

Fiberglass Composite Materials Specification Redevelopment

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Submitted by

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16. Abstract <p>Polymer based structural members have shown to be economically viable when used in marine environments. These polymer materials have higher initial cost than traditional materials (steel, concrete, and timber), but generate return on this investment with longer useful lives. These materials are currently being implemented in a variety of geotechnical structures in the state of New Jersey. This research was performed because the requirements of Section 916 of the New Jersey Department of Transportation Standard Specifications limited the State of New Jersey to a small subset of the commercially available products. Expanding the number of viable products allows for greater competition making it possible for the New Jersey Department of Transportation to spend funds more efficiently.</p> <p>A thorough literature review, an analysis of regional and national specifications for polymer composite materials, as well as an independent engineering design analysis were performed to determine the minimum required material properties for the polymer based structural members. Based on these results, a specification, product qualification standards, and product acceptance standards were created based on statistically determined material properties, maximum allowable degradation, and full-scale structural testing. When selecting material testing standards, it was found that no simple effective test could be performed on round fiber reinforced composite tubes. This lead to the development of two new standard tests. One tests a ring cut from the circular tube with two opposing forces. The other tests an arch segment in flexure.</p>			
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LIST OF ABBREVIATIONS

°F	degree Fahrenheit
AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
ASCE	American Society of Civil Engineers
ASTM	American Society of Testing Materials, ASTM International
CFRP	Carbon Fiber Reinforced Polymer
DOT	Department of Transportation
FCCP	Fiberglass Concrete Composite Piles
FCM	Fiberglass Composite Material
FDOT	Florida Department of Transportation
FRP	Fiber Reinforced Polymer
FRPL	Fiber Reinforced Plastic Lumber
FRPP	Fiber Reinforced Plastic Pile
ft.	foot
GFRP	Glass Fiber Reinforced Polymer
HDPE	High Density Polyethylene
IBC	International Building Code
in.	inch
kip	1000 pounds
ksi	kip per square inch
lb.	pound
LRFD	Load and Resistance Factor Design
min.	minute
NJDOT	New Jersey Department of Transportation
psi	pound per square inch
QPL	Qualified Product List
RTSS	Reinforced Thermoplastic Structural Shapes
TSS	Thermoplastic Structural Shapes
UV	Ultra Violet
VIP	Vacuum Infusion Processed

EXECUTIVE SUMMARY

The purpose of this research project was to develop Section 916, *Fiberglass Composite Materials*, of the New Jersey Department of Transportation (NJDOT) Standard Specifications into an economically competitive specification. Section 916 of the NJDOT standard specification currently covers fiberglass composite materials which are intended for use as pile supported bridge fender systems, bulkheads, and pile foundations for light structures. Currently, the requirements of Section 916 are based on two proprietary products. Other competing materials cannot qualify under these requirements.

In order to determine the required structural properties, the American Association of State Highway Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Bridge Design Specifications and the AASHTO Guide Specification and Commentary for Vessel Collision Design of Highway Bridges were consulted. The required structural properties were the flexural and axial stiffness and capacity. Subsequently, a full literature search including each states standard materials specification and several national standards, specifically: American Society of Testing Materials (ASTM) D7258-14 Standard Specification for Polymeric Piles (2014), the American Society of Civil Engineers (ASCE) Pre-Standard for Load & Resistance Factor Design (LRFD) of Pultruded Fiber Reinforced Polymer (FRP) Structures (2010), the AASHTO LRFD Guide Specifications for Design of Concrete-Filled FRP Tubes for Flexural and Axial Members (2012), was conducted. The results showed that currently the structural properties of the products being produced as pile cannot be determined from current material testing standards. The products being produced and marketed as piles are historically large and complex in nature; in order to determine their structural properties, full-scale specimens must be tested. Testing of these full-scale specimens is impractical for acceptance testing. There exist coupon level tests which can be performed on every product except tubes created from thermoset polymers with circular cross-sections.

In order to develop a complete qualification acceptance plan, a test for thermoset circular tubes needed to be developed. Two standard tests were developed; one on a ring section cut from the circular tube, and one on an arch section. Both tests were validated using materials whose tension properties could be determined from existing standard tests. These materials were aluminum, steel, and unidirectional carbon composite.

An independent engineering analysis using properties provided by representative manufacturers was performed. The different materials had different structural properties, but it was found that working designs could be developed for each material regardless. If the structural properties are known, a working design can be developed using the product.

Finally, a revised Section 916 has been proposed. The focus of the new material specification was to limit degradation and creep. The degradation requirements from AASHTO MP22 were adopted. These requirements seek to limit degradation due to moisture at elevated temperatures, freeze-and-thaw, Ultra Violet light, and alkaline environments. These parameters represent what would be seen in a marine environment. The requirements set to limit creep were taken from Section 1708.3.2 of the International Building Code. No nominal structural values were explicitly given. The focus was on limiting degradation and representing properties statistically using the characteristic value as defined in ASTM D7290 (2006). This method allows the specification to accept materials whose properties are characterized and show sufficient resistance to creep and degradation. Determination on the structural adequacy of these products is to be made by the engineer of record on a project basis.

BACKGROUND

The current New Jersey Department of Transportation (NJDOT) specifications for Fiberglass Reinforced Plastic Lumber (FRPL), Fiberglass Reinforced Plastic Piles (FRPP) and Fiberglass-Concrete Composite Pile (FCCP) covered under section 916, Fiberglass Composite Materials (FCM) are proprietary based: namely, Bedford Technologies' SeaTimber and SeaPile, and Lancaster Composite's Composite Pile 40. Competitive materials cannot meet specification, and therefore cannot be added to the Qualified Product List (QPL). Due to the current state of NJDOT Standard Specification Section 916, it is not possible for competing materials to meet the specifications; this creates a monopoly for the manufacturers of the proprietary products that served as the basis for the specification.

The current specification limits qualified materials by being too restrictive in its parameters. Currently, Section 916 of the NJDOT standards specification dictates geometry, materials, and material properties, regardless of the project's design criteria and material requirements. In addition, the current NJDOT standard specification only speaks on the use of fiberglass reinforced plastic piles although several different composite piles exist, are readily available, and are currently used. These pile types include hollow FRP piles created through various different manufacturing processes. This prevents and/or creates confusion on the use of other types of fiber reinforced composite piling. Therefore, redevelopment of current FCM specification is needed to eliminate these overly restrictive parameters and encourage an openly competitive market based on physical properties and design criteria.

OBJECTIVES

The main objective of this research project was to develop Section 916 of the NJDOT Standard Specification into an openly competitive specification that encourages an economically competitive market. This can be accomplished when:

- 1) The different fiber reinforced materials which are readily available are understood
- 2) How the materials are currently being used in the Civil Engineering Industry
- 3) The minimum material properties required by the American Association of State Highway and Transportation Officials (AASHTO) specifications are understood
- 4) The engineering properties required for design (both short and long-term) are known
- 5) The redeveloped specification can qualify the materials currently on the QPL as well as competitors

INTRODUCTION

The main objective of the research program is to redevelop Section 916 of the NJDOT Standard Specification into a specification that encourages open economic competition. This will be accomplished by creating a performance based specification. Performance based specifications focus on outcomes rather than the processes which accomplish the said outcome. Performance based specifications allow for the specialization of materials for certain tasks, and this often leads to designs with better performance that are more economical.

The fiberglass composite materials covered in Section 916 of the NJDOT standard specification are a subset of what is generally considered Fiber Reinforced Polymer (FRP) composite materials. Composite materials are created from one or more constituent material with different physical properties. When the materials are combined they keep their form but create an individual material with properties different from the constituents.

Section 916 of the NJDOT standard specification currently covers fiberglass composite materials which are intended for use as pile supported bridge fender systems,

bulkheads, and pile foundations for light structures. Figure 1a) shows FRP piles used as a foundation for a walkway, and Figure 1b) shows FRP piles used as a barrier system. FRP materials have found a market in the coastal areas mainly due to their tolerance to natural conditions which corrode or weaken common pile materials (timber, steel, and concrete). The FRP composite materials generally have a higher initial cost but become competitive when design life is considered. While substructure elements are the only application of FRP materials covered in the NJDOT standard specification, they are not the only practical use of FRP composite materials.



a) Walkway



b) Barrier system

Figure 1. FRP composite pile uses

In order to develop a performance based material specification the end use of the material must be considered. This final use dictates the important material properties which require characterization. The material can then be characterized using appropriate materials testing. This is the approach used to redevelop Section 916 of the NJDOT material specification. The new specification is based on performance and design requirements.

COMPOSITE MATERIALS

Composite materials are created when one material is embedded or bonded to another with distinct boundaries between them. Both materials retain their physical and chemical identities, but their combination produces properties which could not be achieved by either of the constituent materials alone. The composite materials covered in Section

916 of the NJDOT Standard Specification can be classified as FRP composites, and these materials are created by combining a high strength fiber with a polymer matrix. The fiber serves as the main load carrying member while the matrix bonds the fibers together. Section 916 focuses on fiberglass, but other commonly used fibers include carbon and aramid.

Polymers are defined as long-chain molecules containing one or more repeating units of atoms. They are broken down into two general categories: thermosets and thermoplastics. Both of these polymer materials are covered in Section 916. Thermoset polymers have their molecules chemically joined through cross-links (Mallick, 1993). Examples of thermoset polymers include epoxies, polyesters, vinyl esters, and polyimides. Thermoplastics have no chemical bonds; their molecules are held together by intermolecular forces. These bonds can be broken with heat and pressure, and the molecules can be realigned and reset (Mallick, 1993). Examples of thermoplastics include nylons, polyether-ether ketone, and high density polyethylene. Generally thermosets have higher strength and stiffness when compared to thermoplastics.

Polymers are viscoelastic materials; their mechanical properties are highly linked to ambient temperature and load rate (Mallick, 1993). Polymers experience a glass transition temperature where the properties change from a solid to a viscous material. It is important for the operating temperature of the composite to be below the glass transition temperature of the polymer material. The mechanical properties are dependent upon load rate. At high rates of loading polymer materials can behave in a brittle glass like manner and at a lower load rate the same material can behave in a ductile manner (Mallick, 1993). Polymer materials are susceptible to both creep and stress relaxation.

Moisture absorption can be a critical parameter for thermoset polymers. It causes resins to swell inducing volumetric changes in the composite material. This swelling can reduce the bond between the fibers and the matrix. Moisture absorption is linked to a reduction in glass transition temperature, and the rate of absorption of water is temperature dependent (Mallick, 1993).

Polymer materials are susceptible to degradation due to Ultra Violet (UV) and visible light. The amount of exposure to sunlight often determines the useful lifetime in outdoor applications (Sing and Sharma, 2008). UV degradation affects the visual and mechanical properties of the polymer.

At present, there are several candidates for use in pile-supported fender systems, bulkheads, and pile foundations for light structures. Current commercially available polymer composite material piles along with their configurations, material compositions, common dimensions, and manufacturers are presented in Figure 2. Creative Pultrusion, Harbor Technologies, and Lancaster Composites manufacture thermoset-based FRP piles.

Bedford Technologies manufactures piles made of high-density polyethylene (HDPE) that may or may not be reinforced with glass-fiber polymer composite bars. HDPE is a commonly available visco-elastic material for which the short-term load-deformation response is load-rate dependent and is appropriately modeled by a non-linear function.

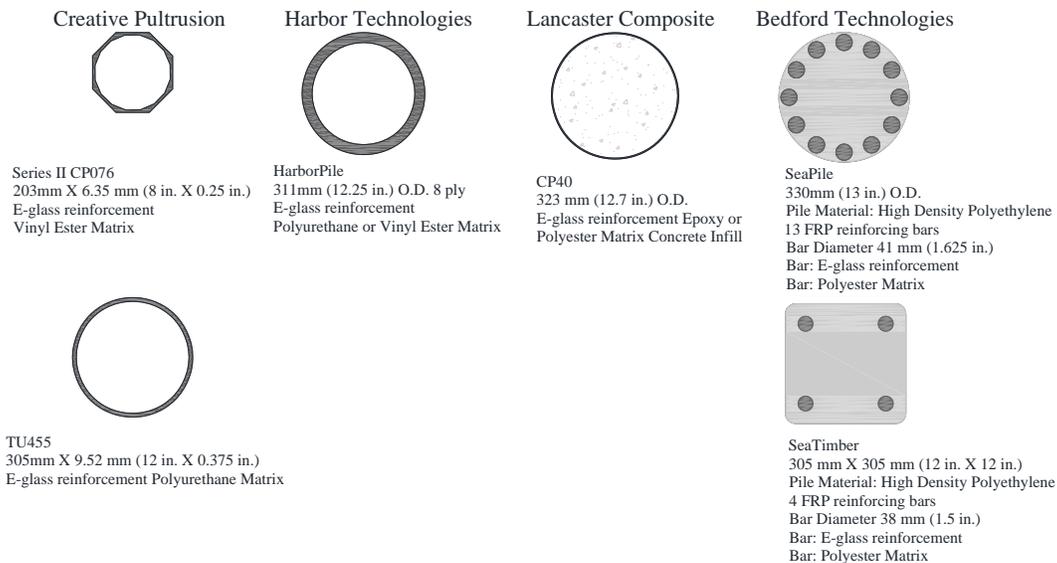


Figure 2. Polymer pile materials

Thermoset Structural Components

Thermoset structural components can be created through several different processes including pultrusion, filament winding, and vacuum infusion. These processes create products with slightly different properties, but they have several key factors which link them together. All of the structural components created using a thermoset polymer resin include continuous fiber reinforcement. They have orthotropic material properties which differ in each direction dependent on the orientation of the fibers. The orientation of the fibers can cause composite materials to experience coupled deformation. For example, an axial load can cause both extension and flexure simultaneously. These coupled deformations can be avoided by implementing balanced symmetric composite materials. A symmetric composite has the fibers placed in the same orientation at the same distance from the centroid. A balanced composite has fibers oriented at exactly opposite angles on opposite sides of the centroid. The fibers at opposite angles do not need to be at the same distance. Due to the complex behavior governed by the fibers, machining of composite materials is difficult. A well-studied example of composite machining is a connection hole in a composite plate. The hole interrupts the fiber continuity and reduces the strength of the composite (Mallick, 1993).

Pultrusion

Pultrusion is a process where composite shapes are continuously formed. The process creates long straight members with constant cross-sections. The majority of the fibers are aligned along the length of the member, and layers of mat are added to improve properties in the transverse direction. Figure 1 shows the pultrusion process. Continuous fibers and strand mats are pulled through a bath of uncured thermoset polymer. Surface veiling is applied to the outside of the fibers to improve surface smoothness and to protect the fibers. The forming and curing dies compact the fibers removing voids and excess resin. Heat is applied at the curing die to cure the thermoset polymer. The pulling system provides movement for the entire process, and the saw cuts the members to length. Because most of the fibers are aligned in the longitudinal direction, pultruded shapes have good mechanical properties longitudinally; they tend to be weaker transversely.

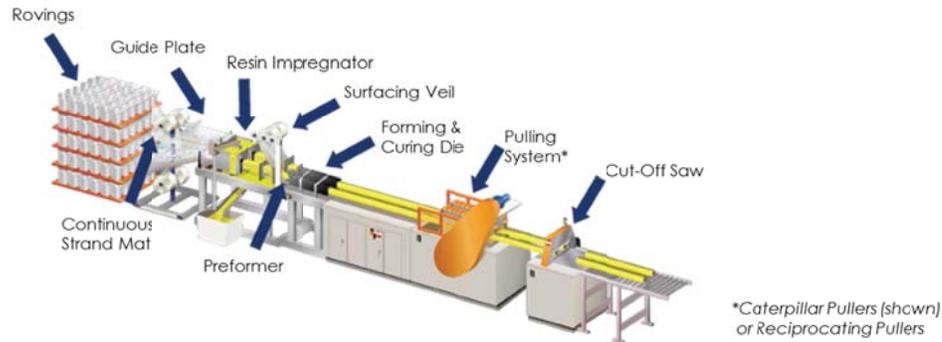


Figure 3. Pultrusion process (Creative Pultrusion, 2016)

Creative Pultrusion is a manufacturer of pultruded shapes located in Alum Bank PA. Their pile products go by the name of SUPERPILE. The piles come in both round and octagonal shapes. The circular shapes range from 12 to 16 inches in diameter with walls of 3/8 to 1/2 an inch. The octagonal piles have outside diameters of 8 and 10 inches with wall thicknesses of 1/4 of an inch.

