of the fender to withstand the impact event.

A medium energy collision is expected to occur infrequently during the operating life of the fender. The fender should not require any repairs after such an event, but the vessel may require some repairs. The velocity for a Class IV, standard hopper barge for this performance condition is assumed to be 3 knots.

High Energy Collision

Both vessel and fender system will suffer permanent damage during such an event. The fender system, which will be unable to absorb all the energy of the vessel, will fail, allowing the vessel to penetrate the protection system and impact the bridge. The deformation and energy absorbed prior to fender failure determines the energy remaining in the vessel that will be delivered to and create collision forces on the bridge.

A high energy collision is expected to occur very rarely during the operating life of the fender. One expects that both the fender and the barge will suffer extensive damage after such a collision. One can also expect that the barge will not sink and will have such diminished kinetic energy that it will deliver a significant force to the bridge pier after penetrating the protection system. The velocity for a Class IV, standard hopper barge for this performance condition is assumed to be 5 knots.

Demand and Capacity Calculations

The design process is based upon energy balance. The energy balance equation can be written as:

$$E_k = E_{fender} + E_{ship} + E_{soil}$$

where:

E_k is the barge's kinetic energy; E_{fender} is the energy stored in the fender components; for a pile system, $E_{fender} = E_{piles} + E_{wales}$, where E_{piles} is the energy stored in the fender piles and E_{wales} is the energy stored in the fender wales. E_{ship} is the energy stored in the colliding vessel, and E_{soil} is the energy dissipated through soil-pile interaction in pile mounted fender units, if applicable.

Calculation of E_{pile} for Elastic Cantilever Piles

For elastic cantilever piles, the energy stored in the piles is:

$$E_{pile} = \frac{1}{2} F.\Delta_p = \frac{1}{2}\frac{F^2 L^3}{3EI}$$

where:

F is the force in the pile

L is the effective pile length

Δ_p is the deflection of the elastic cantilever pile

EI is the effective flexural stiffness

The force, F, resulting from an energy balance computation should be used to ensure that the assumption of elastic pile behavior has not been violated.

All composite piles exhibit linear behavior up to failure, which renders $E_{pile} = \frac{1}{2}\frac{F^2 L^3}{3EI}$ valid all the way up to failure as shown in Figure 9, which shows the load deflection response for various types of piles. This equation can be modified to include inelastic behavior if necessary, e.g. in the case of steel piles. The energy dissipated by the piles prior to failure can be obtained from the load-deflection curves provided by the pile suppliers.

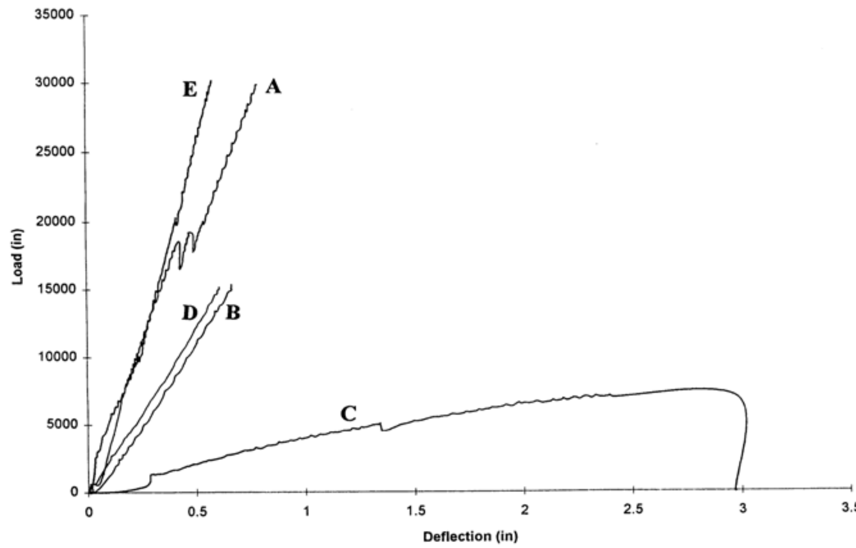


Figure 9
Test results of various types of composite piles (adapted from the *CPAR Report*)

As a loaded pile fails or starts to behave inelastically, it will engage adjacent piles through a 3-D nonlinear geometric action, forcing them to dissipate energy as well. However, the success of this engagement depends on the strength of the connection between the wales and piles. In general, one is on the conservative side if this effect is ignored.

Calculation of E_{wales} – Elastic Fender Wales

The energy absorbed by elastic fender wales is likely small and can be neglected in the energy balance computations.

Calculation of E_{fender} in the case of a Grid of Elastic Piles and Wales

If the wales elastically participate with the piles in resisting the applied impact loads, e.g. as a grid system, then the fender system could be considered as a grid. In this case

$$E_{fender} = E_{pile} + E_{wales} = \frac{1}{2} F_{grid} \Delta_{grid}$$

where F_{grid} is the force applied to the grid of piles and wales, and Δ_{grid} is the resulting deformation. The variables F_{grid} and Δ_{grid} can be obtained from a simple stiffness model that can be constructed using common commercial analysis programs. The model results should be checked to ensure that the assumption of elastic pile and wale behavior has not been violated.

Calculation of E_{fender} – Pile or Pier Mounted Energy Dissipating Fenders

Energy dissipating fenders can be directly mounted onto a bridge pier to reduce vessel impact forces. This is commonly done for berthing systems, where vessels slowly approach and bear against a wharf or pier. However, such an approach is not commonly used for bridge pier projection systems, which rely mostly on stand-alone, pile-mounted systems. The difference between cases is not the amount of energy being dissipated but rather the rate at which the energy is managed, which is a direct function of impact speed. Unlike low speed collisions, higher speed impacts are more damaging because they have the potential for introducing impulsive abrasive and ripping effects that can damage some of the more fragile types of berthing fenders, such as foam filled rubber fenders. The energy absorbed by an energy dissipating fender can be obtained through the force vs. deformation response of the fender as provided by the fender manufacturer. The computed force and deformation levels can be used to ensure that the fender is within its operating limits, and the applied forces can be used to check that the pier is not overloaded.

Calculation of E_{soil}

The energy absorbed by the soil-pile interaction is difficult to compute. One assumes that it is small and is neglected in the energy balance computations.

Calculation of E_{ship}

The energy stored in the vessel is obtained from the AASHTO provisions for vessel collision. Using kip – ft units, the AASHTO provisions are as follows:

$$a_B = \left(\sqrt{1+E_k/5672}-1\right)\left(10.2/R_B\right)$$

$$P_B = \begin{cases} 4112 a_B R_B & a_B < 0.34 \text{ ft} \\ (1349 + 110 a_B) R_B & a_B \geqslant 0.34 \text{ ft} \end{cases}$$

where:

a_B is the depth (ft) of barge crush deformation

$R_B = B_B/35$ (ft)

B_B is the barge width

P_B is the crush force

The crush model is illustrated graphically in Figure 10.

The AASHTO computations described above were developed for barge impact on a bridge pier. They are assumed valid for barge impact on a fender system for the purposes of this work.

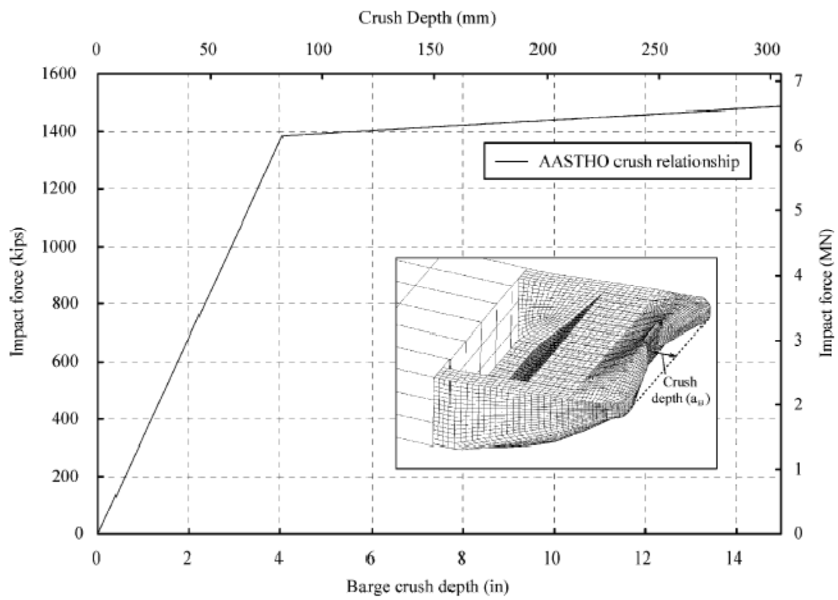


Figure 10
Barge crush model used in AASHTO bridge design specifications
(from: Consolazio and Cowan 2003)

<u>Consequence of Fender Failure</u>

If the fender system fails and the vessel penetrates then the energy remaining in the vessel is:

$$E_{remaining} \approx E_k - \left(E_{fender} + E_{ship} + E_{soil}\right)_{\max}$$

where the *max* subscript implies that the computations are conducted at peak fender capacity. The term $E_{remaining}$ can then be used to obtain a new, reduced vessel impact velocity from which the expected bridge pier impact force can be computed.

$$V_s = \sqrt{2\frac{E_{remaining}}{M_s}}$$

The bridge pier must be checked against this force to ensure that it is not overloaded.