Filament Winding

Filament winding is a process where fibers are impregnated with polymer and wrapped around a rotating mandrel. The final products are hollow, and they take on the shape of the mandrel. Figure 4 shows the filament winding process. Continuous fibers are combed and fed through a polymer bath. The guide moves back and forth as the mandrel rotates. Depending on the guide speed and the mandrel rotation rate fiber orientations from nearly zero to ninety degrees can be achieved.

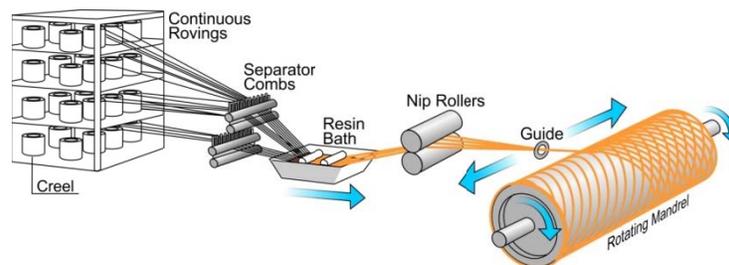


Figure 4. Filament winding process(Nuplex, 2016)

Lancaster Composite, located in Millersville PA, fills filament wound tubes with concrete to create their product, CP40. The composite tubes generally have outside diameters ranging from 12 to 16 inches with a 1/4 inch wall.

Vacuum Infusion

Vacuum infusion is a process where fibers, in the forms of sheets, and uncured polymer are placed in a mold under a vacuum. The vacuum removes the air and compacts the product. The fiber orientation in the final product is based on the orientation of the fibers in the sheets. The final product takes on the shape of the mold used. Figure 5 shows the vacuum infusion process.

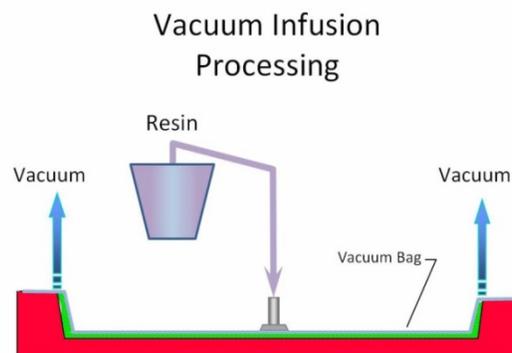


Figure 5. Vacuum Infusion (Moldefiberglass, 2016)

Harbor Technologies is a manufacturer of vacuum infused pile products located in Brunswick ME. Their product is known as HarborPile and has a round cross-section. It is offered in diameters ranging from 11 to 34 inches with wall thicknesses ranging from 3/16 to 5/8 of an inch.

Thermoplastic Structural Components

Thermoplastic structural components are manufactured from High Density Polyethylene (HDPE). The HDPE is reinforced with discrete bars. These bars have been made of steel or pultruded composite. HDPE is a commonly recycled material, and it is an isotropic viscoelastic material. HDPE is non-linear elastic, and depending on the load rate can behave as a solid or viscous material. The behavior of the reinforced thermoplastic structural components is largely a function of the reinforcement. A manufacturer of reinforced thermoplastic structural components is Beadford Technology

located in Worthington, MN. Their pile product is known as SEAPILE. They are manufactured in diameters ranging from 10 to 16 inches. The piles contain between 6 and 16 reinforcing bars, which themselves are FRP composites.

SUMMARY OF LITERATURE REVIEW

AASHTO Design Specifications

The materials covered in NJDOT Standard Specification Section 916 are intended for the use as pile supported bridge fender systems, bulkheads, and pile foundations for light structures. The design of piles for bridge and Highway structures is governed by Section 10.7 in the AASHTO Load and Resistance Factor Design (LRFD) Bridge Design Specifications (2016). The design of a pile involves the determination of the axial bearing resistance, determination of the lateral capacity, determination of the pile structural resistance, and an analysis of drivability. Corrosion and deterioration of the pile by environmental factors must also be considered; these considerations are given in Section 10.7.5 of the AASHTO Specifications.

The axial bearing capacity of the pile can be determined in accordance with Section 10.7.3.8 (AASHTO 2016). It can be determined either through field testing or a static analysis prediction can be made. The geometry of the pile affects the axial bearing capacity determined through the static analysis prediction.

The lateral capacity of a pile is governed by Section 10.7.3.12 of the AASHTO Specifications (2016). The lateral capacity of the pile has to be evaluated as both a function of the pile's structural properties and the geomaterials. The evaluation must occur under factored axial and lateral loads, and this can be accomplished through a P-y analysis. The origin of the P-y analysis is the idea of a beam on an elastic foundation, and the relevant governing differential equation was given by Timoshenko (1941). The pile acts as a beam, and the response of the soil is modeled as nonlinear springs. Terzaghi (1955) realized that if a pile is laterally loaded and instrumented to measure strain and deflection, the spring behavior of the soil can be ascertained from the experimental measurements taken on the pile. This was ultimately accomplished by Matlock and Ripperger (Reese and Van Impe, 2011). The advancement of computers

and numerical methods (finite difference and finite element methods) have made the rapid evaluation of the governing differential equation possible, and also more easily facilitated the inclusion of non-linear flexural properties (Reese and Van Impe, 2011). From section C10.7.3.12 the strength of the laterally loaded pile is reached when the combined bending axial resistance is reached. This is specific for each material type.

The pile structural resistance is governed by Section 10.7.3.13.1 of the AASHTO Specifications. The nominal compression resistance and resistance factors for compression are material specific and are determined through Sections 5, 6, and 8 for concrete, steel, and timber respectively. The structural pile resistances of steel and composite steel and concrete members are given in Section 6.9.4.1 and 6.9.5.1 of the AASHTO Specifications. The limit state for these piles types is buckling. The structural pile resistance of reinforced and prestressed concrete piles is given in sections 5.7.4.4 and 5.7.4.3 of the AASHTO specifications. The considered limit states are crushing of the concrete and buckling. The structural pile resistance for timber piles is governed by section 8.8.2. The limit state includes compression failure parallel to the grain and buckling. Section C10.7.3.13.4 give equations for determining the depth of fixity for piles based on the piles modulus of elasticity and soil properties.

Section 10.7.8 of the AASHTO Specifications states that the drivability of piles must be determined using a wave equation analysis. The wave equation describes how the force in the pile changes as the stress wave caused by the strike of a pile driving hammer moves through the pile, and it is generally based on elastic theory (Budhu, 2000). It is a function of the area and elastic modulus of the pile. The stresses determined from the wave equation analysis must be less than the allowable tension and compression stresses for the specific material.

The design provisions for bridge protection systems, such as fenders and dolphins, are contained in the AASHTO Guide Specification and Commentary for Vessel Collision Design of Highway Bridges (2010). A review of the procedures for calculating the force from a vessel collision is given in Park and Ansari (2003). The design of pile supported fender systems is covered in section 7.3.2 of the AASHTO Guide Specification for Vessel Collision. The specification itself provides few requirements. It states that pile

supported structures can be used to absorb collision impact energy/loads. Pile groups which are rigidly connected can be used to provide high levels of protection. This agrees with the work of Yazdani and Wekezer (2000) who showed that the behavior of a fender system largely depends on the connection of the piles. Stiffer connections between the piles lead to better energy distribution throughout the system. The specification indicates that vertical fender piles resist the impact loads through bending, and that battered piles resist the impact through a combination of compression and bending. Due to the high loads associated with vessel collision, plastic deformation and crushing of the structure are acceptable provided that the vessel is prevented from impacting the bridge pier with a force higher than the piers resistance. This statement indicates that a nonlinear design is acceptable, and a fender system is considered sacrificial and replaceable.

The commentary to section 7.3.2 makes delineation between the fender systems used for vessel mooring systems and those for vessel impact. Piles used in mooring operations are designed to elastically resist low energy impacts from vessels. It is not generally possible to resist a ship collision elastically. The commentary goes on to give examples of different pile supported fender systems implemented throughout the world. A dynamic analysis for the design and analysis of pile supportive protective systems developed by Derucher and Heins (1979) is presented. The method assumes linear elastic material properties for the pile. A distribution factor is used to distribute load based on vertical and horizontal stiffness of the pile system.

From the review of the AASHTO documents a combination of elastic and nonlinear analyses are performed on pile structures. The axial bearing of a pile is a function of the pile geometry and the soil properties. The lateral loading behavior is analyzed with a P-y analysis which can incorporate nonlinear soil and flexural properties. Drivability of a pile is determined using the wave equation, and for this analysis the pile is taken to be linear elastic. The pile structural capacity has different limit states depending on the material type, but generally a buckling component is considered. Due to the large loads seen during vessel impact, pile supported fender systems are expected to deform plastically

and possibly to failure, but fenders used for mooring applications are designed to absorb small loads elastically.

Composite Pile

The first prototype recycled composite pile was driven at The Port of Los Angeles in 1987 (Iskander 1998). Composite materials are considered a viable material for the creating of foundations of light structures and barrier systems in coastal areas. One of the first research studies was funded by the US Army Corps of Engineers (Lampo, 1998). The research project involved a design competition for composite pile systems which were subsequently put through qualification testing and field demonstrations. Performance goals for pile structures were set by investigation of Navy and Army Corps of Engineers requirements and a survey of end users. The Requirements are as follows:

Fender Piles

- Cross-Section shall not exceed 13x13 in.
- The length of one continuous pile without joints must be at least 70 ft.
- Shall not exhibit brittle behavior when subjected to a lateral load at -40° F at a strain rate of 100 percent/ min.
- Minimum flexural stiffness (EI) of 6×10^8 psi.
- Minimum outer fiber fracture strain of 2 percent when tested in bending.
- Minimum energy absorption of 5 ft-kips.
- The angle of approach from water craft is expected to be 180°.
- Under normal service conditions (exposure to UV, seawater, petroleum, and hydrothermal cycles), the mechanical properties shall not degrade by more than 10 percent over the design life of the pile.
- The pile shall have less than 5 percent weight increase due to water absorption.
- Under normal service conditions the pile shall not pose a hazard to the environment and shall meet codes for leaching, flame spread, and ignition
- The product shall be drivable using standard equipment.

Loadbearing Piles

- Cross-Section shall not exceed 16x16 in.
- The length of one continuous pile without joints must be at least 50 ft.
- Minimum compressive strength of 3,500 psi.
- Minimum EA of $9.0.0 \times 10^7$ lbs.
- Under normal service conditions (exposure to UV, seawater, petroleum, and hydrothermal cycles), the mechanical properties shall not degrade by more than 10 percent over the design life of the pile.
- The pile shall have less than 5 percent weight increase due to water absorption.
- Under normal service conditions the pile shall not pose a hazard to the environment and shall meet codes for leaching, flame spread, and ignition
- The product shall be drivable using standard equipment.
- Shall have a fire rating of no less than 4 hours as defined by the National Fire Protection Association Bulletin #307.

The required material properties were based on that of wood. The results of the study showed that FRP composite materials were viable for use as bearing and fender piles in marine environments. Fender piles are loaded as flexural members, but they also receive a “pinching” or radial load upon vessel impact. Loadbearing piles are considered to be loaded axially. The mechanical behavior of the piles changed with temperature, and creep was identified as an issue that warrants further study. The stiffness of the pile directly affected the drivability of the pile, and the interaction of the pile and soil must be studied before composite materials are used in loadbearing applications.

Frost and Han (1999) used a modified direct shear test to study the interaction between FRP and steel surfaces and sand. The FRP material studied showed peak interface friction angles and roughness similar to steel. Pando et al. (2006) also performed interface shear tests which showed that for each composite material tested the friction angle was similar to that of concrete and steel except FRP provided by Lancaster composite (17 degrees).

Han and Frost (2000) performed an analytical study on laterally loaded piles taking into account non-isotropic properties. They found that, since generally composite materials are stiffer longitudinally than they are transversely, shear deformations are important to consider. They found that by using Timoshenko Beam theory the shear deformations could be captured. Increased vertical load caused an increase in lateral deflections, and the shear deformations played a significant role in the lateral deformation. An increase in lateral soil resistance changed the deflection mode from rigid pile rotation to flexure; and when lateral soil resistance was high, the fixity at the top of the pile governed the behavior. Zureick and Kim (2002), Zweben et al. (1979), Marom (1981), Tolf and Per (1984), and Bank (1989) proposed experimental methods for simultaneous determination of the flexural and shear moduli of full scale I and WF FRP beams, to be used in simplified design models such as Timoshenko's beam theory.

Inskandur et al (2001) performed a parametric study using wave equation analysis on the drivability of FRP piles. The study was limited by the scarcity of driving records. The results showed that the wave equation could be used to analyze polymeric piling if it incorporated residual stress analysis and a reduced elastic modulus which accounted for the nonlinear behavior of the polymer. The results showed that the main factors in the drivability of plastic piles were the specific weight and elastic modulus of the piles. For stiffer materials, the soil profile is the main factor governing drivability. Guades et al. (2012) presented extensive review of available FRP piles and their driving performance under impact driving.

There are generally three types of composite piles that are commercially available, and the three types of piles have significant differences in structural composition and failure. The first type of piles is a hollow FRP tube. These tubes can be produced through various different methods (pultrusion, filament winding, and vacuum infusion); they are installed as pipe piles. Manufacturers of these piles include Creative Pultrusion and Harbor Technologies. The second type of pile is an FRP tube filled with concrete. Lancaster composite is a manufacture of this pile type. The final pile type is a reinforced thermoplastic pile. The thermoplastic is generally recycled HDPE, and has been

reinforced with steel and pultruded FRP. A producer of these piles is Bedford Technologies.

FRP Tubes

As to date no, peer reviewed literature has been identified where circular FRP tubes designed for use as pile structures have been installed in the ground and tested either axially or laterally. However, Han et al. (2003) proposed a design method which takes into account the unique stiffness of FRP structural shapes.

Fam and Rizkalla (2002) performed full scale flexural tests on two FRP tubes in four point bending. One tube was created through pultrusion, and the second tube was created through filament winding. The authors indicate that both tubes fail through a process of ovalization and local buckling in the compression zone of the tube. Polyzois et al. (1998) completed a study on the lateral load capacity of tapered thin walled cylindrical FRP poles intended for use carrying electrical transmission lines. The poles were created through filament winding, and they were embedded into a circular concrete foundation base fixed to the floor. Load was applied laterally and three modes of failure were observed. The first involved local buckling failure in the compression area near the fixed support. This was a brittle failure in which member collapsed as soon as local buckling was initiated. The second failure mode was diagonal shear fracture on the compression side near the base, and the final failure mode was tension failure of the pole near the base. This failure was accompanied by large deformations and was considered a ductile failure.

Elghazouli et al. (1998) performed a study on local buckling of glass fiber reinforced polymer. Automated laser scanning was used to evaluate initial imperfections and to monitor changes prior to and after buckling. The results of the study showed that fiber orientation effected the axial stiffness of the tube and the buckling strength. The 0/0 showed highest axial stiffness, while a 0/90 orientation showed the highest buckling strength. The buckling values were found experimentally were lower than the expected linear response.

Ashford and Jakrapiyanun (2001) performed drivability analysis using the wave equation on GRFP (glass fiber-reinforced polymer) composite piles in order to assess the potential of these piles for load bearing applications. Manufacturer material properties were used, and two soil profiles were considered, one assuming end bearing piles and other assuming frictional piles. The results of the study were independent of the soil profile and showed that pipe piles composed solely of GRFP reached refusal at 60 to 75 percent of the other materials tested. This is due to very low impedance of GRFP piles. The authors suggest that to increase the impedance the only practical solution is to fill the piles with concrete.

Chin et al. (1997) investigated matrix resin degradation of vinyl ester and polyester materials under environmental and mechanical stresses such as UV radiation, moisture, temperature, and high pH environment. After exposure to water, salt, and concrete pore solution, no changes in tensile strength or glass transition temperature were observed at room temperature. At increased temperature of 140°F in alkaline and saline environment some degradation of polyester material was observed. UV exposure resulted in surface oxidation. Similar surface erosion and cracking was observed in both materials.

Concrete Filled FRP Tubes

Mirmiran et al. (2002) instrumented and installed FRP piles with concrete cores. They found that no damage was incurred by the concrete filled FRP tubes during pile driving and no special tip was necessary. Pando et al (2003) documents the installation in the ground and axial and lateral testing of steel reinforced concrete filled FRP tubes. The behavior of the tubes was similar to a prestressed concrete pile. Baxter (2005) drove a concrete filled FRP pile to failure. The pile cracked at the top, and pile integrity testing showed significant cracking and damage after pile driving. Juran and Komornic (2006) performed a study on the axial load bearing capacity of FRP piles, and showed that concrete filled FRP tubes are a viable deep foundation. Han et al. (2003) showed that since hybrid concrete FRP piles have similar stiffness to conventional materials (steel, reinforced concrete wood), they can be designed in the same manner as conventional

piles if appropriate modifications to properties such as interaction coefficient and ultimate creep coefficient are made.

Fam and Rizkalla (2001a) performed a study on axial behavior of circular concrete-filled FRP tubes. Six specimens with a length-diameter ratio of 2:1, and the FRP tubes were designed to provide resistance in the axial and hoop directions. The properties of the FRP tube were determined in the axial (both tension and compression) and hoop directions. The properties in the hoop direction were determined using the split-disk method. The axial properties were determined from tension tests performed on coupons cut longitudinally from the tube. The coupons had curved faces. The results of the study showed that assuming the FRP tube only provides confinement for the concrete overestimates the confinement effect. The tube is loaded biaxially, and the biaxial strength of the FRP governed. Filament wound FRP tubes performed better than pultruded tubes. The pultruded tubes split once the concrete began to expand laterally. The stress strain behavior of the concrete filled FRP tubes was bilinear. The transition occurred near the peak strength of the unconfined concrete, and the properties of the second linear portion are governed by the stiffness of the FRP tube. The ultimate strength of each specimen tested was governed by brittle splitting failure of the FRP tube. Fam and Rizkalla (2001b) then provided a confinement model for the concrete. The model is incremental and predicts behavior up to the point where the FRP tube fails. The model was evaluated using existing literature and a parametric study was performed. The parametric study indicated that reducing the longitudinal stiffness reduced the confining effects. Fam and Rizkalla (2002) then performed full scale flexural tests on FRP tubes with and without concrete infill. The concrete filled FRP tubes experienced 4 different failure modes:

1. Local Crushing of the concrete.
2. Rupture of fibers in tension.
3. Local crushing and splitting.
4. Shear splitting of the tube.

Mirmiran et al. (1999) studied the behavior of five concrete filled FRP tubes under flexure and compression. The results of the study showed that the behavior of the

concrete filled FRP tubes could be modeled using Euler-Bernouli beam theory if full composite action is developed. The concrete filled FRP tubes are considerable stronger than an equivalent reinforced concrete section due to the confinement the FRP tube provides. In order to utilize the confinement a compression failure is desired. Mirmiran et al (2000) performed 16 beam-column tests on concrete filled FRP tubes where off the shelf FRP tubes were used. Specimens were designed as over and under reinforced. Bond failure between the concrete and FRP tube was not found to be an issue. For columns it was found that it was not necessary to provide an additional shear transfer mechanism, but it was required for beams. It was found that it was better to design the tubes as over reinforced because it limits the $P-\Delta$ effects. Mirmiran et al. (2001) showed that concrete filled FRP tubes are more susceptible to slenderness effects. They showed that as the slenderness ratio increased from 11 to 36 the strength dropped from approximately 75 to 30 percent of an equivalent short column. The ductility showed a more significant drop. As the slenderness ratio increased from 11 to 36 the axial and hoop strains reduced from 69 and 84 percent to 15 and 13 percent respectively.

Mirmiran et al. (2002) performed a parametric study using the wave equation and no difference in drivability was found between the concrete filled FRP piles and prestressed concrete piles of the same cross-sectional area and concrete strength. Using the wave equation, Iskandur and Stachula (2002) showed that the capacity of concrete filled FRP tubes was mainly governed by the soil parameters and these piles drove similarly to prestressed concrete.

Pando et al (2006) performed durability tests for FRP shells used to create concrete filled FRP piles. The FRP samples were exposed to moisture at different temperatures, and saturated FRP samples were put through freeze thaw cycles. The results showed that the absorption of water degraded the properties of the composite, but freeze thaw cycles had little effect.

Reinforced Thermoplastic

Pando (2003) details the installation in the ground and axial and lateral load tests on a steel reinforced thermoplastic pile. When compared to a concrete filled FRP tube, the

steel reinforced thermoplastic was 2.5 times less stiff. When the pile was loaded laterally, it exhibited a linear load deflection response. This indicates that the reinforcing steel was governing the behavior. Baxter (2005) drove a steel reinforced thermoplastic pile. The pile buckled at the top during driving, and upon extraction, the thermoplastic had been damaged exposing the steel reinforcing bars. Juran and Komornic (2006) installed and studied the axial behavior of three reinforced thermoplastic piles. These piles were a HDPE pile reinforced with short chopped glass fibers, a steel reinforced HDPE pile, and a HDPE pile reinforced with FRP bars. The full-scale axial load tests showed that the failure mode of the HDPE piles involved a distinct plunging effect. During pile driving the HDPE piles saw damage in the first foot below the hammer.

In a second study Baxter (2005) impacted a FRP reinforced HDPE pile with a 85 ton vessel at low speeds and measured the dynamic response of the piles. Steel reinforced piles were also installed but the pile response was reduced due to the piles leaning against a concrete block. Piles were installed using a vibratory hammer to an embedment depth of about 19 feet. Both piles were damaged by the hammer clamps during installation. The results indicated that the piles absorbed the impact energy through both translation and bending. Finally, a dynamic model was proposed that considers damping that occurs during vessel impact. An average damping of 19 percent was estimated using the velocity time history of the vessel recorded during impact. By incorporating damping into the system the maximum displacements, forces and moments at the impact point were reduced by about 25 percent. This reduction may justify the use of smaller or fewer piles.

Juran and Komornic (2006) studied short term axial properties of HDPE piles. It was found that the axial behavior of the HDPE pile reinforced with short glass fibers was strain rate dependent. The properties of the HDPE with FRP and steel reinforcement were governed by the properties of the reinforcement. Juran and Komornic (2006) concluded that more full scale testing was required to determine the structural capacity and failure modes of the HDPE piles. When evaluating the drivability of reinforced thermoplastic piles Iskandar and Stachula (2002) recommended the secant modulus be

used to account for the nonlinear nature of the elastic behavior, and the elastic driving parameter used in the wave equation analysis was approximately $2/3$.

Iskander and Hassan (2001) conducted experimental study to assess durability of FRP material in aggressive environment. Seapile specimens having 12.7 mm diameter and 25.4 mm length were exposed to fixed acidic (pH 2), alkaline (pH 12) and neutral (pH 7) solutions at elevated temperatures in order to accelerate degradation. Unconfined compressive strength was used as an index to quantify degradation. Testing followed American Society of Testing Materials (ASTM) D 695-96. Only acidic environment produced consistent results indicating 25 percent loss in resistance at 1 percent strain at 25°C in 14 years. Assuming constant reaction rate, 50 percent loss is estimated to occur in 33 years.

Conclusions from Composite Pile Literature Search

In order to design a pile in accordance with the AASHTO specifications the elastic and inelastic material properties of the pile must be understood as well as the structural capacity of the pile. Evaluation of the structural capacity is material dependent and includes combined loading. From the AASHTO specifications it can be expected that a pile is loaded axially, laterally, or with a combination of the two. The structural axial capacity of a pile is generally never reached due to failure in the soil, but axial stability must be evaluated. Lateral loading and combined axial and lateral loading are evaluated using a P-y analysis. The piles will reach their limit when their combined axial and flexural resistance is reached. For fendering operations it is acceptable for the pile to experience failure as long as a critical impact is prevented. The analysis of pile failure would need to incorporate all limit states in order to be effective (soil and pile). The pile itself can experience both strength and stability limit states. The geometric and material properties of the pile play a role in each of these limit states. The material properties of some FRP piles have been found to be nonlinear and strain rate dependent.

Table 1 ties the pile properties to specific pieces of literature, and from the table it can be seen that the amount of information is not equal for each pile type. All piles require more study in the areas of stability under flexure and combined loading. Reinforced

thermoplastic piles lack data in the area of axial stability, flexural strength and stability, and combined strength and stability. FRP tubes are lacking in data about field installation, flexural stability, and combined strength and stability. While degradation tests were performed on each type of material, each experimental study used different methods and exposed the materials to different environments. Creep under sustained load has been identified as an area requiring further study. Furthermore physical testing has largely focused on individual piles, and the connection between the piles may be a critical design parameter. The torsion behavior has not been evaluated for any of the materials.

Table 1. Literature on Pile Properties

	FRP Tubes	Concrete Filled FRP Tubes	Reinforced Thermoplastic
Field Installation		Mirmiran et al. (2002)	Baxter (2005)
Axial Field Testing		Pando et al (2003) Juran and Komornic (2006)	Pando (2003) Juran and Komornic (2006)
Lateral Field Testing		Pando et al (2003 and 2006)	Pando (2003 and 2006) Baxter (2005)
Axial Strength	Elghazouli et al. (1998)	Fam and Rizkalla (2001a) Fam and Rizkalla (2001b)	Juran and Komornic (2006)
Axial Stability	Elghazouli et al. (1998)	Mirmiran et al. (2001)	
Flexural Strength	Fam and Rizkalla (2002) Polyzois et al. (1998)	Fam and Rizkalla (2002)	
Flexural Stability			
Combined Axial and Flexural Strength		Mirmiran et al. (1999)	
Combined Axial and Flexural Stability			
Drivability	Ashford and Jakrapiyanun (2001)	Mirmiran et al. (2002) Iskandar and Stachula (2002)	Iskandar and Stachula (2002)
Degradation	Chin et al. (1997)	Pando et al (2006)	Iskander and Hassan (2001)

Summary of DOT Standard Specifications

The standard specifications for all 50 states were evaluated. Only three states (New Jersey, Texas, and Florida) include any type of FRP in their standard specification. California has a standard detail for a FRP column case, and Maryland has a standard detail for a fiberglass FRP cap for timber piles.

New Jersey

The New Jersey Standard specification covers Fiberglass Composite Materials (Section 916). The materials are intended for use as substructure elements, bulkheads, and barriers. The specific products covered in Section 916 are fiberglass reinforced plastic lumber, fiberglass reinforced plastic piles, and fiberglass-concrete composite piles. The requirements for each product are very detailed.

Fiberglass Reinforced Plastic Lumber (FRPL)

Section 916.01 of the NJDOT standard specification has requirements for FRPL plastic, reinforcement, manufacturing, and structural properties. The plastic are to be a mixture of recycled high, medium or low density polyethylene thermoplastic. The FRPL must be manufactured so that it does not absorb moisture, corrode, rot, warp, splinter, or crack. The outer skin must be smooth and black, and a hindered amine light stabilizer must be used to provide resistance to ultraviolet light. The plastic must meet the requirements of Table 2.

For FRPL cross-sections greater than 10in. x 10in., a minimum of four 1.5 in. fiberglass reinforcement rods must cast into the FRPL. These rods must be placed in the corners of the FRPL and meet the requirements given in Table 2. If the FRPL is used for constructing platforms, blocking, and whales 15 percent by weight of glass reinforcing fibers must be added to the plastic.

The FRPL must be manufactured in one continuous piece. The FRPL must consist of a dense outer layer with a less dense core, and interior voids must not exceed 0.75 inch

in diameter. FRPL must be free of twists and curves. The manufacturing tolerances for FRP are given in Table 3.

Table 2. FRPL Material Properties

Property	Requirement	ASTM Specification
Skin Density	55-63 lbs/ft ³	D792
Core Density	34-48 lbs/ft ³	E1547
Skin Water Absorption	2 hrs: <1.0% wt. increase 24 hrs: <3.0% wt. increase	D570
Skin Brittleness	No break at -40°F	D746
Skin Impact Resistance	Greater than 4 ft-lbs/inch	D746
Skin Hardness	44-75 (Shore D)	D2240
Skin Abrasive Resistance	Weight Loss: <0.03g Wear Index: 2.5 to 3.0 (cycles= 10,000; wheel= CS17; Load= 2.2lbs)	D4060
Skin/ Core Chemical Resistance	Sea Water <1.5% weight increase Gasoline <7.5% weight increase No. 2 Diesel <6.0% weight increase	D543
Skin/ Core Tensile Properties	500 psi, min.	D638
Skin/ Core Compression Modulus	40 ksi, min.	D695
Skin Coefficient of Friction	0.25 wet or dry, max	F489
Skin/ Core Nail Pullout	60 lbs, min	D1461
Reinforcement Rods Flexural Strength	70 ksi, min	D4476
Reinforcement Rods Compressive Strength	40 ksi, min	D695

Table 3. FRPL Dimensions and Tolerances

Geometry	Requirement	Tolerance
Length	Per order	±6 in
Width	As shown on Plans	±0.25 in
Height	As shown on Plans	±0.25 in
Corner Radius	1.75 inches	±0.25 in
Outer Skin Thickness	0.1875 inches	±0.125 in
Distance from outer surface to rebar elements	1.5 inches	±0.625 in
Straightness (gap, bend or bulge inside lying on a flat surface)		< 1.5 in per 10 ft. length

The structural requirements for FRPL change depending on the size. Smaller FRPL structural properties are determined using ASTM standards for plastic lumber products. Table 4 gives the structural properties for FRP less than 10 in. x 10 in.

Table 4. Structural Properties of FRPL smaller than 10 inches

Property	Requirement	ASTM Specification
Modulus of Elasticity	175 ksi, min.	D6109
Flexural Strength	No fracture at 1800 psi	D6109
Compressive Strength	1500 psi, min.	D6108
Compressive Strength Parallel to Grain	1750 psi, min.	D6112
Compressive Strength Perpendicular to Grain	600 psi, min.	D6112
Screw Withdrawal	350 lbs, min.	D6117

The structural properties for FRPL with dimensions greater than 10 in. are determined using a modified form of ASTM D790. Full size FRPL specimens are tested in three point bending; the specimen length must exceed 12 ft. The rate of testing is set by the deflection of the FRPL (0.25 in./min.). The strain in the FRPL is calculated using Equation 1.

$$\varepsilon = \frac{6d\Delta}{L^2} \quad \text{Equation 1}$$

where:

d= depth of cross-section

Δ= deflection

L= span length

The modulus of elasticity is calculated at a strain of 0.01 in./in. using Equation 2, and the yield stress is calculated from the maximum load reached prior to failure. The required structural properties of 10 and 12 in. FRPL are given in Table 5.

$$E = \frac{PL^3}{48\Delta I} \quad \text{Equation 2}$$

where:

E= modulus of elasticity

P= applied load

Δ= deflection

L= span length

I= moment of inertia

Table 5. Structural Properties of 10 and 12 in. FRPL

Property	10 in. x 10 in.	12 in. x 12 in.
Modulus of Elasticity	521 ksi, min.	405 ksi, min.
Stiffness EI	4.05x10 ⁸ lb-in ² , min.	6.58x10 ⁸ lb-in ² , min.
Yield Stress in Bending	5.8 ksi, min.	4.4 ksi, min.
Weight	30-37 lbs/ft	42-51 lbs/ft

Fiberglass Reinforced Plastic Pile (FRPP)

Section 916.02 of the NJDOT standard specification has requirements for FRPP plastic, reinforcement, manufacturing, structural properties, recoverable deflection, and wrapping. The material specifications are the same for FRPL and must meet the requirements of Table 2.

FRPP are round and have different reinforcement requirements based on their diameter. The requirements are given in Table 6. These rods must be placed evenly around the perimeter of the pile. FRPP must contain 5 percent glass reinforcing fibers by weight.

Table 6. FRPP Reinforcement Requirements

Outside Diameter	Reinforcement Requirement
10 in.	6- 1 in. fiberglass reinforcing rods
13 in.	13- 1.375 in. fiberglass reinforcing rods
16 in.	16- 1.375 in. fiberglass reinforcing rods

AS with FRPL, the FRPP must be manufactured in one continuous piece. The FRPP must consist of a dense outer layer with a less dense core, and interior voids must not exceed 0.75 inch in diameter. FRPP must be free of twists and curves. The manufacturing tolerances for FRPP are given in Table 7.

Table 7. FRPP Dimensions and Tolerances

Geometry	Requirement	Tolerance
Length	Per order (105 ft max)	±6 in/ -0.0 in.
Outside Diameter	10.000 in./ 12.875 in./ 16.250 in.	±0.375 in
Outer Skin Thickness	0.1875 inches	±0.125 in
Distance from outer surface to rebar elements	0.880 in./ 0.750 in./ 1.250 in.	±0.375 in
Straightness (gap, bend or bulge inside lying on a flat surface)		< 1.5 in per 10 ft. length

The required structural properties of FRPP are measured in the same way as for FRPL, and are given in Table 8. The reported stiffness is the average of the stiffness calculations between zero and half of the specified minimum yield stress. If the FRPP fails before it reaches the specified minimum stress it should not be used. The stress is

to be calculated on the tension side of the FRPP at the load point. The results of testing can only be extrapolated through engineering calculations to FRPP of smaller diameter.