Energy Demand Calculations

Assumptions:

Class IV, standard hopper barge

Speed = 1, 3, or 5 knots (corresponding to low, medium, and high energy collisions)

Displacement = 1900 tons

The kinetic energy of a Class IV barge is determined using the method outlined in "Criteria for: The Design of Bridge Piers with Respect to Vessel Collision in Louisiana Waterways." The kinetic energy of a moving ship can be calculated as

$$E_k = \frac{1}{2} * \left(M_s + m\right) * V_s^{\,2}$$

where

E_k = kinetic energy of the barge

M_s = mass of the ship

m = hydrodynamic mass

V_s = velocity of the ship

For this case, the mass of the ship is described by the weight of the ship's displacement divided by the acceleration due to gravity given by 32.2 ft/s^2. From Table 4 of the design criteria book, the loaded displacement of a Class IV, standard hopper barge is 1900 tons. The hydrodynamic mass accounts for the additional hydrodynamic forces of the water moving with the ship. The most commonly used values for the hydrodynamic mass are

m = (0.05 – 0.1) *M_s for head-on impact

m = 0.4* M_s for sideways impact

Two examples are provided below for determining the kinetic energy of a ship using the above assumptions for both head-on impact and sideways impact.

<u>Head-on Impact</u>

M_s = 1,900 tons = 3,800 kips

$$= \frac{3800 kips}{32.2 \frac{ft}{\sec^2}} = 118 kips * (\frac{s^2}{ft})$$

V_s = 1, 3, or 5 knots = 1.69, 5.06 or 8.44 ft/sec

$$E_k = \frac{1}{2} * \left(118 + 0.05 * 118\right) * V_s^2$$

E_{k1} = 177 k-ft = 2,123 k-in

E_{k2} = 1,583 k-ft = 18,992 k-in

E_{k3} = 4,403 k-ft = 52,841 k-in

<u>Sideways Impact</u>

M_s = 1,900 tons = 3,800 kips

$$= \frac{3800 kips}{32.2 \frac{ft}{\sec^2}} = 118 kips * (\frac{s^2}{ft})$$

A commonly accepted assumption is that the impact velocity is one half the head-on impact velocity, hence:

V_s = 0.5, 1.5, or 2.5 knots = 0.844, 2.53 or 4.22 ft/sec

$$E_k = \frac{1}{2} * (118 + .04 * 118) * V_s^2$$

E_{k1} = 59 k-ft = 704 k-in

E_{k2} = 528 k-ft = 6,329 k-in

E_{k3} = 1,467 k-ft = 17,611 k-in

Impact Energy Absorption Alternatives

The viability of various impact energy absorption alternatives is examined in this section. Head-on collision is assumed in the following calculations. For a Class IV, standard hopper barge

B_B = 35 ft

R_B = 35/35 =1 ft

For low energy collision:

E_{k1} = 177 k-ft = 2,123 k-in

a_B = 0.16 ft

P_B = 657 kips

For medium energy collision:

E_{k2} = 1,583 k-ft = 18,992 k-in

a_B = 1.34 ft

P_B = 1496 kips

For high energy collision:

E_{k3} = 4,403 k-ft = 52,841 k-in

a_B = 3.39 ft

P_B = 1722 kips

For any collision level, the impact force, F, is related to the dissipated energy through the following expression:

$$E_{ship} = 0.5\frac{F^2}{343}\text{ k-in} \qquad \text{for } F < 1400 \text{ kips}$$

$$E_{ship} = 0.5\frac{F^2}{343} + \frac{1}{2}\left[\left(\frac{F-1400}{8.77}+1400\right)+1400\right]\left(\frac{F-1400}{8.77}\right)\text{ k-in} \qquad \text{for } F > 1400 \text{ kips}$$

Ignoring E_{wales} and E_{soil}, the energy balance equation simplifies down to:

$$E_k = E_{pile} + E_{ship}$$

The objective of the following exercises is to apply this equation to compute the force and deformation levels on various types of fender systems.

For *sideways impact*, one assumes that impact force is related to dissipated energy through the same equations used for head-on impact. This approximation is made because of a lack of information about the sideways impact response of barges and should be modified once more information becomes available.

Pier Mounted Aluminum Foam Fender

Aluminum foams such as Duocel (http://www.ergaerospace.com/literature/energy.htm) are marketed as having much potential for energy absorption during impact events. Duocel is an open-cell foam material that exhibits controlled energy absorption properties that the manufacturer claims can be tailored to meet specific performance requirements in acoustic, blast, high velocity impact, and low strain rate impact energy absorption applications. Aluminum foams have the properties of the base metal from which they were made, such as corrosion resistance, electrical and thermal conductivity, and intrinsic strength. On the other hand, they have all of the advantages of a foam structure: a high strength to weight ratio, low density, high porosity, and an extremely large surface area. Aluminum foams can be cut, turned, milled, ground, lapped, drilled, rolled, and finished with special machine-shop equipment to normal tolerances. Through forming, aluminum foams can also easily conform to complex shapes. Any bonding technique that can be used for the parent metal can be used for aluminum foam, which also accepts colors, finishes, and coatings just as the parent metal does.

Figure 11 shows the stress strain relationship for Duocel foams with various relative densities. Assuming 10% relative density, the strain energy density can be modeled by the expression $0.5\varepsilon^2$ ksi up to a strain of 0.5, where ε is the strain. At 0.5 strain, the peak capacity of the foam is 0.5 ksi.

Assume that a typical foam fender strip is 3ft x 6ft with a thickness of 2 ft. These strips could be placed 10 ft center to center, such that a 35 ft wide barge would fully engage 3 of these fenders.

For a low energy collision:

E_{k1} = 177 k-ft = 2,123 k-in

Applying the energy balance equation, the force level is: 840 kip.

The ship remains elastic, but the fenders suffer a 2.6 in deformation.

For a medium energy collision:

E_{k2} = 1,583 k-ft = 18,992 k-in

Applying the energy balance equation, the force level is: 1478 kip.

The ship deforms inelastically, and the fenders suffer a 4.6 in deformation.

For a high energy collision:

E_{k3} = 4,403 k-ft = 52,841 k-in

Applying the energy balance equation, the force level is: 1675 kip.

The ship deforms inelastically, and the fenders suffer a 5.2 in deformation.

The cost of Duocel foam is in the range of \$3 - \$7 per cubic inch. This implies that the cost of fendering strips would be prohibitive.

Conclusion: Clearly, the use of aluminum foam for this particular application is not feasible because of cost. Another problem is that the foam would transfer impact forces to the bridge and, at the same time, suffer permanent damage during low, medium, and high energy collisions, and requires maintenance and periodic panel replacement.

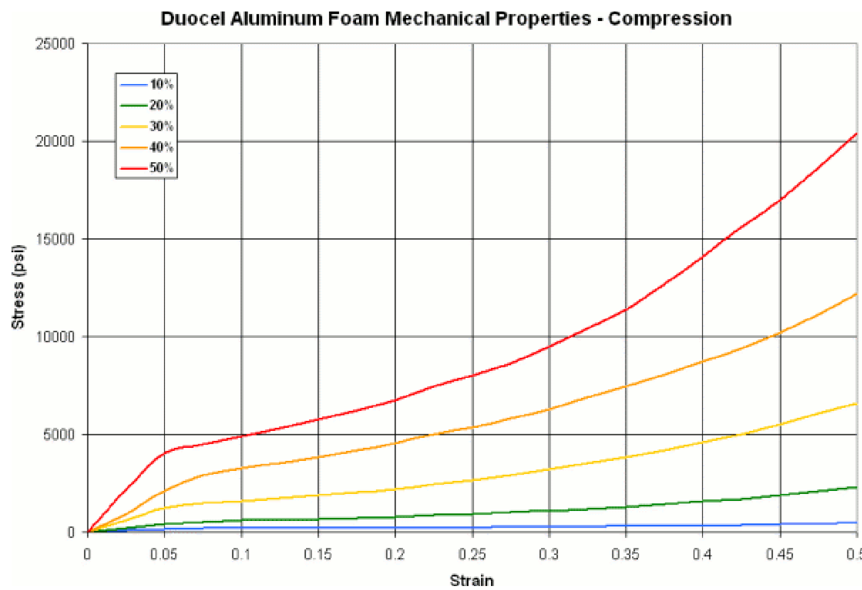


Figure 11
Stress-strain relationship for Duocel

Pier Mounted Hidro-Cushion Camel

Derucker and Heins discuss the use of the Hidro-Cushion Camel developed at Treasure Island Naval Station in San Francisco, California in 1967. The Hidro-Cushion Camel consists of eighty-four; three foot water filled cells, grouped into four clusters, sandwiched between two timber rubbing faces and held in place by cables. The water filled cylinders maintain constant pressure during compression upon impacting forces by forcing water out through small orifices in the tops of the cylinders. High energy absorption results from the compression of the cylinders and the resulting fluid dynamics action, bending of the timber faces, and crushing of the timber elements. Synthetic (e.g. kevlar) cables are more advantageous to use. Figure 12 shows a schematic of the system.

Conclusion: Since the possibility of snagging on the smooth face of the fender is small, this system may be a viable pier mounted fender system. However, a web search did not yield any manufacturers for such a system, and therefore, it does not appear to be commercially available at this time.

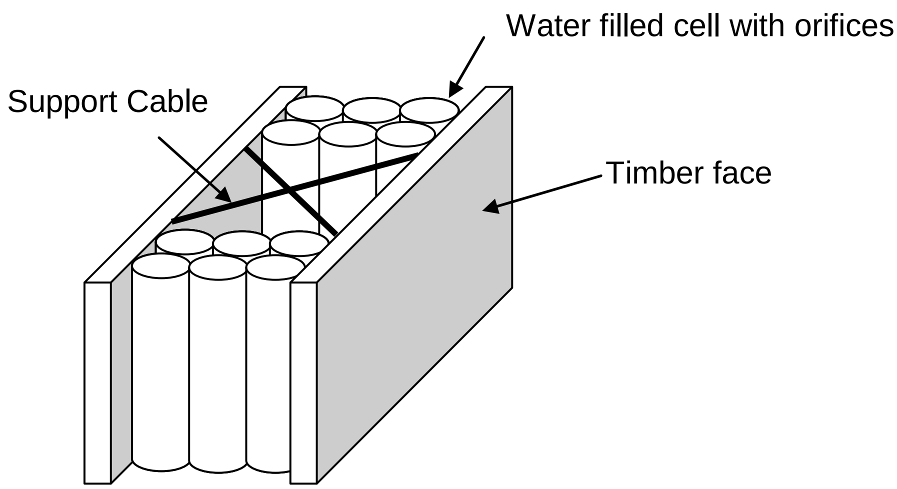


Figure 12
Hidro cushion camel

Independently Supported Seaward Seapiles – Cantilevered Piles (2-pile clusters)

Seaward Seapiles are manufactured from 100% recycled plastic reinforced with fiberglass reinforcing bars. Assuming that the piles are used in 15 ft deep water and that the piles can be assumed fixed 5 ft below the mudline, then the cantilever pile length is 20 ft. Choosing a 16-1.375 product with EI = 3.21e6 kip-in^2 and assuming that wales do not contribute to energy absorption, then for head on collision (for n piles):

$$E_{pile} = \frac{1}{2} n \frac{F^2 L^3}{3EI}$$

This equation is valid as long as the piles are able to support the applied force, i.e. they do not fail.