Table 8. Structural Properties of FRPP

Property	10 in. OD	13 in. OD	16 in. OD
Modulus of Elasticity	458 ksi, min.	1054 ksi, min.	997 ksi, min.
Stiffness EI	2.25x10 ⁹ lb-in ² , min.	1.48x10 ⁹ lb-in ² , min.	3.21x10 ⁹ lb-in ² , min.
Yield Stress in Bending	4.3 ksi, min.	8.6 ksi, min.	7.8 ksi, min.
Bending Moment at Yield	422 in-kip, min.	1860 in-kip, min.	3168 in-kip, min.
Weight	24-29 lbs/ft	45-55 lbs/ft	66-81 lbs/ft

The recoverable deflection of FRPP is determined through a 4 point bending test on a minimum of 30.5 ft. long specimen with a minimum shear span of 15 ft. A minimum applied load of 40 percent of the FRPP's bending moment at yield is applied for a minimum of 200 cycles. The bending moment at yield is calculated using Equation 3. The value of EI cannot reduce by more than 5 percent.

$$M = f \frac{I}{c} \quad \text{Equation 3}$$

where:

M= bending moment at yield

f= yield stress in bending

I= moment of inertia

c= distance from neutral axis to point of stress

FRPP placed in clusters are to be wrapped with 5/8 in OD (1/2 in. diameter steel) polypropylene impregnated wire rope.

Fiberglass-Concrete Composite Piles (FCCP)

Section 916.03 the NJDOT standard specification addresses FCCP. FCCP consist of a FRP composite tube filled with concrete. The section has specifications for the composite tube, coatings for the tube, allowable degradation of the tube, dimensional and physical stability of the tube, concrete to fill the tube, ultimate flexural strength of the complete FCCP, and wrapping. FCCP consist of a hollow composite tube, a concrete core, and a durable coating.

Composite tubes are to be formed by means of pultrusion, filament winding, or resin infusion. The tube must have continuous fiber reinforcement which makes up 50 to 70 percent of the tube by weight. The tube must contain a minimum of 25 percent resin by weight. The resin can be vinyl ester, polyester, or epoxy resin. It must contain a ultraviolet inhibitor. FCCP must be manufactured to provide sufficient strength to withstand stresses incurred during fabrication, handling, and driving of piles; the manufacturing tolerances for the composite tube are given in Table 9. The fiberglass reinforcement for the composite tube must conform to either ASTM D2310 or ASTM D2996.

Table 9. FCCP Composite Tube Manufacturing Tolerances

Property	Tolerance
Minimum Length	+1 foot
Maximum Sweep	0.08% of total length
End out of Square	1.0% of diameter

The physical properties of the tube must meet the requirements given in Table 10. In all cases ASTM D695 is modified to be performed on the full diameter of the composite tube, and the test height is equal to 1 in. The compression tool described in ASTM D695 is not to be used; a steel plate is to be placed onto the specimen to distribute load from the test machine.

Table 10. FCCP Physical Properties

Property	12 in. OD	14 in. OD	16 in. OD	ASTM Standard
Elastic Modulus- Axial Tensile	4000 ksi	3350 ksi	2800 ksi	D2105
Elastic Modulus - Axial Compressive	2800 ksi	2350 ksi	1900 ksi	D695
Elastic Modulus - Hoop Tensile	4500 ksi	4500 ksi	4500 ksi	D1599
Strength- Axial Tensile	70 ksi	58 ksi	49 ksi	D2105
Strength- Axial Compressive	39 ksi	35 ksi	29 ksi	D695
Strength- Hoop Tensile	35 ksi	35 ksi	35 ksi	D1599
Wall Thickness	0.20 in.	0.21 in.	0.23 in.	

A grey or black ultraviolet resistant film, which is 3 mil thick, is to be applied to all portions of the composite tube exposed after installation. The ultraviolet resistance provided by the coating and the ultraviolet inhibitors included in the resin must prevent the degradation of the tube from exceeding the limits set in Table 11 when tested with either ASTMs G152, G155, G154, or B117.

Table 11. Allowable Degredation of FCCP Composite Tube

Property	Maximum Allowable Loss	ASTM Standard
Strength- Axial Tensile	10%	D2105
Strength- Axial Compressive	10%	D695
Strength- Hoop Tensile	10%	D1599
Color Film Adhesion Loss	10%	D4541

The physical and dimensional stability of all the materials used in the manufacturing of the composite tube used to create FCCP must conform to the evaluation criteria found in ASTM D696. The concrete used to fill the composite tube must be Class A as specified in NJDOT Standard Specification Section 903.3. Care must be taken so that the concrete acts composite with the composite tube. This can be accomplished by using a tube with a textured inside surface, bonding agents, or shrinkage compensated concrete. FRPP placed in clusters are to be wrapped with 5/8 in OD (1/2 in. diameter steel) polypropylene impregnated wire rope.

Texas

The state of Texas has two instances of FRP composite materials in their standard specification. Department of Materials Specification 4410 covers fiber reinforced plastic sign supports while Department of Materials Specification 4700 covers externally bonded FRP systems for repairing and strengthening concrete structure members. Table 12 gives the material requirements for sign supports.

Table 12. Texas DMS 4410 Material Requirements

Property	Requirement	ASTM Specification
Dimensions	3 in. \pm 0.025 in.	D3917
Glass Content	Must not vary by \pm 5% when a min of 5 samples are tested	D2584
Hardness	Must not vary more than 6 when a min of 5 samples are tested	D2240
Color	Yellow before and after 2000 hrs. of exposure in accordance with ASTM G155	Tex-839-B
Tensile Strength	Must not vary more than 15 ksi when a min of 5 samples are tested	F711- modified for curved specimen
Apparent Hoop Tensile Strength	Must not vary more than 25% when a min of 5 samples are tested	D2290- modified for 1/2 in. wide specimen
Density	Must not vary by \pm 0.12 when tested in a helium pycnometer	Operate pycnometer according to manufacturer specs.

The requirements for FRP materials externally bonded to concrete structures depend on whether the FRP material is used for structural member protection or strengthening. The requirements for materials used for protection are given in Table 13 and the requirements for materials used for strengthening are given in Table 14. Additional requirements are given in Table 15.

Table 13. Texas DMS 4700 Material Requirements for Structural Member Protection

Property at Room Temperature (69–73 °F)	Requirement	ASTM Specification
Ultimate tensile strength in primary fiber direction based on gross-laminate area, Min.	50 ksi	D 3039 (10 specimens)
Ultimate tensile strain, Min	1.50%	D 3039 (10 specimens)
Tensile modulus based on gross-laminate area, Min.	3000 ksi	D 3039 (10 specimens)
Glass transition temperature for FRP and bonding agent, Min.	150°F	ASTM E 1640; Coupons prepared according to ASTM D 7565 or ASTM D 4065 (5 specimens)
Fiber volume, Min.	30%	D 3171 (5 specimens)
Bond strength to substrate concrete, Min.	200 or $(0.065 \sqrt{f'c})$ psi	D 7234 (5 specimens)
Retained flexural strength, Min. (required when harsh environmental conditions are expected)	90%	C 581 (10 specimens)
Coefficient of Thermal Expansion (1×10^{-6} in./in./°F), Max	3.0	D 696 (5 specimens)

Table 14. Texas DMS 4700 Material Requirements for Structural Member Strengthening

Property at Room Temperature (69–73 °F)	Requirement	ASTM Specification
Ultimate tensile strength in primary fiber direction based on gross-laminate area, Min.	100 ksi	D 3039 (10 specimens)
Ultimate tensile strain, Min	0.85%	D 3039 (10 specimens)
Tensile modulus based on gross-laminate area, Min.	8000 ksi	D 3039 (10 specimens)
Glass transition temperature for FRP and bonding agent, Min.	150°F	ASTM E 1640; Coupons prepared according to ASTM D 7565 or ASTM D 4065 (5 specimens)
Fiber volume, Min.	30%	D 3171 (5 specimens)
Bond strength to substrate concrete, Min.	200 or $(0.065 \sqrt{f'c})$ psi	D 7234 (5 specimens)
Composite inter-laminar shear strength (required when two or more layers are used)	6.5 ksi	D 2344 (5 specimens)
Coefficient of Thermal Expansion (1×10^{-6} in./in./°F), Max	3.0	D 696 (5 specimens)

Table 15. Texas DMS 4700 Additional Material Requirements

Fibers	Allowable fiber types include carbon (graphite), glass, aramid, and other suitable fibers. The fiber must occupy 30–70% of the matrix volume in the composites.
Resins	Resins used to produce FRP should provide a matrix that is able to effectively transfer load to fibers without significant pullout before failure. Only thermoset resins are allowed, including polyesters, epoxies, vinyl esters, polyurethanes, and phenolics.
Bonding Agent	The FRP producer must provide or specify the bonding agent. Epoxies are commonly used as the bonding agent.
Design Values	The design strength and strain values are determined based on tested values and the approved methodology.
Durability	The FRP system must perform well under humid and hot field conditions and be compatible with concrete, an alkaline material. If paint compatible with the FRP system is not provided for UV protection, the producer must provide certification to demonstrate the UV degradation is minimal.

Florida

The Florida DOT has a comprehensive set of standards and guidelines for FRP composites. The Florida Standard Specification has a specific section dedicated to fender systems. Prior to 2015 Section 471 covered polymeric fender systems. This section then referenced Section 973 (Structural Plastics). This version of Section 973 matches very closely the current NJDOT standard specification section 916. The materials and requirements are almost identical. However, both Sections 471 and 973 were updated in 2015. Section 471 became Fiber Reinforced Polymer Fender Systems, and Section 973 became Fiber Reinforced Polymer (FRP) Composite Structural Shapes. The state of Florida also maintains a set of Structural Design Guidelines and a Materials Manual which are referenced in their standard specification. The Structural Design Guidelines give the design requirements for FRP fender systems, and the Materials Manual gives procedures for the development of quality control plans for the manufacture, storage, and transportation of FRP materials.

FRP Fender Systems

Section 471 of the Florida Standard Specification covers FRP Fender System. The section is broken down into 8 sections.

1. Description.
2. Materials.
3. Product Acceptance.
4. Shop Drawings and Design Calculations.
5. Design Criteria.
6. Storage Handling and Installation.
7. Methods of Measurement.
8. Basis of Payment.

The sections on Materials, Shop Drawing and Design Calculations, and Design Criteria give the details required for design and material characterization for FRP Fender Systems. All FRP composites (Piles, Wales, Spacer-blocks, and Decking & Splice Plates) must meet the requirements of Section 973 FRP Structural Shapes. FRP materials can only be obtained from producers who have a formal quality control plan based on the guidelines set forth in the Florida DOT Materials Manual (Section 121). If concrete is used to fill hollow piles, it must meet the requirements of Section 347, and only stainless steel made of SAE Type 316 can be used as connection hardware.

The design of FRP fender systems must be done in accordance with the most current version of the FDOT Structures Design Guidelines and the FDOT Detailing Manual based on the desired energy capacity rating. The specific energy absorption of the fender system must be included on the shop drawings. The flexural properties of the pile must be determined by an independent lab in accordance with ASTM D6109, and the characteristic value used for design must be determined in accordance with ASTM D7290.

Separate design criteria are given for the wales and the piles of the FRP fender systems. The wales must be continuous over two spans, and all of their hardware must be recessed. They must have sufficient creep resistance to prevent hardware from loosening and sufficient stiffness to distribute vessel impact. Hollow members must have sufficient capacity not to crush on vessel impact, and sufficient strength to prevent

bolt pull through. The whale must meet the requirements of Table 5-1 in Section 973 of the FDOT Standard Specification. The piles must also have their hardware recessed, and provide sufficient creep resistance to prevent the hardware from loosening. Hollow piles must have sufficient crushing and bolt pull through.

Design of Fender Systems

Section 3.14 of Florida DOT's Structures Manual covers the design of Fender Systems. Fender systems are navigation tools which delineate the navigable channel. They must be robust enough to survive a large number of small impacts and shapes, but also be able to absorb the kinetic energy from and redirect errant vessels. The fender must minimize the damage to vessels during minor impacts and also be able to redirect and absorbed the energy from more severe impacts. The requirement for fender systems is evaluated by Florida DOT and the U.S. Coast Guard.

Section 3.14.2 gives the design requirements for the engineer of record for the fender system. The first step in designing a fender system is the determination of the vessel traffic. If no steel hulled barges pass the point, a standard detail is specified for use. If there is barge traffic, a fender design is required; and the fender system is laid out to accommodate the proper horizontal navigation clearance. The design of the fender is based on energy absorption values determined by following the procedure as outlined in the commentary of the AASHTO "Guide Specification and Commentary for Vessel Collision Design of Highway Bridges", Second Edition, 2009, Section C3.8, and the maximum allowable deflection. The fender must not be able to deflect and come into contact with the bridge pier. It is preferred the entirety of the fender system be constructed with FRP materials. The requirements for the fender system must involve the design of all related components involving catwalks, ladders, lighting systems, clearance gages, and any accommodations required for existing utilities.

Section 3.14.3 gives the contractor's design procedures. Generally, fender systems are designed to be flexible enough to absorb impact energy. The fender system is to increase in stiffness as it approaches a bridge's piers. The increase in stiffness reduces deflection and guides vessels away from the pier. The increases in stiffness also helps

prevent vessels from snagging on the fender, and this decreases damage and associated maintenance. Abrupt changes in stiffness are to be avoided. The design criteria for FRP structural members is given in the Florida DOT Structures Manual Volume 4. If a member is determined to be non-ductile the flexural resistance, as determined by Section 471 of the Florida DOT Standard Specifications, is reduced by 20 percent. A non-ductile member is defined as a member whose ratio of ultimate displacement to yield displacement is less than 1.25.

The design of the fender system is completed using a computer program to model the piles cantilevered out of the ground. The program must model the soil using P-Y curves. It must also be capable of modeling pile-to-wale interaction. The preferred software is Florida Bridge MultiPier. The main structural members are modeled as nonlinear (it does not specify if this is material or geometric). The entire design of the whale is performed using the computer program. The minimum tip elevation of the pile is determined by applying a force which generates the ultimate moment resistance of the pile. The tip elevation is then raised until the program does not converge or the deflections become excessive. The energy absorption of the fender system is created by generating a lateral load vs. deflection curve for the system and computing the area under the curve. The system connections and splices are designed to withstand the forces generated when the lateral load vs. deflection curve was generated.

FRP Structural Shapes

Section 973 of the FDOT Standard Specification covers FRP structural shapes. It covers three specific types of FRP structural shapes: Thermoset Pultruded Structural Shapes, Vacuum Infusion Processed (VIP) Structural Shapes, and Thermoplastic Structural Shapes (TSS).

Thermoset Pultruded Shapes must meet the requirements of the American Society of Civil Engineers (ASCE), Pre-Standard for Load & Resistance Factor Design (LRFD) of Pultruded FRP Structures. They must be inspected according to ASTM D3917 for dimensional tolerances and ASTM D4385 for visual defects. When they are used on

bridge or overhead sign structures, they shall meet a flame spread index of Class B in accordance with ASTM E84 and meet the requirements of UL94 with a rating of V-1.

VIP Structural Shapes must be made from commercial grade glass fibers that conform to ASTM D578 and each structural element must contain a minimum of 40 percent (by weight) of glass fibers oriented in a minimum of two directions. The resin, fibers, and additives must all be compatible. The minimum required physical properties are given in Table 16.

Table 16. FDOT Section 973 Minimum Physical Properties of VIP FRP

Property	Requirement	ASTM Specification
Barcol Hardness	> 40	D2583
Glass Transition Temperature	> 180 F	D4065
Coefficient of Thermal Expansion	< 7.5×10^{-6} in/in/F (longitudinal)	D696
Moisture Equilibrium Content	< 2%	D570, Section 7.4

VIP FRP shapes can take the form of plates or structural shapes. The characteristic mechanical properties determined using ASTM D7290 must exceed the values in Table 17 for VIP plates and Table 18 for VIP shapes. As with pultruded FRP shapes, VIP structural shapes when used on bridge or overhead sign structures must meet a flame spread index of Class B in accordance with ASTM E84 and meet the requirements of UL94 with a rating of V-1. When impact resistance is stipulated, it must be determined with ASTM D7136.