2-Pile Clusters: A 35 ft x 195 ft barge will engage 6 clusters of 2 piles each (clusters placed 6 ft apart), i.e. a total of 12 piles, during a head on collision. The same barge will engage 32 clusters during a sideways collision. One assumes that the barge engages all clusters simultaneously in both scenarios.

For a 16-1.375 Seapile product, the permissible stress is 7.899 ksi and I = 3217 in^4. The moment capacity is therefore 3176 k-in. Assuming a factor of safety of 1.5 for low to medium energy collisions, the force that can be applied to the tip of a cantilever is 3176/20/12/1.5 = 8.82 k.

For high energy collision, the factor of safety is removed (since failure is permissible at this stage), and so the force per pile is 13.23 kips.

Head on low energy collision:

E_{k1} = 177 k-ft = 2,123 k-in

Applying the energy balance equation, the force level is: 15.6 kips/pile.

This situation cannot be sustained. The fender will fail, and the ship will penetrate the protection system. At failure, the energy absorbed by the fender system is (no factor of safety is applied in this case):

$$E_{pile} = \frac{1}{2} n \frac{F^2 L^3}{3EI} = 1511 \text{ k-in}$$

Assuming that the energy absorbed by the ship is small, the remaining energy in the ship is:

$$E_{remaining} \approx E_k - \left(E_{pile} + E_{ship} + E_{soil}\right)_{\max} = 612 \text{ kip-in}$$

The new, reduced vessel impact velocity, that is used to obtain the bridge pier impact force, is:

$$V_s = \sqrt{2 \frac{E_{remaining}}{M_s}} = 0.93 \text{ ft/sec, i.e. with a 45\% reduction in speed.}$$

Sideways low energy collision:

E_{k1} = 59 k-ft = 704 k-in

Applying the energy balance equation, the force level is: 3.75 kips/pile.

Both ship and fenders remain elastic.

Head-on medium energy collision:

E_{k2} = 1,583 k-ft = 18,992 k-in

This situation cannot be sustained. The fender will fail, and the ship will penetrate the protection system. At failure, the energy absorbed by the fender system is (no factor of safety is applied in this case):

$$E_{pile} = \frac{1}{2} n \frac{F^2 L^3}{3EI} = 1511 \text{ k-in}$$

Assuming that the energy absorbed by the ship is small, the remaining energy in the ship is:
$E_{remaining} \approx E_k - \left(E_{pile} + E_{ship} + E_{soil}\right)_{\max}$ = 17481 kip-in.

The new, reduced vessel impact velocity from which the expected bridge pier impact force is:

$V_s = \sqrt{2\frac{E_{remaining}}{M_s}}$ = 4.96 ft/sec, i.e. almost no reduction in speed.

Sideways medium energy collision:

E_{k2} = 528 k-ft = 6,329 k-in

The applied load is 11.09 kips/pile.

The fender will not fail; however, the factor of safety of 1.5 will be violated.

Head-on high energy collision:

E_{k3} = 4,403 k-ft = 52,841 k-in

This situation cannot be sustained. The fender will fail, and the ship will penetrate the protection system.

Sideways high energy collision:

E_{k3} = 1,467 k-ft = 17,611 k-in

The applied load is 18.4 kips/pile.

This situation cannot be sustained. The fender will fail, and the ship will penetrate the protection system.

Conclusion: 2-pile clusters of cantilevered piles will not provide protection for any head-on collision level. For a sideways collision, energy balance computations show that the pile system will successfully withstand a low energy collision and likely a medium energy collision (factor of safety will be violated) but not a high energy collision. These computations assume that the barge will engage all pile clusters simultaneously. During oblique collisions, the barge may engage only a few piles, progressively failing them until the fender system is breached. This situation should be checked using a simulation model.

Independently Supported Seaward Seapiles – Cantilevered Piles (3-pile clusters)

A 35 ft wide barge could engage 6 clusters of 3 piles each (clusters placed 6 ft apart), i.e. a total of 18 piles.

Head-on low energy collision:

E_{k1} = 177 k-ft = 2,123 k-in

This situation may be sustained. The demand is 12.8 kips/pile, which is just below the capacity of a pile. The factor of safety is only 1.04.

Head-on medium energy collision:

E_{k2} = 1,583 k-ft = 18,992 k-in

This situation cannot be sustained. The fender will fail, and the ship will penetrate the protection system with essentially no reduction in speed.

Head-on high energy collision*:*

E_{k3} = 4,403 k-ft = 52,841 k-in

This situation cannot be sustained. The fender will fail, and the ship will penetrate the protection system with essentially no reduction in speed.

Conclusion: 3-pile clusters of cantilevered piles may provide some protection for a low energy head on collision; however, the factor of safety is too low to assure reliable protection. This configuration cannot provide protection for medium and high energy head on collisions.

Independently Supported Seaward Seapiles – Battered Pile System

The piles can be arranged in a truss-like configuration, as shown in Figure 13. A batter angle of 1:2 is commonly used.

The axial capacity based on material strength (7.899 ksi) is 1588 kips.

Assuming that the batter pile is effectively fixed at the embedded end and pinned at the other end, its effective buckling length is 0.7 x 22.4-ft = 15.7-ft.

The buckling capacity of the batter pile is therefore:
= 892 kips < 1588 kips. The buckling capacity of the batter pile controls.

If the applied force at collision is F, then the compressive force in the battered pile is 2.24F and the tensile force on the vertical pile is 2F.

Again assuming that the trusses are placed 6-ft apart, a total of 6 trusses will be able to resist a head-on collision.

Furthermore, it will be assumed that all energy will be lost in the colliding barge and not the truss system, which is very stiff.

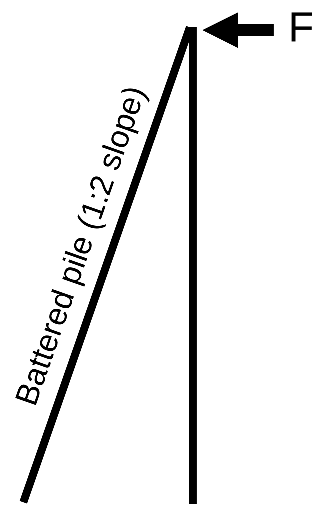


Figure 13
Battered pile configuration

Head-on medium energy collision:

E_{k2} = 1,583 k-ft = 18,992 k-in

Using energy balance calculations, the collision force will be 1498 kips.

The compressive force in the battered piles is 559-kips per pile, which is below the pile capacity of 892/1.5 = 595 kips (where 1.5 is a factor of safety).

The tensile force is 499 kips per pile. The embedment must be computed to support this demand.

Head-on high energy collision:

E_{k3} = 4,403 k-ft = 52,841 k-in

Using energy balance calculations, the collision force will be 1705 kips.

The compressive force in the battered piles is 636 kips per pile, which is less than the 892 kips capacity of the piles. However, the factor of safety is 1.4, which is now less than 1.5.

The tensile force is 568 kips per pile. The embedment must be computed to support this demand.

Conclusion: It is possible to achieve protection for medium and high energy head on collisions using piles in a battered configuration. The success of the configuration depends on the ability of the vertical pile to develop the necessary tensile force.

Independently Supported Seaward Seapiles – Minidolphin Configuration

A new system, termed minidolphin, has been proposed. In this system, a small cap is attached to the top of independently installed piles to force them into a frame-like action that more efficiently utilizes their capacity. A cantilever pile loaded at its tip is most heavily stressed at its base and essentially understressed, and therefore underutilized, elsewhere. In the new system, the cap of the minidolphin forces a pile to deform in double bending, as shown in Figure 14, mobilizing more of the pile, making it more efficient. In addition to the structural advantages, minidolphins do not need battered piles. The main disadvantage of the system is that the piles are subjected to additional compressive and tensile forces, the effect of which must be evaluated.

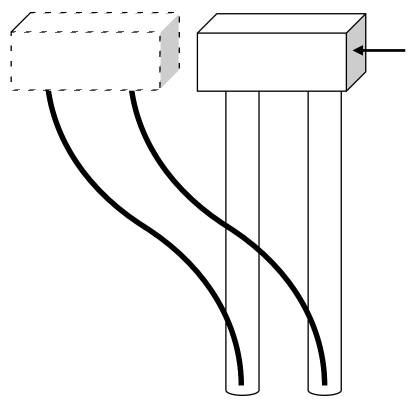


Figure 14
Minidolphins

To evaluate this system, assume that a pile cap mobilizes two piles each, i.e. each minidolphin is comprised of a cap that covers two piles. Assuming that the piles are used in 15 ft deep water and that the piles can be assumed fixed 5 ft below the mudline, then the pile length is 20 ft. Choosing a 16-1.375 product with EI = 3.21e6 kip-in^2 and assuming that wales do not contribute to energy absorption, then for head on collision (for n piles):

$$E_{pile} = \frac{1}{2} n \frac{F^2 L^3}{12EI}$$

A 35 ft x 195 ft barge will engage 6 minidolphins (placed 6 ft apart), i.e. a total of 12 piles, during a head-on collision.