Table 17. FDOT Section 973 Required Mechanical Properties of VIP FRP Plates

Property	Minimum Requirement	ASTM Specification
Longitudinal Tensile Strength	20,000 psi	D3039
Transverse Tensile Strength	7,000 psi	
Longitudinal Tensile Modulus	1.8×10^6 psi	
Transverse Tensile Modulus	0.7×10^6 psi	
Longitudinal Compressive Strength	24,000 psi	D6641
Transverse Compressive Strength	15,500 psi	
Longitudinal Compressive Modulus	1.8×10^6 psi	
Transverse Compressive Modulus	1×10^6 psi	
Longitudinal Flexural Strength	30,000 psi	D790
Transverse Flexural Strength	13,000 psi	
Longitudinal Flexural Modulus	1.6×10^6 psi	
Transverse Flexural Modulus	0.9×10^6 psi	
In-Plane Shear Strength	6,000 psi	D5379
In-Plane Shear Modulus	0.4×10^6 psi	
Interlaminar Shear Strength	3,500 psi	D2344

Table 18. FDOT Section 973 Required Mechanical Properties of VIP FRP Shapes

Property	Minimum Requirement	ASTM Specification
Longitudinal Tensile Strength	30,000 psi	ASTM D3039
Transverse Tensile Strength	7,000 psi	
Longitudinal Tensile Modulus	3×10^6 psi	
Transverse Tensile Modulus	0.8×10^6 psi	
Longitudinal Compressive Strength	30,000 psi	ASTM D6641
Longitudinal Compressive Modulus	3×10^6 psi	
Transverse Compressive Modulus	1×10^6 psi	
In-Plane Shear Strength	8,000 psi	ASTM D5379
In-Plane Shear Modulus	0.4×10^6 psi	ASTM D5379
Interlaminar Shear Strength	3,500 psi	ASTM D2344

Section 973 of the FDOT standard specification defines TSS as a thermoplastic matrix reinforced with chopped fiberglass filaments. A TSS can then be reinforced with continuous FRP reinforcing bars creating a Reinforced Thermoplastic Structural Shape (RTSS). These are the products referred to as FRPL and FRPP in section 916 of the NJDOT Standard Specification. The FDOT specification significantly reduces the number of requirements for these products.

TSS and RTSS are to be a mixture of recycled high, medium or low density polyethylene thermoplastic. It must be mixed with UV inhibitors, colorants, hindered amine stabilizers, antioxidants, and a minimum of 15 percent (by volume) chopped fiberglass reinforcement. RTSS must meet the requirements of Table 19. If a separate skin and core are used, they both must meet these requirements. The material surrounding the FRP reinforcing bar within 1 inch must not contain voids greater than 3/4 in. and extend no further than 2 in. along the length of the member. The member should not contain voids exceeding 1-1/4 inches in diameter, and the sum of all voids greater than 3/8 inches in diameter must not exceed 5 percent of the cross-sectional area. The required properties of TSS are given in Table 20, and the tolerances for both RTSS and TSS are given in Table 21.

Table 19. FDOT Section 973 Required Mechanical Properties of RTSS

Property	Requirement	ASTM Specification
Density	48-63 lbs/ft ³	D792
Water Absorption	2 hrs: <1.0% wt. increase 24 hrs: <3.0% wt. increase	D570
Brittleness	Brittleness temperature < minus 40°F	D746
Impact Resistance	>0.55 ft-lbs/ in	D256 Method A (Izod)
Hardness	44-75 (Shore D)	D2240
Ultraviolet	500 hrs. <10% change in Shore D Hardness	D4329 UVA
Abrasion	Weight Loss: <0.02 oz. (cycles= 10,000; wheel= CS17; Load= 2.2lbs)	D4060
Chemical Resistance	Sea Water <1.5% weight increase Gasoline <9.5% weight increase No. 2 Diesel <6.0% weight increase	D543
Tensile Properties	2,200 psi at break	D638
Compression Modulus	40 ksi, min.	D695
Static Coefficient of Friction	0.25 wet max	D1894
Screw Withdrawl	400 lbs, min	D6117

Table 20. FDOT Section 973 Required Mechanical Properties of TSS

Property	Requirement	ASTM Specification
Density	50-65 lbs/ft ³	D792
Impact Resistance	>0.55 ft-lbs/ in	D256 Method A (Izod)
Hardness	44-75 (Shore D)	D2240
Ultraviolet	500 hrs. <10% change in Shore D Hardness	ASTM D4329 UVA
Chemical Resistance	Sea Water <1.5% weight increase Gasoline <9.5% weight increase No. 2 Diesel <6.0% weight increase	ASTM D756 or D543
Tensile Properties	3,000 psi at break, min.	D638
Static Coefficient of Friction	0.25 wet max	D2394
Nail Withdrawl	250 lbs, min	D6117
Screw Withdrawl	400 lbs, min	
Secant Modulus at 1% Strain	150,000 psi, min	D6109
Flexural Strength	2,500 psi, min.	
Compressive Strength	2,200 psi, min	D6108
Compressive Strength Perpendicular to grain	700 psi	

Table 21. FDOT Section 973 Tolerances for RTSS and TSS

Dimensions	Tolerance
Length	0/+6 inch
Width- RTSS	±1/2 in
Width- TSS	±1/4 in
Width- RTSS	±1/2 in
Width- TSS	±1/4 in
Clear cover from outer surface to rebar element (RTSS)	≥ 3/4 in(wales) ±1/2 in (other)
Straightness (while lying on flat surface)	< 1-1/2 in per 10 ft

Fiber Reinforced Polymer Guidelines

Volume four of the Florida DOT Structures Manual contains Fiber Reinforced Polymer Guidelines. The guidelines delineate six different types of FRP. Those being:

1. Glass Fiber Reinforced Polymer (GFRP) and Carbon Fiber Reinforced Polymer (CFRP) Reinforcing Bars.
2. Carbon Fiber Reinforced Polymer (CFRP) Strands.
3. Carbon Fiber Reinforced Polymer (CFRP) Structural Strengthening.
4. Thermoset Pultruded Structural Shapes.
5. Vacuum Infusion Process (VIP) Structural Shapes.
6. Thermoplastic Structural Shapes.

A specific section is dedicated to each type of material; and permitted uses, design criteria, and additional guidance for the use of each type of material are given.

GFRP and CFRP bar are permitted to be used in approach slabs, bridge decks and deck overlays, cast-in-place flat slab substructures, pile bent caps (if not in contact with water), retaining walls, noise walls, perimeter walls, pedestrian railings, bulkheads and bulkhead copings, MSE wall panels, MSE wall coping, drainage structures, and concrete sheet piles when approved by State Structures Design Engineer. Concrete members designed with FRP bars and prestressing are to be designed with American Concrete Institute (ACI) 440.1 and 440.4 respectively. All bridge decks containing FRP reinforcing bars are to be designed in accordance with the AASHTO LRFD Guide Specifications for GFRP-Reinforced Concrete Bridge Decks and Traffic Railings.

Square and sheet piles prestressed using CFRP strands have been created as part of Florida DOT Developmental Standards D2260 and D22440 respectively. Design of concrete members using CFRP strands are to be performed using ACI 440.4.

When approved, CFRP can be externally bonded for strengthening and repairs. The design of the CFRP systems should follow the AASHTO Guide Specifications for Design of Bonded FRP systems for Repair and Strengthening of Concrete Bridge Elements.

Thermoset pultruded structural shapes are approved for use in bridge fender systems and stay in place formwork for bridge decks. They may be considered for use as pedestrian bridges, sign supports, light poles, sheet piles and other miscellaneous structures. Concrete filled tubes can be considered for use as arch beams for bridge culverts. Bridge culverts are to be designed following the AASHTO LRFD Guide Specifications for the Design of Concrete-Filled FRP Tubes for Flexural and Axial Members. The design of pedestrian bridges must follow the AASHTO Guide Specifications for Design of FRP Pedestrian Bridges. All other structures are to be designed in accordance with the ASCE Pre-Standard for Load & Resistance Factor Design of Pultruded Fiber Reinforced Polymer Structures.

The use of VIP structural shapes is permitted for bridge fenders. They may also be considered for pedestrian bridges, sign supports, light poles, sheet piles, stay-in-place formwork, and tubes for bridge culverts (when filled with concrete). Bridge culverts are to be designed following the AASHTO LRFD Guide Specifications for the Design of Concrete-Filled FRP Tubes for Flexural and Axial Members. All other structures are to be designed in accordance with the ASCE Pre-Standard for Load & Resistance Factor Design of Pultruded Fiber Reinforced Polymer Structures.

Select Nation Material Specifications for FRP Composites

There are many national standards for composite materials targeted at different industries and markets. The specifications which are most germane to the materials being investigated are AASHTO MP 22-13: Standard Specification for Fiber Reinforced Composite Materials for Bridge Structures, ASTM D7258: Standard Specification for Polymeric Piles, the AASHTO LRFD Guide Specification for the Design of Concrete-Filled FRP Tubes, and the ASCE Pre-Standard for Load & Resistance Factor Design (LRFD) of Pultruded Fiber Reinforced Polymer (FRP) Structures.

AASHTO MP22-13

MP22-13 covers the requirements for FRP composites used in bridge or highway structures. The specification requires that the components of the FRP product be fully described as well as the quality control procedures used. The specification requires the

characteristic values, calculated with ASTM D7290, of the material properties meet the requirements in Table 22.

Table 22. AASHTO MP22-13 Required Material Properties

Property	Requirement	ASTM
Glass Transition Temperature	40° higher than the maximum design temp defined in the AASHTO Specifications	E1640
Tensile Failure Strain	> 1%	D3039
Moisture Equilibrium	< 2% <10%	D5229 D5229 M

When the composite is conditioned in the environments given in Table 23, the glass transition temperature and ultimate strain must retain 85 percent of their characteristic value. The environments were developed by Steckel et al. (1999a, 1999b), and Hawkins et al. (1999), under the sponsorship of the California Department of Transportation (Caltrans).

Table 23. AASHTO MP22-13 Conditioning Environments

Environment	Requirements	ASTM
Distilled Water	3000 hours at 100 ± 3°F	
Alternating UV Light and Condensation	3000 hours	G154-06
Alkali	3000 hours at 73 ± 3°F in a calcium hydroxide solution (pH~12)	
Freeze-thaw	3000 cycles	T161

ASTM D7258

This is the only national/international standard specification that claims to be applicable to polymer composite pile systems of round and rectangular cross-sections. Section 11 of this standard specification stipulates the approach for calculating values of allowable flexural, shear, and bearing (parallel to the extrusion direction) stresses. Careful examination of this standard specification reveals many technical flaws that can jeopardize the safety of some polymer composite pile systems. A few major weaknesses of ASTM D7258 are highlighted below:

1- The base allowable flexural stress value in ASTM D7258 is defined as the product of an unadjusted flexural stress multiplied by factors that account for time, temperature, and stability. The unadjusted flexural stress is obtained from results of tests conducted in accordance with ASTM D6109 (2013) where the flexural stress is computed from an equation applicable only to a solid rectangular isotropic cross section. Of great importance, however, is that the scope of ASTM D6109 stipulates that “Flexural strength cannot be determined for those products that do not break or that do not fail in the extreme outer fiber.” Such a limitation excludes many commercially available polymer composite systems, for which tests have shown a wide range of failure modes other than that controlled by breakage at the extreme outer fiber. Evidence of these failure modes are addressed in Fam and Rizkalla (2002), Polyzois et al. (1998), Mirmiran et al. (2000), and Zureick and Kim (2002).

2- The stability adjustment factor defined in Article 11.7.3.1 of ASTM D7258 is written such that the flexural and shear rigidity terms are the products of material modulus values (e.g. apparent modulus of elasticity, shear modulus) and cross-sectional geometrical properties (moment of inertia, area of cross section). This approach is inapplicable to piles made of multiple materials and requires modifications if applied to anisotropic polymer composite piles. Furthermore, Section 11 of ASTM D7258 defines the shear modulus as that determined from tests performed in accordance with ASTM D2344 (2013), which is a test for determining only the short-beam shear strength of polymer composite materials.

AASHTO LRFD Guide Specification for the Design of Concrete-Filled FRP Tubes

In this Guide, values of the flexural and axial strength are calculated in accordance with Articles 2.9.5.1 and 2.10, respectively. The computation of these strength values depends upon tensile material properties. The methods used to determine these values are specified in Section 3 of the Guide. These provisions stipulate that, “The ultimate tensile strain shall be derived from specimens tested in accordance with ASTM D3039, or other tension test methods designed to determine tensile properties of composite laminates at the frequency and number specified in Article 3.8.1.” It should be noted that

tensile test specimens conforming to ASTM D3039 cannot be excised from circular polymer composite tubes, and thus the test is inapplicable to these types of systems.

ASCE Pre-Standard for Load & Resistance Factor Design (LRFD) of Pultruded Fiber Reinforced Polymer (FRP) Structures

This ASCE document represents the technical background information upon which future ASCE standard design provisions of pultruded fiber-reinforced polymer structures will be based. No guidelines are given for the determination of the flexural and shear strength of circular tubes. The document gives explicit equations for the axial strength of circular pultruded tubes, but it provides no guidance as to how to determine moduli values for these tubes. In situations like this, where limited experimental data is available, the strength of a structural member can be determined in accordance with Article 2.3.2. The structural performance is determined by laboratory testing approved by the Engineer of Record.

Conclusion from Review of Standards

Each DOT has slightly different terminology and standard tests for FRP materials. The state with a specification closest to New Jersey's current specification was Florida. Florida in addition to their standard material specification, maintains a structures manual and a material specification. These three documents work together to form all of the specifications on FRP. In Florida the design engineer specifies a required energy absorption and maximum allowable deflection. The contractor is then responsible for providing a fender system which meets these requirements.

The Florida DOT Specification, the ASCE Pre-standard for Pultruded Sections, and AASHTO MP22-13 implement ASTM D7290 to define the characteristic value for the material properties. The characteristic value is a statistically-based material property representing the 80 percent confidence bound on the 5th-percentile value of a specified population (ASTM D7290). The characteristic value is a way to set nominal values for composite materials (Zureick et al., 2006); it allows for acceptance and qualification criteria to be set for different products. The AASHTO Guide Specification for Concrete-filled FRP Tubes has minimum requirements for glass transition temperature, but no

other minimum requirements. The remaining specifications are all based on minimum values.

The NJDOT, Florida, and Texas Specifications as well as the ASCE Pre-standard for pultruded shapes have minimum values for the majority of the properties of the composites. If there is no solid engineering purpose for these minimum values, they merely serve as baselines or targets. They serve to limit the range of products that can be used, and subsequently limit the market. Notably missing from AASHTO MP22-12 are strength requirements for the composite materials. There are only requirements for glass transition temperature and ultimate strain. The limits for glass transition are given so that the composite material can function in the specified environment, and the minimum strain value is employed to ensure a base level of ductility. The strength requirements are left to the engineer of record; the design requirements dictate the strength.

In theory, the strength of polymer composite piles can be estimated using available national guidelines and standards, but close examinations of these documents revealed various limitations and difficulties in properly assessing the strength of these unique systems. The only acceptable way to determine strength parameters for all of the available products is through laboratory testing of full-scale members.

Consulting Engineering Review of NJDOT Specifications

In their Memorandum dated 12/10/15, Hardesty and Hanover presented a review of the NJDOT Standard Specification Section 916.01. This review relates to the issues encountered in the design practice of structures utilizing FCM. The results of the review are:

- The current specification is based on proprietary products marketed by limited manufacturers which has encouraged high bids from material suppliers.
- The proprietary nature prevents products manufactured in different ways with equal properties from being used which adversely effects value engineered projects.

- The standard specification dictates a general set of material parameters which exist independent of the project requirements.
- The current standard rejects the majority of FRP pile products on the market today.
- The current specification does not include requirements for shear modulus, Young's modulus, and Poisson's ratio which are used in the P-y analysis for lateral deflection of fender and dolphin systems.
- The current specification does not define maximum allowable stress parameters to use when evaluating drivability of FCM piles pile drivability.
- Current specification do not ensure integrity of the FCM piles which are often compromised by impact and vibratory hammers that are best suited for driving conventional piles.
- Sheet piling is not included in the specification.

A complete memorandum is included in Appendix A.

In their memorandum dated 7/26/16 Hardesty and Hanover (H&H) has presented the results of their investigation of various FCM piles currently available on the market with the purpose of identifying those (if any) which are not meeting requirements for use in fender and dolphin structures. The investigation considered products included in the current specification as well as additional products available on the market.

Load-displacement curve was identified as the governing factor in the process of assessing the adequacy of the design. It was stated that load-displacement curve depends on soil resistance defined through P-Y curves, and structural stiffness defined through pile-to-wale connection. Only structural stiffness is impacted by the fabrication method and/or material composition of FCM piles. H&H conducted soil-structure analysis which varied structural properties of readily available FCM piles in order to meet desirable load-deflection curve characteristics. The results showed that all products considered in the study are viable options, and that various pile group configurations can be designed to meet project criteria. A complete memorandum is included in Appendix B.