For a 16-1.375 Seapile product, the permissible stress is 7.899 ksi and I = 3217 in^4. The moment capacity is therefore 3176 k-in. Assuming a factor of safety of 1.5 for low to medium energy collisions, the force that can be applied to the tip of a pile in a minidolphin is 2x3176/20/12/1.5 = 17.64 k.

For high energy collision, the factor of safety is removed (since failure is permissible at this stage), and so the force per pile is 26.46 kips.

Head-on low energy collision:
E_{k1} = 177 k-ft = 2,123 k-in

Applying the energy balance equation, the force level is: 35.8 kips/pile.

This situation cannot be sustained. The fender will fail, and the ship will penetrate the protection system.

Head-on medium energy collision:
E_{k2} = 1,583 k-ft = 18,992 k-in

This situation cannot be sustained. The fender will fail, and the ship will penetrate the protection system. At failure, the energy absorbed by the fender system is (no factor of safety is applied in this case):

$$E_{pile} = \frac{1}{2} n \frac{F^2 L^3}{12EI} = 1507 \text{ k-in}$$

When the piles reach their capacity, the ship will have absorbed 146 kip-in; the remaining energy in the ship is therefore:

$$E_{remaining} \approx E_k - \left(E_{pile} + E_{ship} + E_{soil}\right)_{\max} = 17339 \text{ kip-in}$$

The new, reduced vessel impact velocity from which the expected bridge pier impact force is:

$$V_s = \sqrt{2\frac{E_{remaining}}{M_s}} = 4.94 \text{ ft/sec, i.e. almost no reduction in speed.}$$

Head-on high energy collision:
E_{k3} = 4,403 k-ft = 52,841 k-in

This situation cannot be sustained. The fender will fail, and the ship will penetrate the protection system with essentially no reduction in speed.

Conclusion: A minidolphin system essentially doubles the force capacity of a regular cantilever pile and forces the piles to behave in a more efficient manner. However, the piles are subjected to additional compressive and tensile forces whose effect must be evaluated. Moreover, the system does not provide protection for all head-on collision levels. However, it could prove effective for shallower depths.

Independently Supported Seaward Seapiles – End Dolphins

Dolphins supported on piles are a viable alternative for protecting against a head-on collision. If the pile cap were sufficiently strong, the piles could be engaged in double bending. Assume a 20-ft pile length, as in previous examples. The proposed dolphin configuration is as shown in Figure 15.

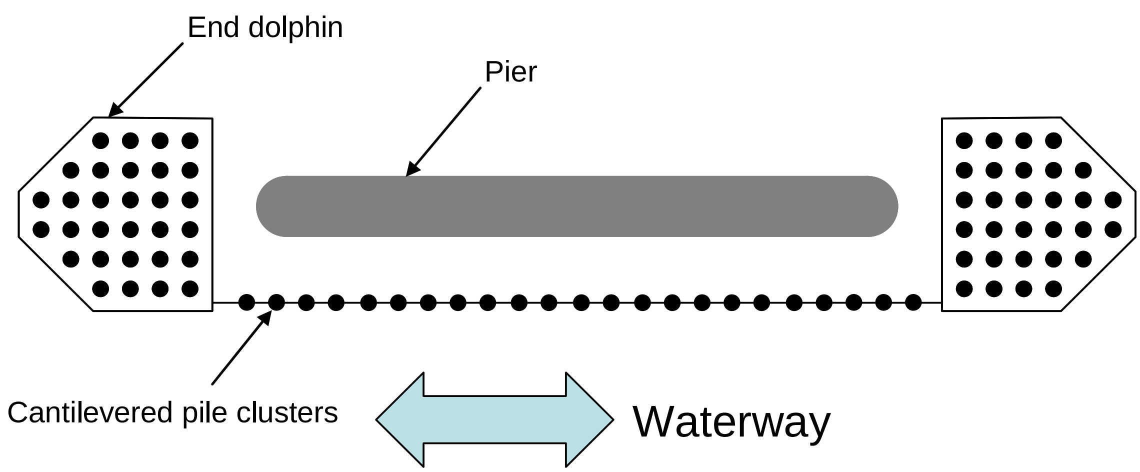


Figure 15
End dolphin configuration

Head-on low energy collision:
For low energy collisions, a 16-1.375 Seapile product will resist 17.64 kips, assuming a factor of safety of 1.5.

E_{k1} = 177 k-ft = 2,123 k-in

Energy balance computations show that 31 piles will be required.

Head-on medium energy collision:
For medium energy collisions, a 16-1.375 Seapile product will resist 17.64 kips, assuming a factor of safety of 1.5.

E_{k2} = 1,583 k-ft = 18,992 k-in

Energy balance computations show that 84 piles will be required.

Head-on high energy collision:
For high energy collision, the factor of safety is removed (since failure is permissible at this stage), and so the force per pile is 26.46 kips.

E_{k3} = 4,403 k-ft = 52,841 k-in

Energy balance computations show that 63 piles will be required. This is less than the 84 required for a medium energy collision because of the factor of safety (1.5) used for the medium energy case.

Conclusion: A dolphin system will require a large number of piles in order to be able to completely protect a bridge against a head-on collision.

Simple Spring Fenders as Crash Cushions

It is possible to place simple elastic springs as pier mounted fenders. The system would operate as an existing elastic vehicle crash cushion that would absorb the impact energy in an elastic manner. An example of such a system is the QUADGUARD® ELITE CRASH CUSHION SYSTEM by Energy Absorption Systems, Inc[1]. The system could be arranged as shown in Figure 16.

Figure 16
Schematic configuration showing elastic crash cushions attached to pier

A parametric study is conducted to investigate the effect of using simple spring buffers as fenders. The energy stored in the spring is $E_{spring} = \frac{1}{2}\frac{F^2}{K}$, where F is the applied force and K is the stiffness of the spring. The relationship between the total energy expended and stored during a *head-on* collision and the applied force versus spring stiffness is shown in Figure 17.

[1] http://www.energyabsorption.com/products/permanent/quad_guard_elite_crash_cushions.htm

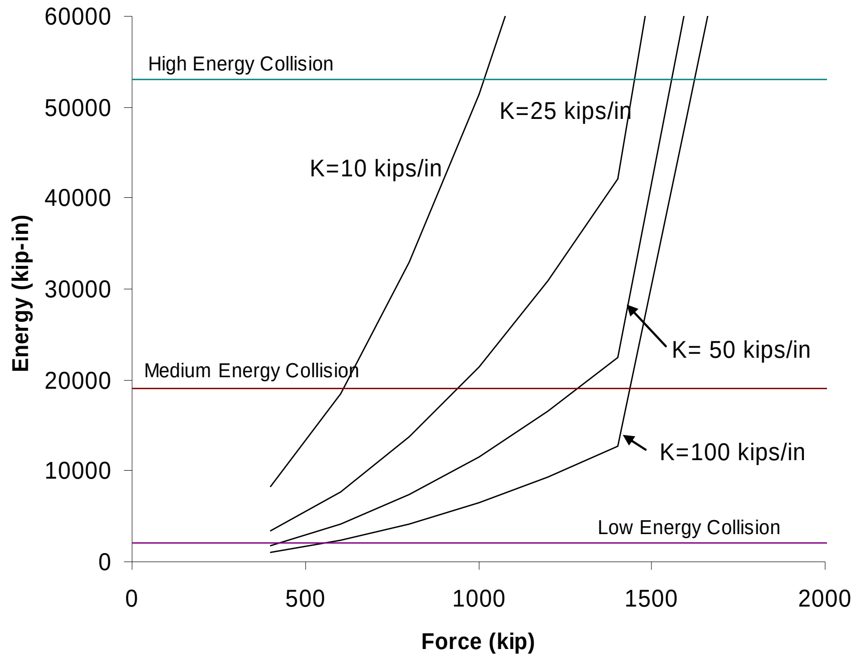


Figure 17

Relationship between various parameters in a collision

Figure 17 shows that the head-on impact force decreases as the spring constant decreases. For a high energy collision, the impact force is 1020 kips when K=10 kips/in, which implies that the spring must be able to deform 102 inches. In spite of such a large deformation, the impact force is still substantial.

Based on the observations made, the use of elastic spring fenders is not practical for high energy head-on impact. Soft springs (with low stiffness) must be used to reduce the impact force. However, using such soft springs necessitates a large deformation that is difficult to accommodate in practice. For the least stiff spring considered for a high energy collision, the impact force is still high (1020 kips), in addition to the need to accommodate the large deformation.

The advantage of elastic springs is best for medium and low energy collisions. For example, for a medium energy head-on collision, the impact force is reduced from 1400 kips to 600 kips by reducing K from 100 to 10 kips/in. In this situation, the spring must accommodate a displacement of 60 inches, which is still substantial.

Conclusions: Elastic spring fenders appear to be somewhat impractical for high energy head-on collisions. They do not adequately shield the supporting system (bridge or dolphin) from high forces, and at the same time; they must accommodate large deformations. They appear to be somewhat more feasible for medium energy head-on collisions, where the impact forces could be reduced to relatively low values, but they still need to accommodate relatively large deformations.

Plastic Energy Absorbing Fenders as Crash Cushions

As with elastic fenders, inelastic energy absorbing fenders could be used as pier mounted crash cushions. Again, such a system would be similar to existing vehicle crash cushions that absorb the impact energy through inelastic deformation. Many examples of such systems are commercially available. The inelastic cushions could be arranged as shown in Figure 18, in modular panels that would be easily replaceable after a collision.