CRITICAL PROPERTIES

Based on the review of the AASHTO specifications the structural properties shown in Table 24 are required for design.

Table 24. Required Structural Properties for Pile Design

Property
Flexural Stiffness
Flexural Capacity (Strength/ Stability)
Axial Stiffness
Axial Capacity (Strength/ Stability)
Specific Weight

For common civil engineering materials (i.e. steel, concrete, and timber), structural properties are based on geometry and materials properties developed from coupon testing. Due to the size and nature of the products being produced, it is currently not possible to follow this model. Material testing procedures are not available for thermoset tubes with circular cross-sections. While the individual material components of reinforced thermoplastic piles can be characterized at a component level, the interaction between thermoplastic and its reinforcement is not well understood. The only type of member whose structural properties could be developed from component level materials testing is a FRP tube with a polygonal cross-section. All of the structural properties for the other polymer based piles must come from testing of full sections and specimen.

Lack of coupon level materials tests not only effects the determination of structural properties, but also degradation and acceptance testing. The products currently being produced and marketed as pile materials are historically large. Full-scale testing of these products is difficult and expensive. There are a limited number of facilities capable of testing a full pile in flexure. The amount of force required to induce axial failure in these products, in tension or compression, well exceeds 1 million pounds. The amount of force also limits the facilities capable of performing the testing. This makes full-scale testing infeasible for acceptance on every project. Degradation testing of large

components also poses a challenge. The larger the test specimen, the larger the environment needed to degrade the specimen.

Existing standard coupon level materials test exist for all products except thermoset tubes with circular cross-section. Existing ASTM standard test methods addressing the mechanical properties of polymer and reinforced polymer composite plastic circular tubes or pipes can be classified into two groups and are given in Table 25.

Table 25. ASTM Standard Tests for Mechanical Properties of Polymer and Reinforced Polymer Composite Circular Tubes

Group I	Group II
ASTM D3039	ASTM D695
ASTM D638	ASTM D1599
ASTM D5083	ASTM D2105
ASTM D3410/D3410M	ASTM D2412
ASTM D3846	ASTM D2290
ASTM D6641/D6641M	ASTM D2344
ASTM D5379/D5379M	ASTM D5448/D5448M
ASTM D3518/D3518M	ASTM D5449/D5449M
	ASTM D5450

Group I tests are conducted on flat coupons, and thus, are most appropriate during the design and selection of fiber architecture prior to fabrication. Depending upon the manufacturing process, the mechanical properties of the as-manufactured tubular members will inevitably have various degrees of differences from those properties determined from flat coupons before manufacturing.

Group II tests all have specific purposes and limitations. They each serve their purpose, but are not sufficient for performing a comprehensive structural analysis or design. A major restriction on many of these standards is the size of the component. For example, ASTM D695 can only be applied to tubes less than 2 in. in diameter without machining. ASTM D2105 test method is intended for determining the longitudinal tensile properties of glass-fiber reinforced thermoset-resin pipes and tubes having diameters only smaller than or equal to 6 in. ASTM D2344 is only applicable to materials less than or equal to 0.25 in. thick. ASTM D2412 is used for comparing different polymer composite pipe and circular tube components by establishing the load-deflection characteristic of pipe pieces compressed between two rigid flat plates. For a nominal pipe diameter less than

or equal 60 in., the length of the test pieces is specified to be 6 in. For the case of thermoplastic materials the length is set at three times the pipe diameter or 12 in.. For a nominal pipe diameter larger than 60 in., the length of the test pieces shall be a minimum of 20 percent of the pipe nominal diameter. Finally, ASTM D5448/D5448M , ASTM D5449/D5449M ,and ASTM D5450 test methods are intended for determining the inplane shear properties, the transverse compressive properties, and transverse tensile properties, respectively. The test specimen diameter and length in such tests are limited to 4 in. and 5.5 in., respectively. ASTM D1599 requires pressurizing the tubes until failure. For tubes with large diameters and wall thicknesses, this can require a great deal of energy, and safety is a concern. ASTM D2290 is developed for determining only the apparent hoop tensile strength of unreinforced and reinforced plastic pipes. While the most salient advantage of this test method comes from its versatility to accommodate pipes of any diameter, its manageable drawback is evident due to the necessity to fabricate, for each pipe diameter, split-disk test fixtures that fit properly within the inner surface of the pipe ring specimens.

Based on the above brief summaries, it is clear that a standardized test method for determining the engineering properties of fiber-reinforced polymer composite pipes and circular tubes is required for product qualification and acceptance. To overcome the lack of coupon level test methods for circular tubing members of any diameter, the Ring test and the Arch test were developed. These testes are used to determine an apparent transverse modulus. The arch test is also conceptualized to determine an apparent flexural strength.

DEVELOPMENT OF NEW STANDARD TESTS FOR CIRCULAR COMPOSITE TUBES

Two new standard tests were developed, namely the Ring Test and the Arch Test. The tests are intended to determine apparent transverse flexural properties for circular tubes. The properties are considered to be apparent due to the fact that the analysis is based on isotropic material properties. The validation process involved three steps:

- 1) Development of a test fixture.
- 2) Mechanical analysis of the specimen.
- 3) Validation against materials with measurable properties.

Common materials were used to validate both tests.

Validation Materials

The validation of the new test methods was performed on materials whose properties could be determined through existing methods. These materials were 6061-T651 aluminum, AISI 1026 steel, and carbon composite created through hand lay-up. Two metallic tubes, steel and aluminum, with nominal outside diameters of 12 in. and nominal wall thicknesses of 0.25 in. were obtained. Rings with a nominal width of 1 in. were cut from the tube, and several of these rings were further reduced into arcs. Three longitudinal pieces were cut from each tube, and each of the pieces was then machined flat. Care was taken to minimize the amount of heat produced when machining. The flat rectangular bars were then machined into 0.5 in. wide standard sheet-type specimen in accordance with ASTM E8. The rings, arcs, and tension test specimen are shown in Figure 6a. Tension tests were then performed in accordance with ASTM E8. The average elastic modulus and average yield stress for the steel and aluminum specimens are given in Figure 7a and Figure 7b, respectively.



a) Steel and aluminum tubing



b) Carbon Composite

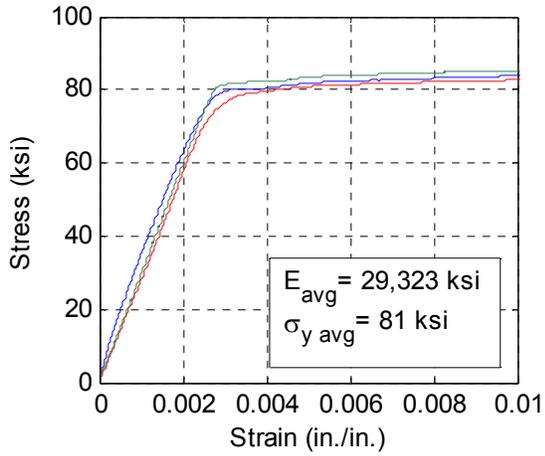
Figure 6. Validation materials

Composite rings and coupons were created through hand lay-up. The composite was created using one-inch-wide unidirectional carbon fiber fabric, and the fabric was impregnated with two-part epoxy. The rings were created on a circular aluminum mold with a 11 in. diameter. Figure 6b shows the rings and coupons. The coupons were tested in accordance with ASTM D3039, and the average elastic modulus and average ultimate stress are given in Figure 7c.

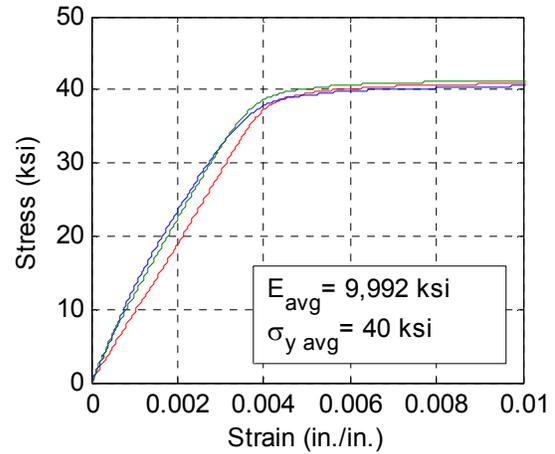
Both of the proposed tests are intended to determine an apparent flexural modulus. For comparison, flexural tests were performed on each material. A point load was applied at mid-span of each simply supported coupon. Table 26 gives the coupon dimensions and the test results. Figure 8 gives the load deflection behavior. The properties used for validation are summarized in Table 27.

Table 26. Dimensions of Flexural Test Coupons and Test Results

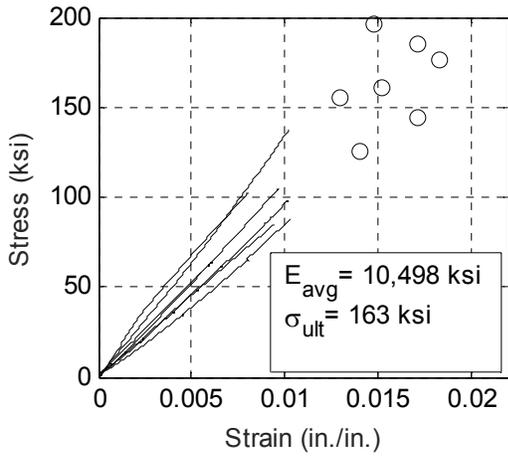
Specimen	Length (in.)	width (in.)	thickness (in.)	Slope (lb/in)	E (ksi)
FA	6.67	0.9659	0.1969	1088.1	10,947
FS	6.67	0.9696	0.1989	3176.4	30,885
FC1	6.67	1.118	0.03705	7.6	9912
FC2	6.67	1.278	0.042038462	8.76	7758
FC3	6.67	1.119	0.035038462	6.497	10017
FC4	6.67	1.158	0.043538462	10.77	8358



a) Steel tension test results



b) Aluminum tension test results

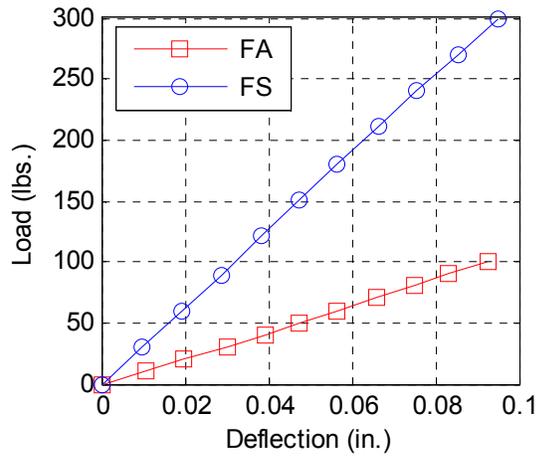


c) Carbon composite tension test results

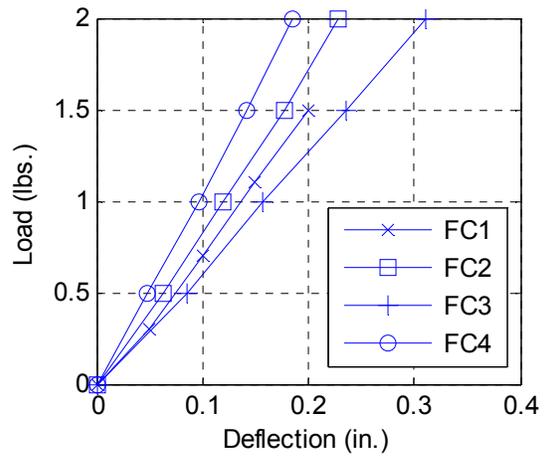
Figure 7. Tension test results

Table 27. Validation Material Properties

Material	E_{Tension} (ksi)	E_{Flexure} (ksi)	$\sigma_{\text{y or ult.}}$ (ksi)
Steel	29,323	30,855	81
Aluminum	9,992	10,947	40
Carbon Composite	10,498	9,011	163



a) Metallic specimen



b) Composite specimen

Figure 8. Load-deflection behavior of flexural coupons

Ring Test

This test method is intended to determine an apparent transverse modulus by testing a ring cut from a circular tube.

Development of Test Fixture

The ring test fixture is intended to be as simple as possible. The ring is held between two pins and tension is applied to the ring. The test apparatus and a ring fixture in a universal testing machine are shown in Figure 9.

Mechanical Analysis

To obtain the transverse properties, the ring is modeled as a circular frame in tension. Figure 10 shows the structural analysis model of the ring and the moment diagram. From Figure 10b, it can be seen that the moment diagram has two lines of symmetry, one vertical and one horizontal. The orientation of the moment on a quarter of the ring is shown in Figure 11, and the moment across this portion of the ring is given in Equation 4.

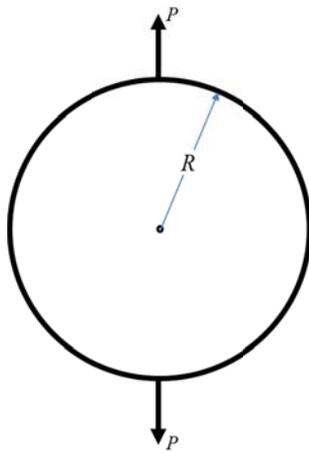


a) Test apparatus

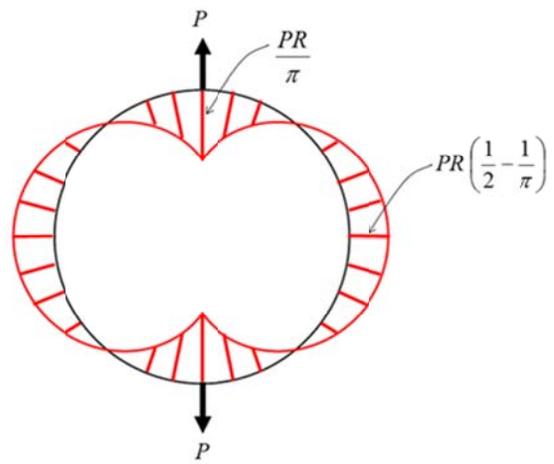


b) Ring fixture in universal testing machine

Figure 9. Ring test



a) Circular frame



b) Moment diagram

Figure 10. Structural models of the ring test

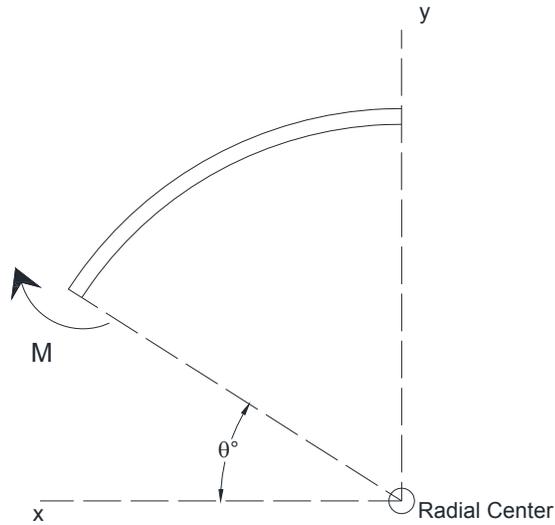


Figure 11. Moment in quarter of ring

$$M = PR \left(\frac{1}{2} \cos(\theta) - \frac{1}{\pi} \right) \quad \text{Equation 4}$$

where

P = magnitude of the applied forces

R = radius to the centroid of the cross-section

θ = angle from x-axis

Under defined tension forces of magnitude P , the change in the ring diameter in the direction of the force is given by Equation 5. This relationship can be derived using the equation for moment and any energy based structural analysis method.

$$\delta_p = 0.148 \frac{PR^3}{EI} \quad \text{Equation 5}$$

where

P = magnitude of the applied forces

R = radius to the centroid of the cross-section

δ_p = diameter change resulting from applied forces P

E = circumferential apparent elastic modulus of the ring

I = moment of inertia of the ring cross section

From Equation 5, the modulus of elasticity at any given load can be determined from Equation 6.

$$E = 0.148 \frac{PR^3}{\delta_p I} \quad \text{Equation 6}$$

where

P = magnitude of the applied forces

R = radius to the centroid of the cross-section

δ_p = diameter change resulting from applied forces P

E = circumferential apparent elastic modulus of the ring

I = moment of inertia of the ring cross section

Furthermore, if a series of linear load-deflection points are known, the circumferential elastic modulus can be based on the slope (m) of the line (Equation 7).

$$E = 0.148 \frac{mR^3}{I} \quad \text{Equation 7}$$

where:

m = slope of linear load-deflection data

R = radius to the centroid of the cross-section

E = circumferential apparent elastic modulus of the ring

I = moment of inertia of the ring cross section

Measurement of Rings

Before testing could be completed, a method for measuring the geometry of the rings was required. The most challenging part of the process was determining the diameter/ radius of the rings. Prior to testing, the diameter, width, and thickness of each ring were measured as follows:

- 1) A mark, labeled Point A, was placed on an arbitrary location on the ring circumference.
- 2) The inner circumference of the ring was then traced on a drafting paper and the mark, labeled A, was also noted on the traced circumference as shown in Figure 12a.