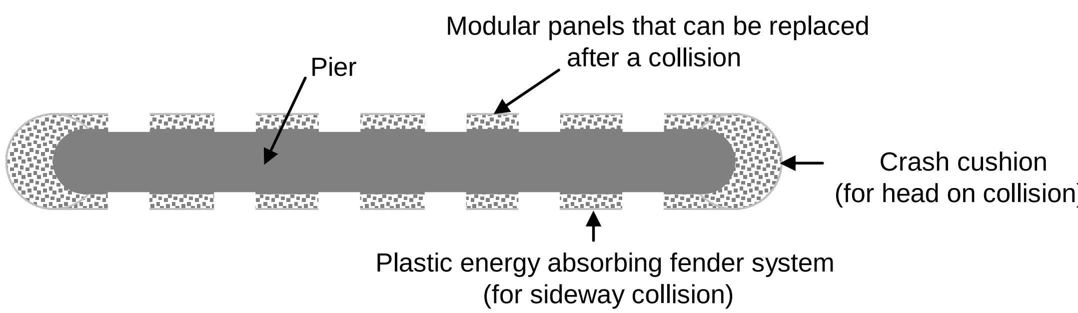


Figure 18
Schematic configuration showing plastic energy absorbing crash cushions attached to pier

The advantage of using inelastic energy absorbing fenders over purely elastic fenders is that the level of force can be more easily controlled. The disadvantage, of course, is that the panels will be damaged during collision and must therefore be replaced after an accident. However, inelastic crash cushions could be designed to be undamaged for low energy collisions and fully damaged and in need of immediate replacement after a high energy collision. For medium energy collisions, the panels could be repaired or replaced, although not immediately. Such a design philosophy will ensure the economy of the energy absorbing panels.

Ignoring the elastic component, the total energy stored in a plastic spring is approximated as $E_{spring} = \frac{1}{2} F \Delta$, where F is the applied force, and Δ is the spring deformation. The relationship between the total energy stored in the fender and ship during a *head-on* collision and the force versus fender deformation is shown in Figure 19. The figure suggests that the head-on impact force decreases as the plastic deformation increases. For a high energy collision, the impact force is 550 kips when Δ=200 in. Figure 20 shows a concept based on a vehicle crash cushion system, as shown in Figure 21.

Conclusion: Plastic-energy absorbing fenders appear to be more practical than elastic fenders. The force on the pier can be controlled more readily than with elastic fenders. However, the system still requires a large deformation to dissipate the required energy with a reasonably low impact force.

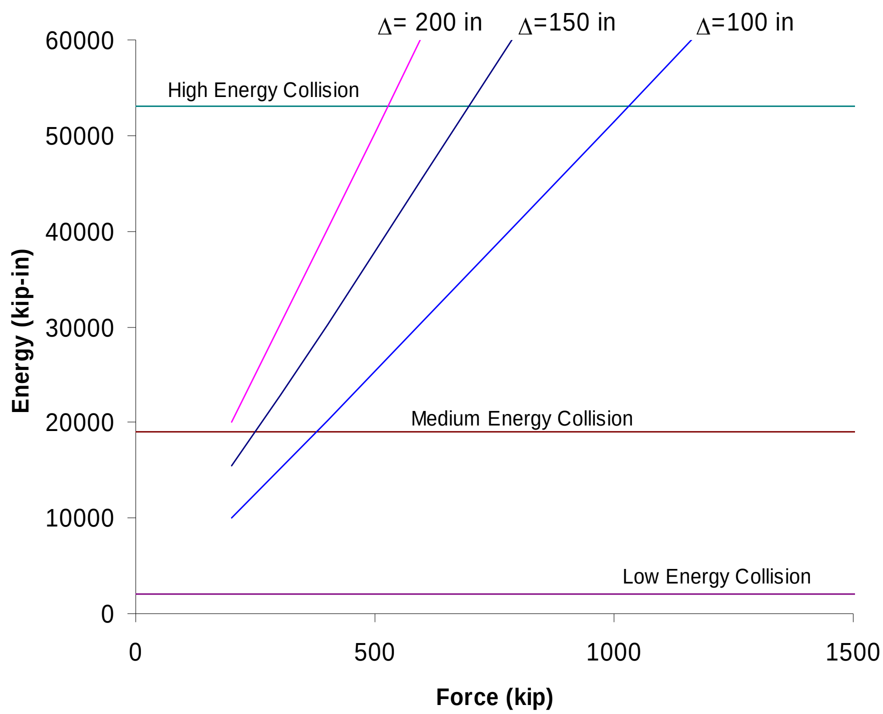


Figure 19
Relationship between various parameters in a collision

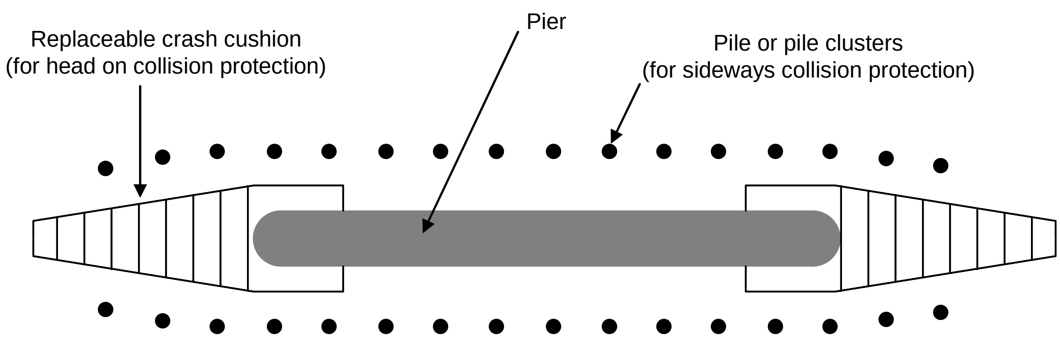


Figure 20
Crash cushion for head on collision protection and cantilever piles for sideway protection
This system is analogous to the vehicle crash cushion system in Figure 21.

(a) A typical crash cushion system found on a highway

(b) The boxes inside the system are filled with sand or water

Figure 21
Typical vehicle crash cushion

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Project Objectives and Summary

The objective of this project was to identify existing protective systems and propose new systems that could be used to mitigate the effects of bridge/vessel collisions. A comprehensive literature review was conducted as a first step of the research program. The survey identified existing systems in other states and countries and categorized them into six main types. A historical survey of various vessel/bridge collisions was also compiled. Based on the results of the survey conducted, a number of alternative fender systems was identified. A new performance-based design philosophy was proposed to evaluate their protective ability.

Assuming a Class IV, standard hopper barge as the specified design vessel, three performance levels were considered in the developed design methodology: low energy, medium energy, and high energy collisions. In the first performance level, both fender system and barge are expected to behave elastically during impact. A low energy collision is expected to occur frequently during the operating life of the fender. The fender and barge should not require any repairs after such an event. The velocity for the design barge for this performance condition is specified to be 1 knot. In the second performance level, the fender system is expected to behave elastically and does not suffer permanent damage. However, the vessel may undergo some limited inelastic deformation. A medium energy collision is expected to occur infrequently during the operating life of the fender. The fender should not require any repairs after such an event, but the vessel may require some repairs. The velocity for the design barge for this performance condition is specified to be 3 knots. In the third and most severe performance level, both fender and barge will suffer extensive damage after such a collision. It is also expected that the barge will not sink and will have such diminished kinetic energy that it will not deliver a significant impact force to the bridge pier after penetrating the protection system. A high energy collision is expected to occur rarely during the operating life of the fender. The velocity for the design barge for this performance condition is specified to be 5 knots.

Using the developed performance-based framework, fiber reinforced polymer (FRP) piles arranged in clusters of two piles were shown to provide adequate sideways protection for the low and medium energy performance levels. However, they cannot provide protection for head- on collisions for any of the performance levels. For such an application, pier-mounted, energy-absorbing plastic fenders were shown to be suitable for absorbing crash energy and reducing impact forces to acceptable levels. As with vehicle crash cushions that are commercially available, the proposed fender systems can be tailored to achieve a wide range of applicability. Additional analytical and experimental research is needed to develop optimized designs that can be installed in the field.

Conclusions

The following conclusions can be drawn from the research results obtained in this project:

- Clusters of two or more FRP piles are capable of providing adequate sideways protection for the low and medium energy performance levels. However, they cannot provide protection for head-on collisions for any of the performance levels.

- Pier mounted elastic spring fenders are not practical for high energy head-on impact. Springs with low enough stiffness must be used to reduce the impact force to acceptable levels. However, using such soft springs necessitates large deformations that are difficult to accommodate in practice. Therefore, the advantage of elastic spring fenders is best for medium and low energy collisions.

- Inelastic energy absorbing fenders are well suited for use as pier mounted crash cushions. Such fenders would be similar to existing vehicle crash cushions that absorb vehicular impact energy through inelastic deformations. The advantage of using inelastic energy absorbing fenders over purely elastic fenders is that the level of force can be more easily controlled. The disadvantage, of course, is that the panels will be damaged during collision and must therefore be replaced after an accident. However, inelastic crash cushions could be designed to be undamaged for low energy collisions and fully damaged and in need of immediate replacement after a high energy collision. For medium energy collisions, the panels could be repaired or replaced, although not immediately. Such a multi-tiered design philosophy will ensure the economy of the energy absorbing panels. Additional research is needed to develop suitable inelastic fender systems.

Recommendations and Benefits of Implementation

Fiber-reinforced polymer (FRP) composites for sideways protection combined with metal crash cushions for head-on protection are a cost effective alternative to traditional timber piles. A successful implementation of this project will have far reaching safety benefits to the state of Louisiana and other states. In particular, the use of high performance FRP piles and metallic crash cushions will reduce the hazard associated with vessel collision with bridge piers and therefore improve the safety of bridges that cross navigable waterways.