3) The corner of right-angle triangle or a carpenter square drafting tool was placed at Point A and two additional marks, A' and B, were made at the intersecting points of the drafting tool and the traced circumference (Figure 12b).

4) Using the drafting tool with its corner placed at B and with one of its sides coinciding with line segment A-B, the intersection of the drafting tool and the other side of the traced circumference was marked as B' (Figure 12c).

5) The center of the circle was then located by intersecting the two line segments A-A' and B-B' (Figure 12d).

6) Using a protractor, the circle was then divided into twenty-four, 15°, arc-length segments and twelve diameters were measured (Figure 12d).

7) The ring width and thickness were measured at 30-degree increments from Point A, resulting in 12 measurements.

The mean values corresponding to the diameter, width, and thickness of each test ring are presented in Table 28.

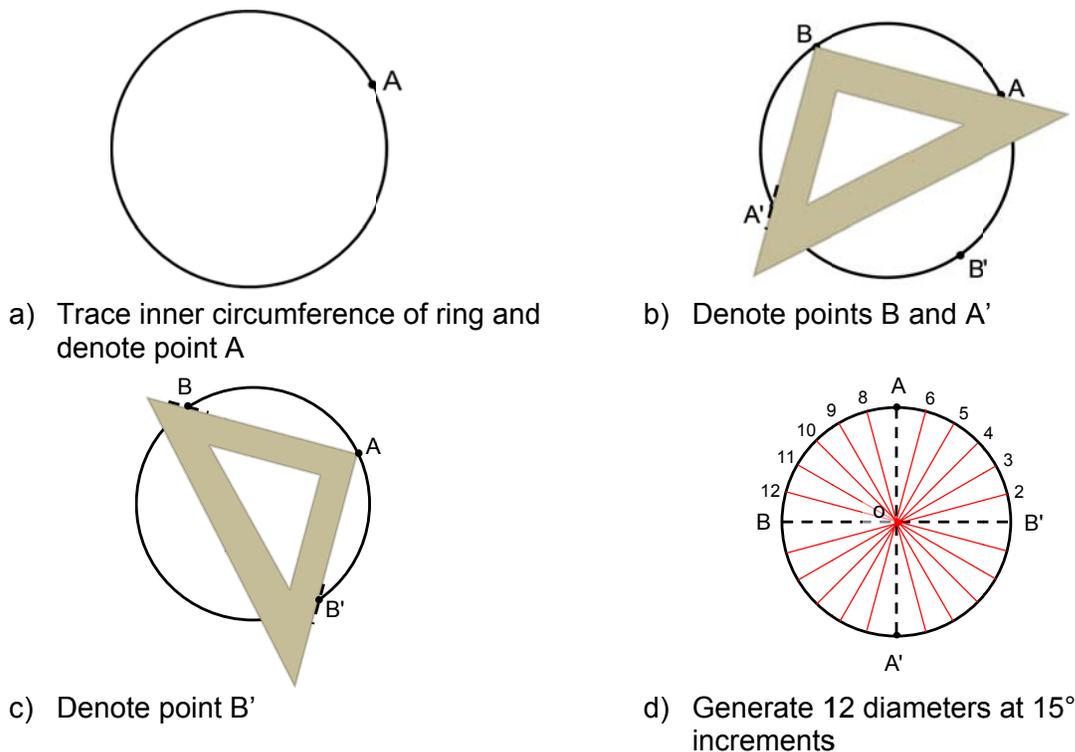


Figure 12. Measurement of rings

Table 28. Ring Specimen Geometry

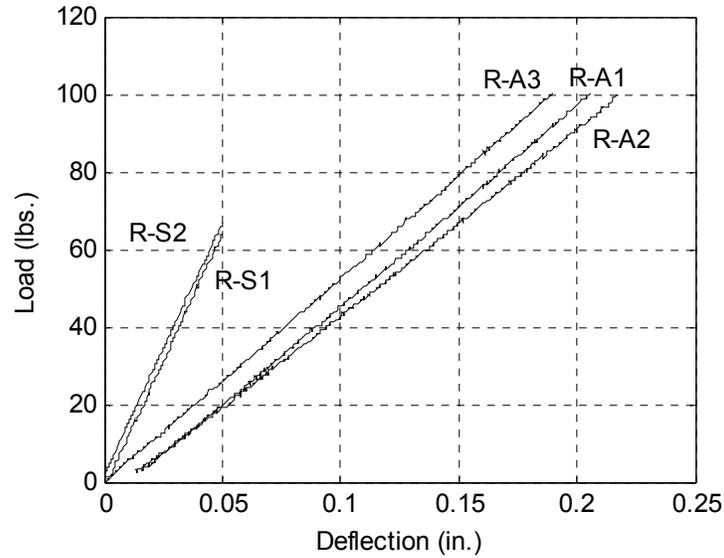
Material	Ring Test ID	Inside Radius in.	Width in.	Thickness in.
Steel (AISI 1026)	R-S1	5.745	1.109	0.2456
	R-S2	5.741	1.064	0.2460
Aluminum (6061-T651)	R-A1	5.743	1.037	0.256
	R-A2	5.732	1.175	0.256
	R-A3	5.744	1.168	0.256
Carbon Fiber-Reinforced Polymer Hand Lay-up	R-C1	5.537	1.183	0.043
	R-C2	5.511	1.194	0.042
	R-C3	5.506	1.193	0.043
	R-C4	5.544	1.182	0.043
	R-C5	5.484	1.167	0.036

Validation Testing and Results

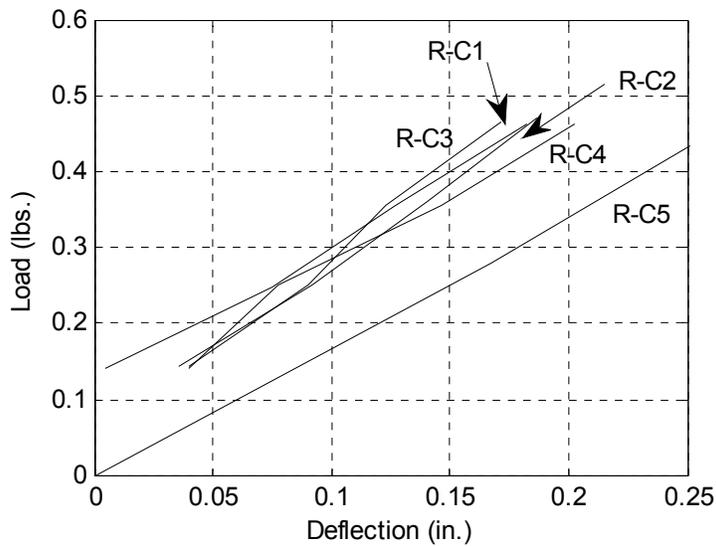
The load-deflection plots for the rings tested are given in Figure 13. The slopes of the lines shown in Figure 13 are given in Table 29. Using Equation 7, the slope is used to determine the modulus. This apparent modulus is then compared to the moduli, both tension and flexural, for the validation materials. The average ratios of the modulus determined through the ring test to the tension modulus and flexural modulus are 0.926 and 0.964 respectively.

Table 29. Results of Ring Test Validation

Material	Ring Test ID	Slope	E_{Ring}	$E_{Tension}$	E_{Flex}	$\frac{E_{Ring}}{E_{Tension}}$	$\frac{E_{Ring}}{E_{Flex}}$
		(lb/in.)	(ksi)	(ksi)	(ksi)		
Steel (AISI 1026)	R-S1	1320.1	28,821	29,323	30,885	0.98	0.93
	R-S2	1311.1	29,656	29,323	30,885	1.01	0.96
Aluminum 6061-T651	R-A1	476.0	9,834	9,992	10,947	0.98	0.90
	R-A2	512.3	9,288	9,992	10,947	0.93	0.85
	R-A3	528.4	9,369	9,992	10,947	0.94	0.86
Carbon Fiber-Reinforced Polymer Hand Lay-up	R-C1	2.667	8,545	10,498	9,011	0.81	0.95
	R-C2	2.769	8,991	10,498	9,011	0.86	1.00
	R-C3	2.764	8,676	10,498	9,011	0.83	0.96
	R-C4	2.638	8,673	10,498	9,011	0.83	0.96
	R-C5	2.022	11,466	10,498	9,011	1.09	1.27



a) Metallic ring results



b) Carbon composite ring results

Figure 13. Load -deflection plots from ring tests

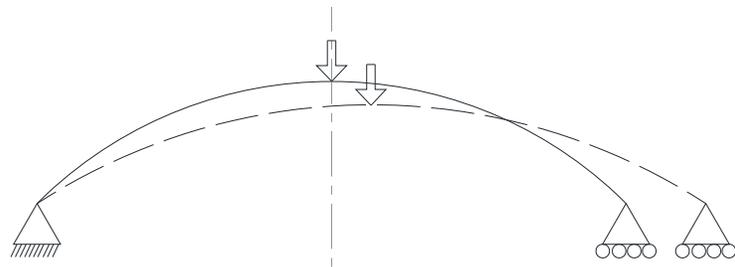
Arch Test

This test method is intended for determining an apparent transverse flexural modulus and an apparent transverse flexural strength for circular composite tubes. One-third of the tubes cross-section is tested in a mechanism consisting of four rollers.

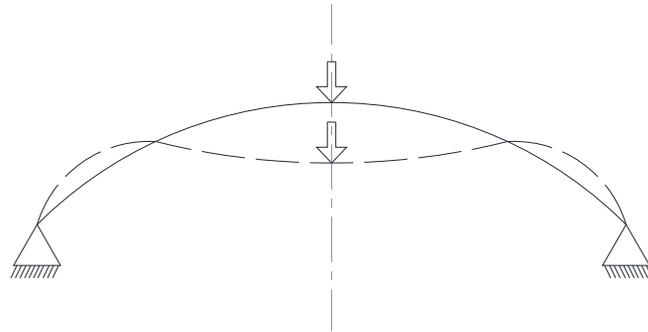
Development of Test Fixture

The development of the test method began with the evaluation of an arch. The main difference that distinguishes the deformation of an arch from a beam is that while a beam loaded transversely to its longitudinal axis experiences mostly vertical deformation, an arch loaded transversely experiences significant vertical and horizontal deformation. As with any beam or structure, the boundary conditions have a large influence on the behavior. Figure 14 shows the deformed shapes of arches with different boundary conditions.

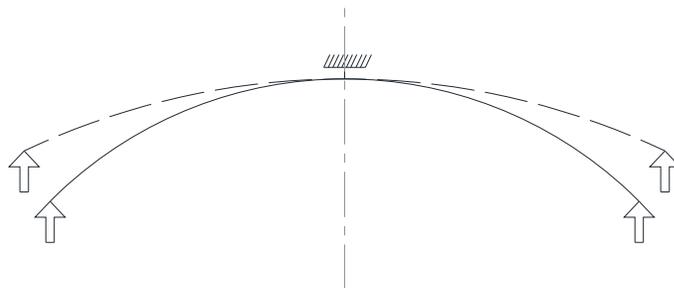
When considering boundary conditions for a flexural test simple supports are usually first to be considered (Figure 14a). They make the evaluation of forces a matter of only statics. The difficulty with using simple supports with an arch is the amount of lateral movement the arch experiences. The center of the arch wants to move away from the pinned connection. In order to fix a load at one location on the arch, the load would have to move with the arch. To prevent the lateral movement of the arch, a second pin support can be implemented (Figure 14b). The addition of the second pin prevents horizontal movement of the arch, but, in doing so, it induces increased axial force in the arch. Axial force combined with flexure leads to buckling. Buckling is an undesirable failure mode when attempting to determine a material strength parameter. Figure 14c shows an arch supported by a fixed support in the center. In this case, the arch is statically determinate, and a simple analysis of the reaction forces shows that the fixed support only provides a vertical reaction. The fixed support could be replaced with a roller as seen in Figure 15. This arch is no longer statically determinate; it is a mechanism. The mechanism is in a state of unstable equilibrium as long as the loads are applied symmetrically.



a) Simply supported arch



b) Pin-pin arch



c) Fixed support at center

Figure 14. Deformation of arches

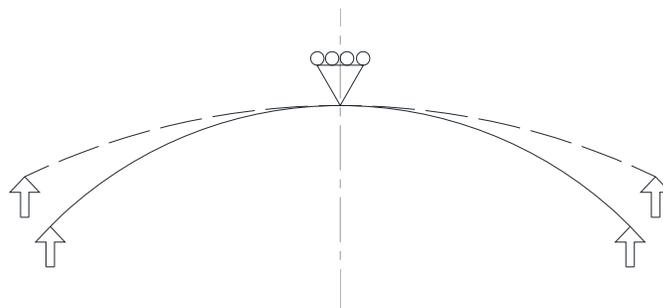


Figure 15. Arch mechanism

The mechanism shown in Figure 15 has a maximum moment located directly below the roller support. This maximum moment is due to the location of the loads and boundary conditions as well as the shape of the arch itself. In the real world the point of support induces stress concentrations due to bearing, and this can complicate strength calculations. If two roller supports are spaced symmetrically, as shown in Figure 16, a maximum moment is developed at the highest point of the arch located midway between the two roller supports. Also, the addition of the second roller only makes the system unstable in the horizontal direction. As long as no horizontal force is applied, the system will remain in unstable equilibrium.

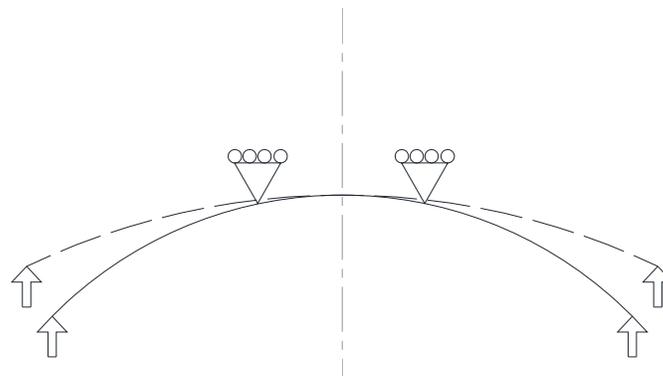


Figure 16. Arch mechanism with two roller supports

In materials testing, it is rare to apply individual loads; most loads are applied through a testing machine which accomplishes loading through the movement of the supports as shown in Figure 17. In the vertical direction the load-deflection behavior of the arch mechanism is nonlinear due to changes in its geometry. The roller supports at the top are able to move horizontally, and on the bottom the roller supports move in both the vertical and horizontal directions. The system will remain in unstable equilibrium if the loading does not apply a horizontal force.

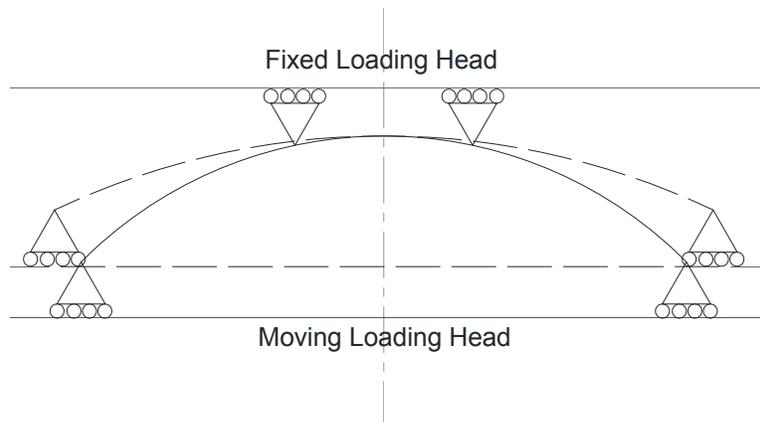


Figure 17. Arch in testing machine

The geometric nonlinearity can be reduced if the arch is allowed to move independently over a roller system as shown in Figure 18. In this case, the changes in the horizontal distance of the supports are strictly a function of the change in the angle of interaction between the arch and the rollers. Again, the mechanism is in a state of unstable equilibrium, but now the mechanism cannot resist moments about the radial center of the arch.