FUTURE RESEARCH OPPORTUNITIES

The research conducted in this project has shown that pier mounted, inelastic crash cushions are well suited for protecting bridge piers against barge traffic in shallow waterways. Additional research is needed to provide proof-of-concept and to engineer a viable and marketable product. **One envisions that both experimental and computational research will be needed to develop and optimize a system that could be widely adopted in the state of Louisiana and across the country.**

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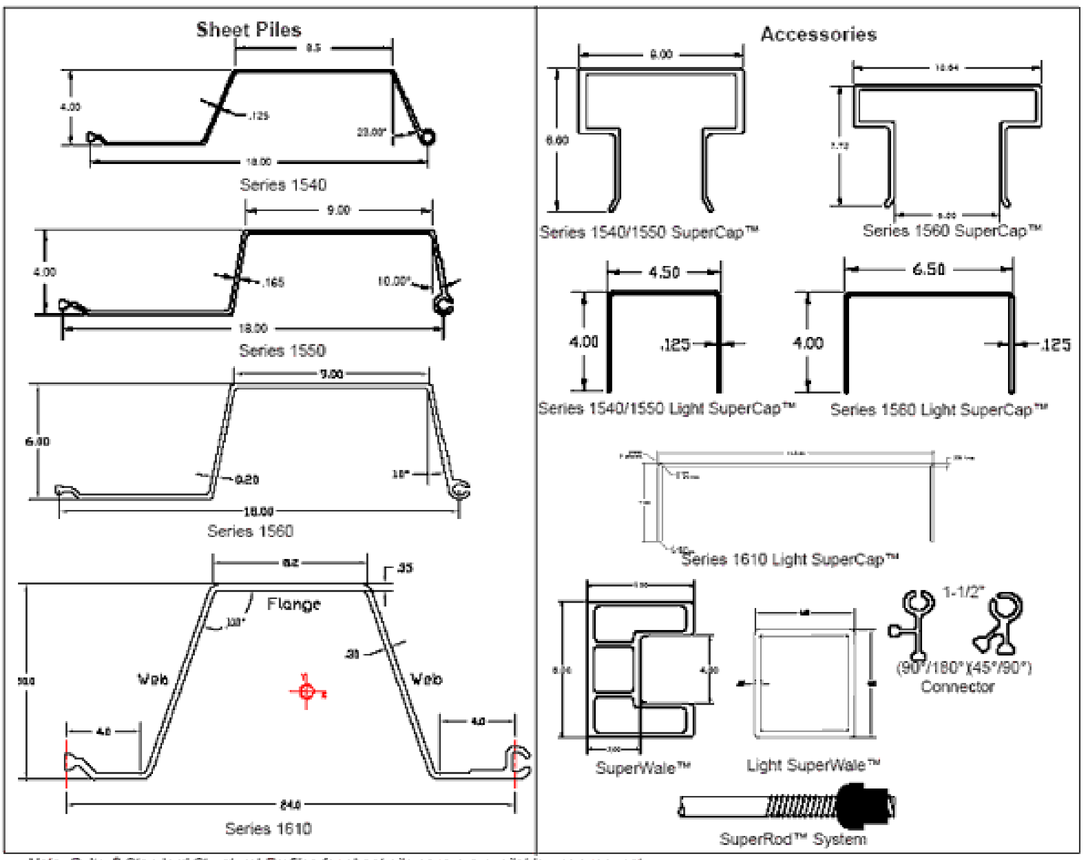
APPENDIX

PROPERTIES OF COMMERCIALLY AVAILABLE HEAVY DUTY SHEET PILES

AI.1: Superloc Composite Sheet Piles

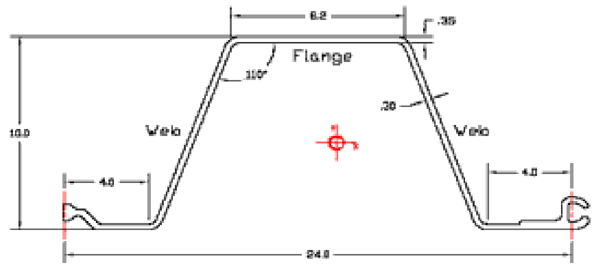
Superloc sheet piles are commercially available sheet piles that can be used as fenders *(http://www.leecomposites.com/sheetpile.html).* Figures A-1 through A-3 show the geometric characteristics of the system. They are constructed with fiberglass reinforced polymers with the properties in Table A-1.



Note: Pultex® Standard Structural Profiles for sheet pile caps are available upon request.

Figure 22 Superloc sheet pile geometry

Physical Properties	
Depth of Sheet (in)	10.00
Width of Sheet (in)	24.00
Typical Thickness (in)	0.30
Weight (psf)	5.45
Section Modulus (in^3/ft)	18.41
Moment of Inertia (in^4/ft)	101.25
Area of the web (in^2/ft. of wall)	3.00
Webs per foot of wall	1.00
Angle of the web (degrees)	20.00
Cross-Sectional Area of the sheet (in^2)	13.45



Note: Values are not factored, an appropriate safety factor must be applied

Figure 23 Physical properties of Superloc system

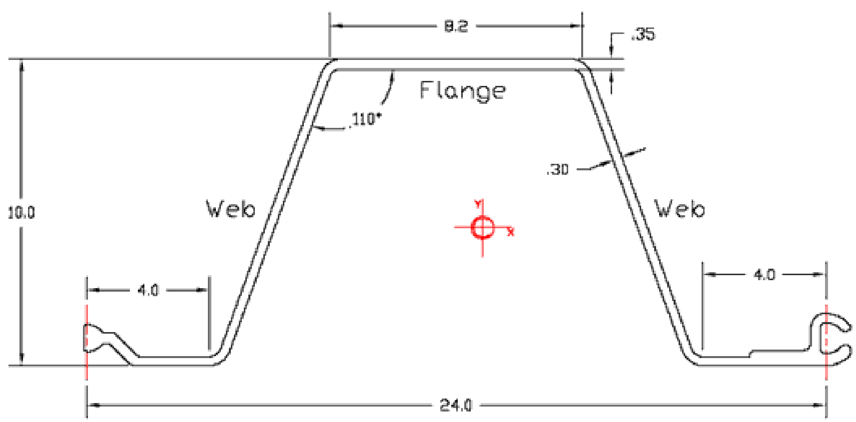


Figure 24 Geometric properties of 1610 Superloc system

Table 9
Mechanical properties of the Superloc system

Mechanical Properties	Test Method		Average Values
Full Section Modulus of Elasticity (psi)	***	*Calculated*	*3.8E+06*
Shear Modulus (psi)	***	*Calculated*	*500,000*
Shear Capacity (lbs./ft of wall)	***	*Calculated*	*15,000*
Web Buckling Capacity from Wale Force (lbs./ft of wall)[3]	***	*Calculated*	*12,400*
Moment Capacity (lbs.-ft../ft of wall)	***	*Calculated*	*45,900*
Average Stress at Failure	***	*Calculated*	*30,000*
Minimum Ultimate Values			
Specific Gravity	**ASTM**	D-792	1.7
IZOD Impact LW (ft. lb./in. notch)	**ASTM**	D-256	30
IZOD Impact CW (ft. lb./in. notch)	**ASTM**	D-256	7
Tensile Strength Flange LW (psi)	**ASTM**	D-638	40,000
Tensile Strength Flange CW (psi)	**ASTM**	D-638	10,000
Tensile Modulus Flange LW (psi)	**ASTM**	D638	3.8E+06
Tensile Modulus Flange CW (psi)	**ASTM**	D638	2.0E+06
Compression Modulus Flange LW (psi)	**ASTM**	D695	3.8E+06
Compression Modulus Flange CW (psi)	**ASTM**	D695	2.2E+06
Compression Modulus Web CW (psi)	**ASTM**	D695	2.2E+06
Compression Strength of Flange LW (psi)	**ASTM**	D695	35,000
Compression Strength of Flange CW (psi)	**ASTM**	D695	25,000
Compression Strength of web CW (psi)	**ASTM**	D695	25,000
Bearing Strength LW (psi)	**ASTM**	D953	30,000
In-Plane Shear of Web LW (psi)	**ASTM**	Mod.D2344[1]	5,000
CTE LW (10^{-6} in/in/F)	**ASTM**	D696	5.5
CTE CW (10^{-6} in/in/F)	**ASTM**	D696	10.5

CW = Crosswise **LW = Lengthwise**

1. Follow ASTM D2344, but rotate the coupon 90 degrees (cut section of coupon length faces up)
2. Values are published as ultimate. Appropriate Safety Factors must be applied.
3. Based on 6"-8" wide wale sections

Refer to the SuperLoc™ Design/Installation Manual for Comprehensive Information

See Back For Detailed Drawing & Recommended Safety Factors

AI.2: PZ – 27 Steel Sheet Pile

Properties of steel sheet piles are shown in Figure A-4 and Table A-2. They can also be found at (*http://www.hmc-us.com/hmcsp/spile.html*). The yield strength, Young's modulus, and Poisson's ratio can be assumed to be 50 ksi, 29,000 ksi, and 0.3, respectively.

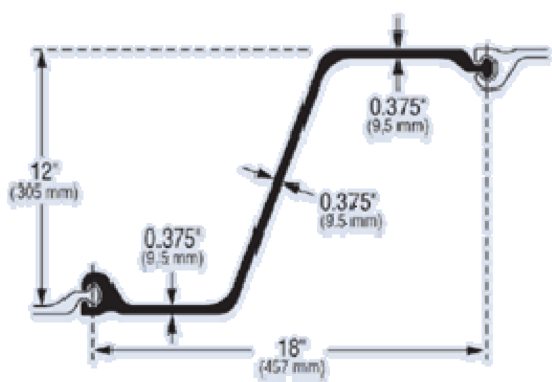


Figure 25
Geometric properties of PZ-27 steel sheet piles

Table 10
Properties of steel sheet piles

SHEET PILING TECHNICAL DATA

Section Designation	AREA		WIDTH		HEIGHT		WEIGHT (MASS) PER SINGLE		WEIGHT (MASS) PER WALL		MOMENT OF INERTIA		SECTION MODULUS Per Single		SECTION MODULUS Per Wall		SURFACE AREA Total Area		SURFACE AREA Nominal Area*	
	in^2	cm^2	in	mm	in	mm	lb/ft	kg/m^2	lb/ft^2	kg/m^2	in^4	cm^4	in^3	cm^3	in^3/ft	cm^3/m	ft^2/ft	m^2/m	ft^2/n	m^2/m
PZ22	11.9	76.6	22.0	559	9.0	228.6	40.3	60.1	22.0	107	151	6301	32.5	532	17.7	952	4.92	1.50	4.48	1.37
PZ27	12.1	78.2	18.0	457	12.0	304.8	40.5	61.3	27.5	134	282	11734	45.3	742	30.2	1622	4.93	1.50	4.48	1.37
PS27.5	13.4	86.6	19.7	500	—	—	45.1	67.9	27.8	136	5.02	209	3.19	52.2	1.94	104	4.58	1.40	3.88	1.18
PS31	15.2	98.2	19.7	500	—	—	50.9	77.0	31.5	154	5.51	229	3.35	55.0	2.04	110	4.58	1.40	3.87	1.18

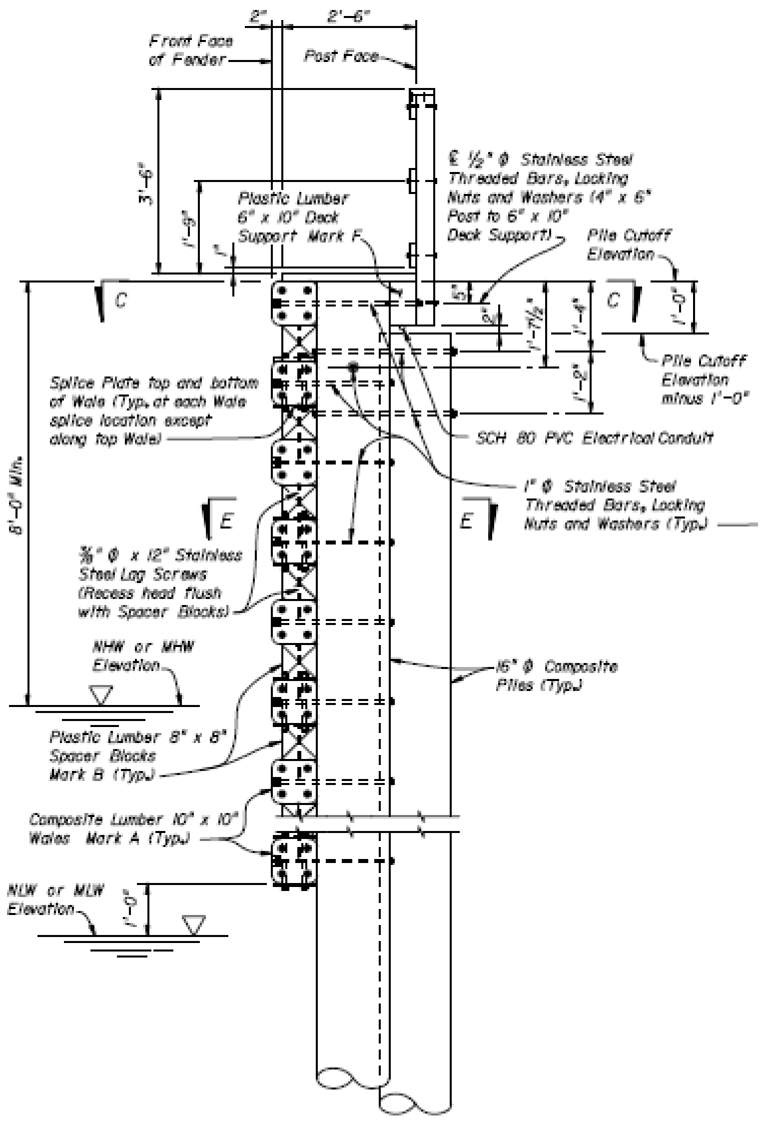
*Note: Nominal coating area excludes socket interior and ball of interlock.

FDOT FENDER DETAILS

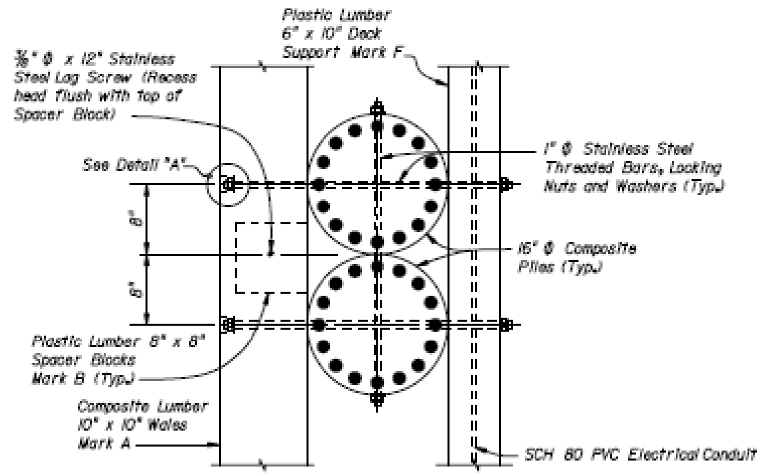
Heavy duty fender system: Comprised of plastic lumber (Appendix II, Figure AII.1), this fender system has an energy capacity of 295 kip-ft and can resist two loaded jumbo hopper barges and a push boat approaching at 15^o and moving at 4.0 knots. Alternatively, it can resist two empty jumbo hopper barges and a push boat approaching at 15^o and moving at 9.8 knots.

Medium duty fender system: Comprised of plastic lumber (Appendix II, Figure AII.2), this fender system has an energy capacity of 132 kip-ft and can resist one loaded jumbo hopper barge and a push boat approaching at 15^o and moving at 3.6 knots. Alternatively, it can resist one empty jumbo hopper barge and a push boat approaching at 15^o and moving at 7.8 knots.

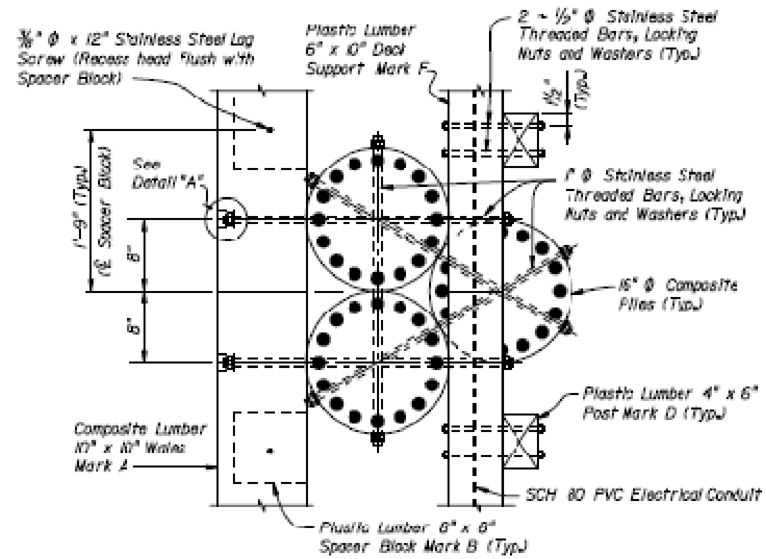
Light duty fender system: Comprised of concrete piles and a plastic wale system (Appendix II, Figure AII.3), this fender system has an energy capacity of 38 kip-ft and can resist one empty jumbo hopper barge and a push boat approaching at 15^o and moving at 3.6 knots. Alternatively, it can resist a push boat approaching at 15^o and moving at 5.6 knots.



(a) Elevation

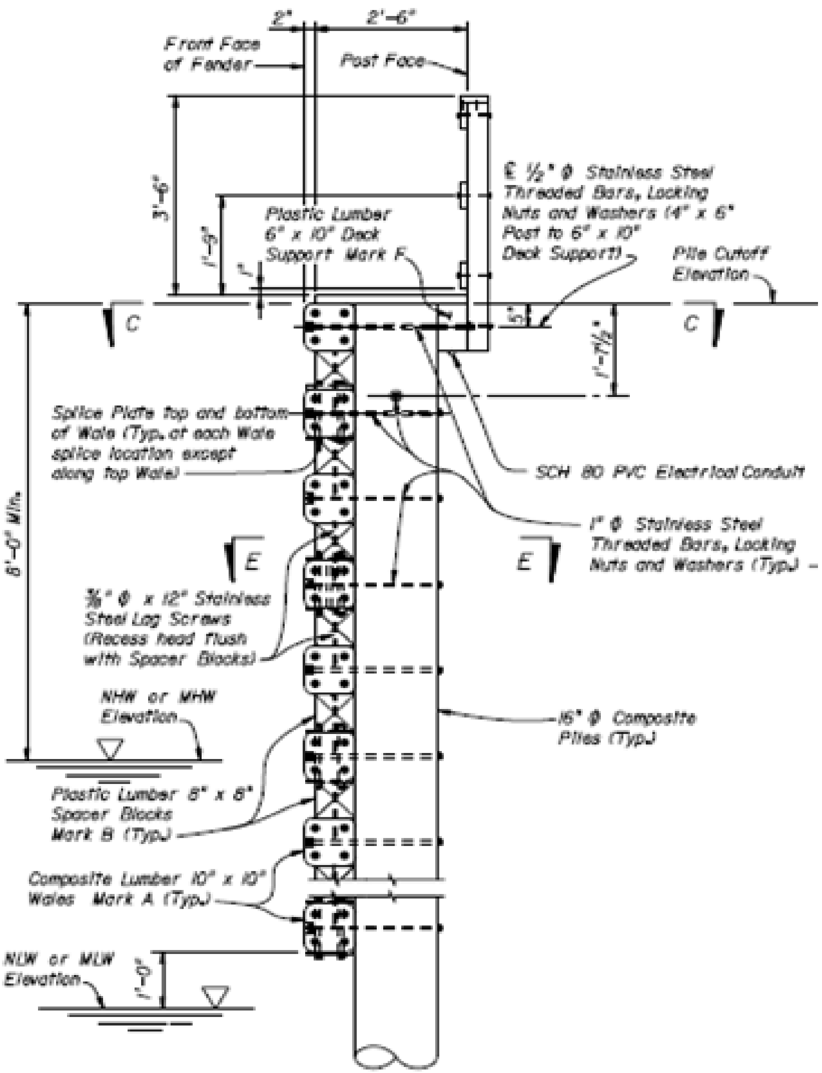


(b) Typical intermediate section

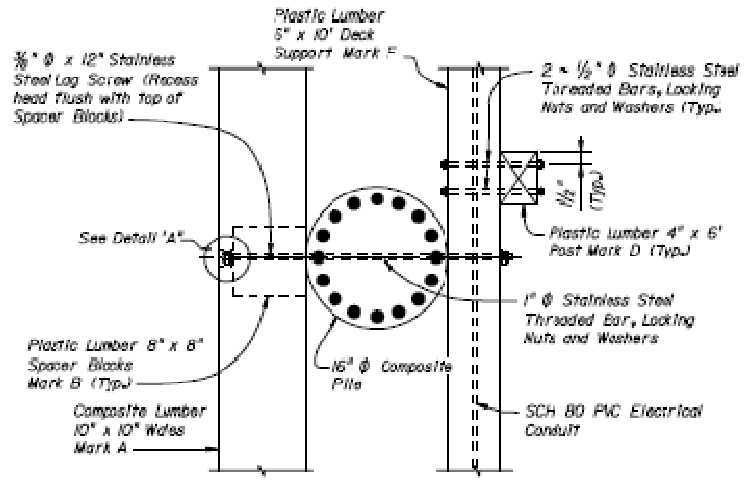


(c) Typical corner section

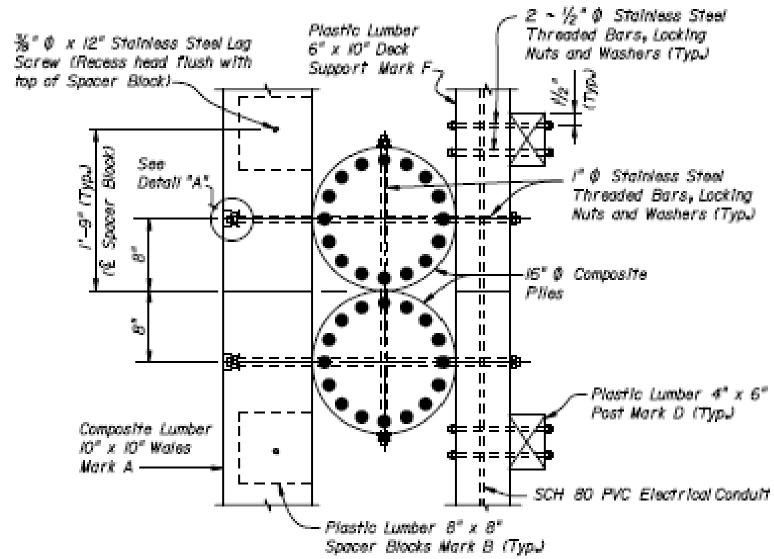
Figure 26 Typical intermediate piles for FDOT heavy duty plastic lumber pile system



(a) Elevation

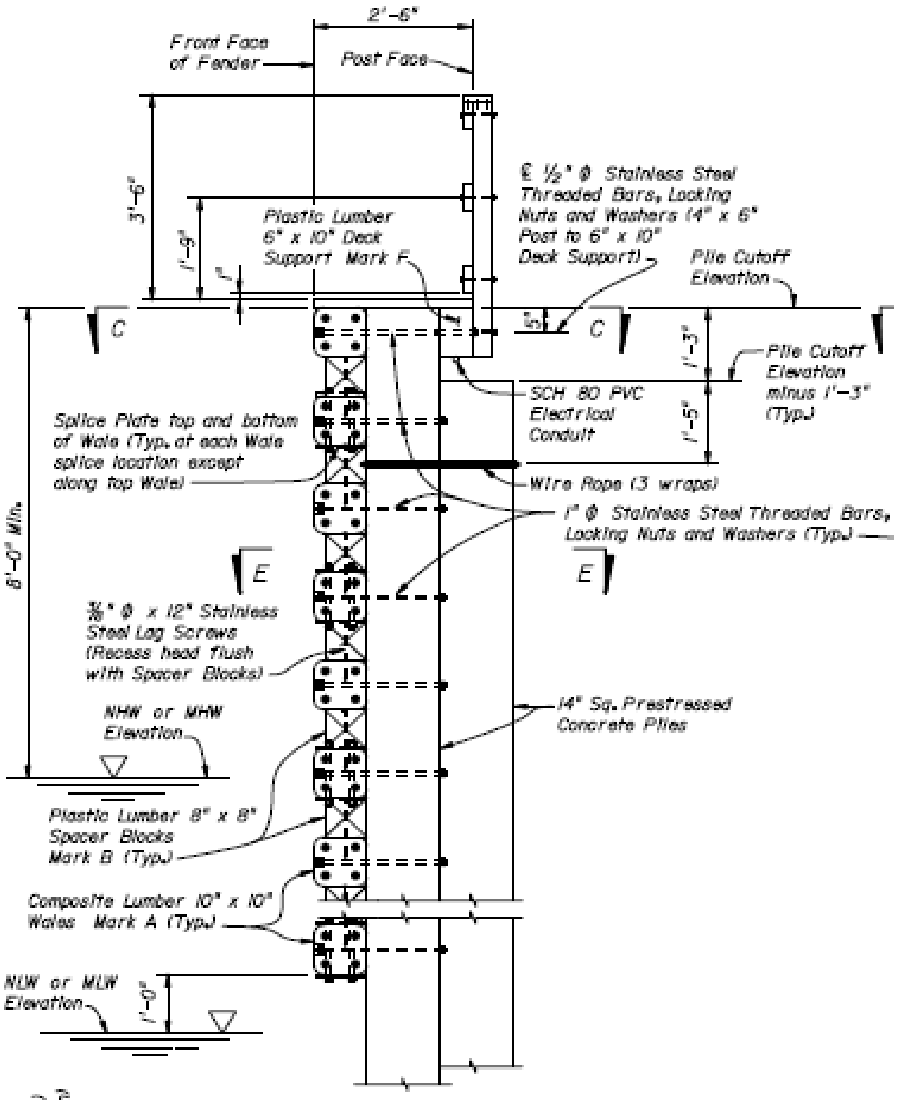


(b) Typical intermediate section

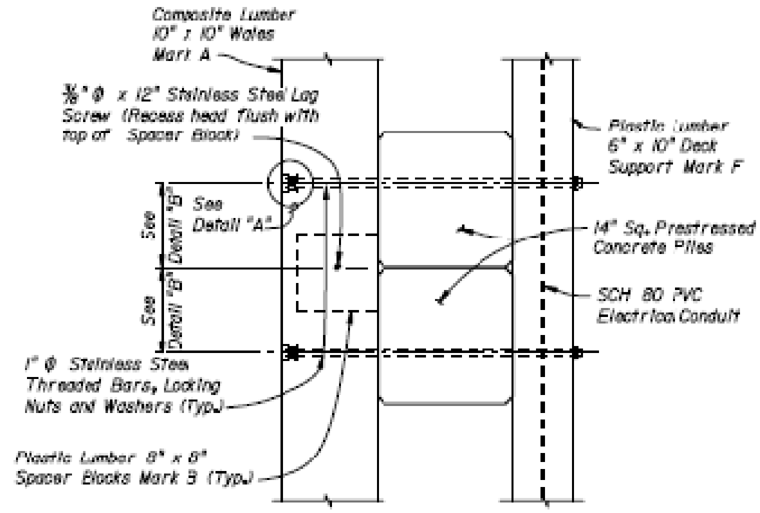


(c) Typical corner section

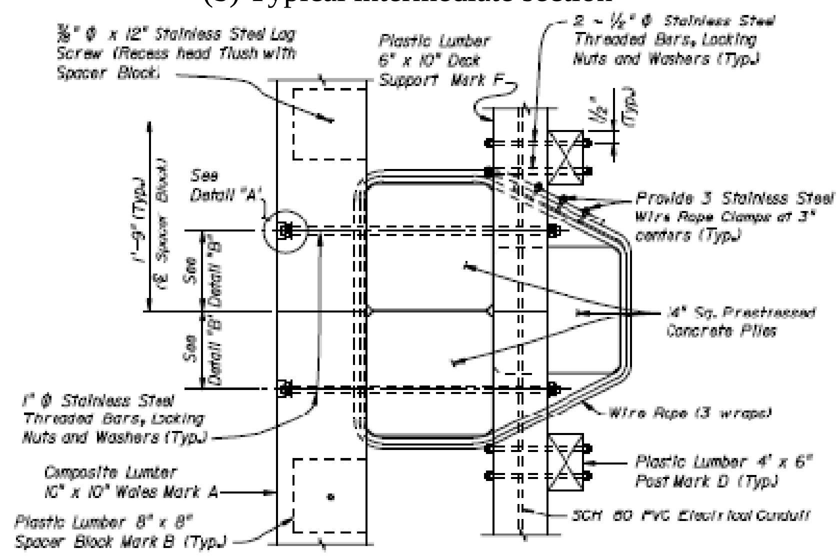
Figure 27 Typical intermediate piles for FDOT medium duty plastic lumber pile system



(a) Elevation



(b) Typical intermediate section



(c) Typical corner section

Figure 28 Typical intermediate piles for FDOT light duty fender system

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