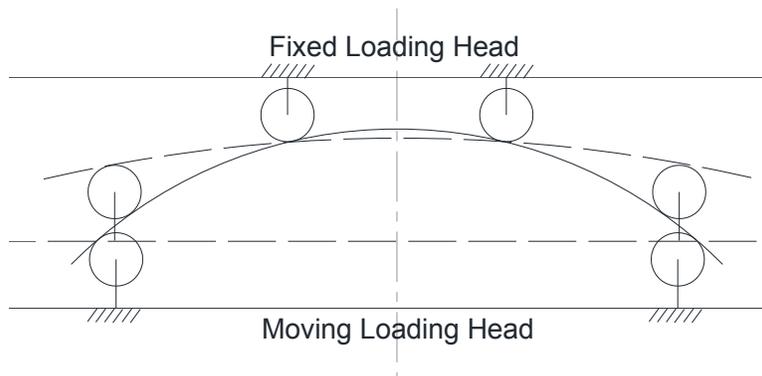


Figure 18. Arch in testing machine supported over rollers

Figure 19 shows the free-body diagram for the arch symmetrically supported by rollers. If rolling friction is minimized, a roller can only provide force perpendicular to a contact surface, and the force acts radially from the center of the roller. As long as symmetry is

held, the arch section will remain in unstable equilibrium no matter what the deformed shape. If a load P is applied vertically to the system, symmetry dictates that the vertical force in each roller be equal to $P/2$. Since the rollers do not interact with the arch at 90° , a horizontal force is developed. This horizontal force is transferred to the rollers supports, and is ultimately cancelled out in the base plate supporting the roller system.

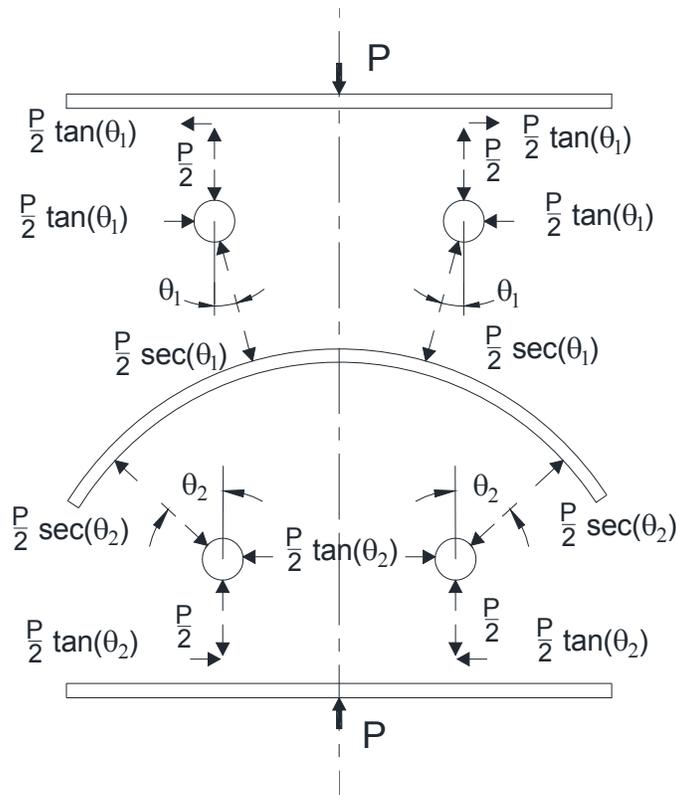


Figure 19. Free-body diagram of arch with roller supports

Mechanical Analysis

The arch supported by rollers creates a unique mechanism. While by definition the mechanism is unstable because it cannot resist moments about the radial center of the arch, the rollers are not capable of producing this moment. The test is intended to be used for specimens taken from circular cross sections; this creates arches with circular geometry. Rollers by definition are also circular. Forces from rollers act directly from the rollers center to a contact point. The force always acts at a right angle to the tangent of

the contact point. By the definition of a circle the radius of the circle must be at a right angle to the tangent taken to any point on the circle. This geometric relationship is shown in Figure 20.

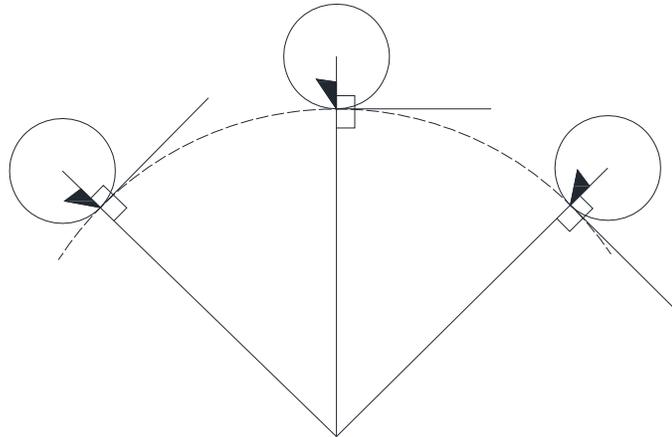


Figure 20. Geometric relationship between rollers and arch

In its initial condition the arch will have circular geometry. Work will then be done to the system changing the total energy of the system. The relationship between work and the total energy of the system is given in Equation 8. Since the arch is a mechanism it can experience changes in both Kinetic Energy (KE) and Potential Energy (PE), but since the roller supports cannot produce moments about the radial center of the arch, the mechanism cannot be activated. If the mechanism is not activated there cannot be a change in kinetic energy. The work done on the initial system can only produce a change in potential energy. The initial energy must be stored elastically in the arch. The arch needs to deform before any other part of the system consumes energy (friction, roller movement, etc.). Therefore, an energy analysis can be used to determine the initial stiffness of the arch.

$$Work = \Delta KE + \Delta PE$$

Equation 8

where

ΔKE = change in kinetic energy

ΔPE = change in potential energy

The mechanics of the Arc Test are based off of the flexure of curved beams. Curved beams differ from standard flat beams in the fact that instead of the major stress acting

along the longitudinal axis, it acts circumferentially along the curve. The deformation of curved beams can be evaluated using energy methods (Boresi and Schmidt, 2003). The analysis of the Arch can be simplified if the interaction angle between the rollers and the arch are fixed. The interaction angle for the bottom roller was set at 45° , and the interaction angle for the top roller was set at 13° . Equation 9 and Equation 10 give the location of the center of the roller supports based on the set interaction angles and the radii of the roller support and the specimen. Using the force system shown in Figure 21, equations for the internal axial force (Equation 11), shear force (Equation 12), and bending moment (Equation 13) were developed.

$$\text{Bottom roller location} = (r - r_r) \cos(45^\circ)$$

Equation 9

$$\text{Top roller location} = (r + t + r_r) \cos(77^\circ)$$

Equation 10

where:

r = the inner radius of the specimen

t = the thickness of the specimen

r_r = the radius of the roller support

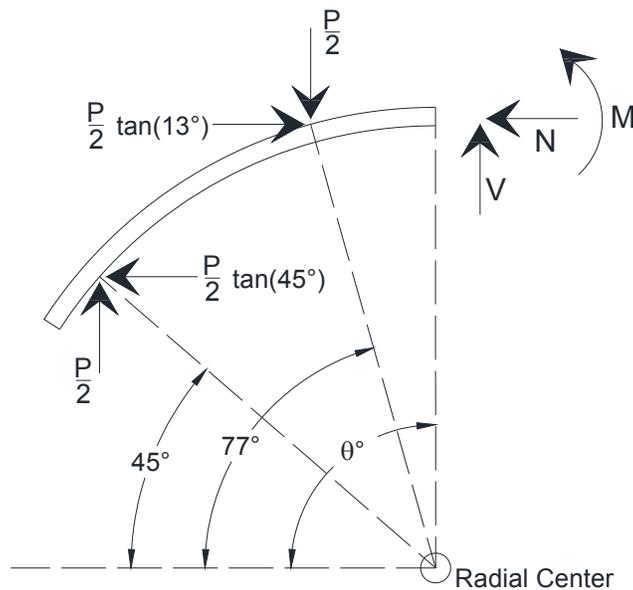


Figure 21. Arch internal force system

$$N = \begin{cases} \frac{P}{2} [\cos(\theta) - \sin(\theta)] & 45^\circ \leq \theta < 77^\circ \\ \frac{P}{2} [\sin(\theta)(1 - \tan(13^\circ))] & 77^\circ \leq \theta < 90^\circ \end{cases} \quad \text{Equation 11}$$

where:
 P = the applied force

$$V = \begin{cases} \frac{P}{2} [\cos(\theta) + \sin(\theta)] & 45^\circ \leq \theta < 77^\circ \\ \frac{P}{2} [\cos(\theta)(\tan(13^\circ) - 1)] & 77^\circ \leq \theta < 90^\circ \end{cases} \quad \text{Equation 12}$$

where:
 P = the applied force

$$M_y = \begin{cases} \frac{P}{2} \left[r \cos(45^\circ) - \left(\frac{t}{2} + r \right) \cos(\theta) \right] & 45^\circ \leq \theta < 77^\circ \\ \frac{P}{2} \left[r \cos(45^\circ) - \left(\frac{t}{2} + r \right) \cos(\theta) \right] - \frac{P}{2} \left[(t + r) \cos(77^\circ) - \left(\frac{t}{2} + r \right) \cos(\theta) \right] & 77^\circ \leq \theta < 90^\circ \end{cases}$$

$$M_x = \begin{cases} \frac{P}{2} \left[\left(\frac{t}{2} + r \right) \sin(\theta) - r \sin(45^\circ) \right] & 45^\circ \leq \theta < 77^\circ \\ \frac{P}{2} \left[\left(\frac{t}{2} + r \right) \sin(\theta) - r \sin(45^\circ) \right] + \frac{P}{2} \tan(13^\circ) \left[(t + r) \sin(77^\circ) - \left(\frac{t}{2} + r \right) \sin(\theta) \right] & 77^\circ \leq \theta < 90^\circ \end{cases}$$

where:
 P = the applied force
 r = the inner radius of the specimen
 t = the thickness of the specimen

Equation 13

Castigliano's Theorem was then used to determine the deflection under the top roller due to flexure. Castigliano's Theorem is based on complimentary energy and, and the deflection under a point load can be determined by taking the partial derivative of the total complementary energy in terms of the point load. When the arch set-up is placed in a universal testing machine, the machine will be able to measure force and displacement in the vertical direction. The goal of the analysis is to relate these two by determining the initial stiffness of the arch. The initial structural analysis model is given in Figure 22. Two equal vertical loads of P and Q are applied. Because the loads are applied through a roller, they will both have vertical and horizontal components. The applied loads will create two vertical reaction forces R_a and R_b ; these too will have horizontal counterparts. R_a and R_b are given in Equation 14.

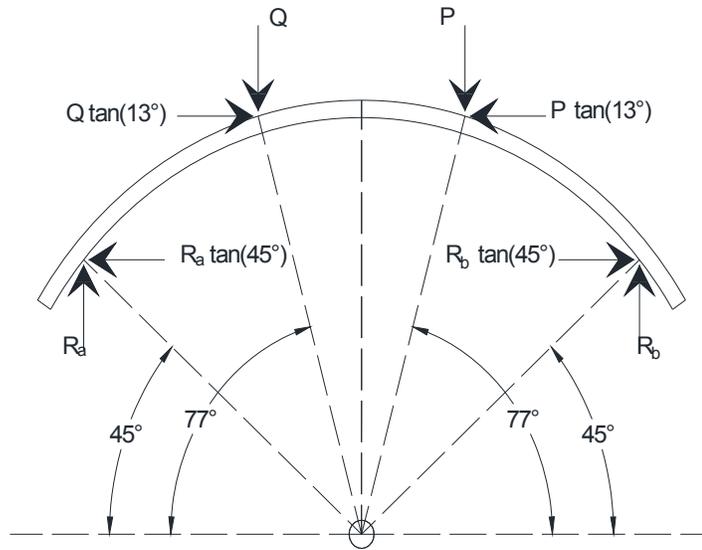


Figure 22. Initial structural analysis model.

$$R_a = \frac{Q(r\cos(45^\circ) + (t + r)\cos(77^\circ)) + P(r\cos(45^\circ) - (t + r)\cos(77^\circ))}{2r\cos(45^\circ)}$$

Equation 14

$$R_b = \frac{P(r\cos(45^\circ) + (t + r)\cos(77^\circ)) + Q(r\cos(45^\circ) - (t + r)\cos(77^\circ))}{2r\cos(45^\circ)}$$

where:

P = the applied force

r = the inner radius of the specimen

t = the thickness of the specimen

With these reaction forces the equations for moment due to forces in both the x and y direction can be redeveloped for both the left (a) and right portions (b) of the beam (Equation 15).

$$M_{ya} = \begin{cases} R_a \left[r \cos(45^\circ) - \left(\frac{t}{2} + r\right) \cos(\theta) \right] & 45^\circ \leq \theta < 77^\circ \\ R_a \left[r \cos(45^\circ) - \left(\frac{t}{2} + r\right) \cos(\theta) \right] - Q \left[(t + r) \cos(77^\circ) - \left(\frac{t}{2} + r\right) \cos(\theta) \right] & 77^\circ \leq \theta < 90^\circ \end{cases}$$

$$M_{xa} = \begin{cases} R_a \tan(45^\circ) \left[\left(\frac{t}{2} + r\right) \sin(\theta) - r \sin(45^\circ) \right] & 45^\circ \leq \theta < 77^\circ \\ R_a \tan(45^\circ) \left[\left(\frac{t}{2} + r\right) \sin(\theta) - r \sin(45^\circ) \right] + Q \tan(13^\circ) \left[(t + r) \sin(77^\circ) - \left(\frac{t}{2} + r\right) \sin(\theta) \right] & 77^\circ \leq \theta < 90^\circ \end{cases}$$

$$M_{yb} = \begin{cases} R_b \left[r \cos(45^\circ) - \left(\frac{t}{2} + r\right) \cos(\theta) \right] & 45^\circ \leq \theta < 77^\circ \\ R_b \left[r \cos(45^\circ) - \left(\frac{t}{2} + r\right) \cos(\theta) \right] - P \left[(t + r) \cos(77^\circ) - \left(\frac{t}{2} + r\right) \cos(\theta) \right] & 77^\circ \leq \theta < 90^\circ \end{cases}$$

$$M_{xb} = \begin{cases} R_b \tan(45^\circ) \left[\left(\frac{t}{2} + r\right) \sin(\theta) - r \sin(45^\circ) \right] & 45^\circ \leq \theta < 77^\circ \\ R_b \tan(45^\circ) \left[\left(\frac{t}{2} + r\right) \sin(\theta) - r \sin(45^\circ) \right] + P \tan(13^\circ) \left[(t + r) \sin(77^\circ) - \left(\frac{t}{2} + r\right) \sin(\theta) \right] & 77^\circ \leq \theta < 90^\circ \end{cases}$$

where:

Ra= the reaction at point a (Figure 22)

Rb= the reaction at point a (Figure 22)

r= the inner radius of the specimen

t= the thickness of the specimen

Equation 15

The total energy due to flexure of a curved beam is given as (Boresi and Schmidt, 2003):

$$U = \int_0^\theta \frac{A_m M^2}{2A(RA_m - A)E} d\theta \quad \text{Equation 16}$$

where:

A= cross-sectional area

M= moment

$A_m = b \ln\left(\frac{c}{a}\right)$

a= internal radius

c= external radius

b= thickness

R= Radius to centroid of cross-section

E=elastic modulus

If the ratio of the diameter to thickness is greater than two, the equation can be simplified to (Boresi and Schmidt, 2003):

$$U = \int_0^\theta \frac{M^2}{2EI} R d\theta \quad \text{Equation 17}$$

where:

M = moment

R = Radius to centroid of cross-section

E =elastic modulus

I = moment of inertia

The total energy stored in the initial flexural deformation of the arch can be determined by:

$$U = \int_{45^\circ}^{77^\circ} \frac{(M_{ya} + M_{xa})^2}{2EI} R d\theta + \int_{77^\circ}^{90^\circ} \frac{(M_{ya} + M_{xa})^2}{2EI} R d\theta + \int_{45^\circ}^{77^\circ} \frac{(M_{yb} + M_{xb})^2}{2EI} R d\theta + \int_{77^\circ}^{90^\circ} \frac{(M_{yb} + M_{xb})^2}{2EI} R d\theta \quad \text{Equation 18}$$

where:

M_{ya} = moment Equation 15

M_{xa} = moment Equation 15

M_{yb} = moment Equation 15

M_{xb} = moment Equation 15

R = Radius to centroid of cross-section

E =elastic modulus

I = moment of inertia

The vertical deflection under either roller can be determined by taking the partial derivative of the total energy by P or Q respectively. This is shown in Equation 19.

$$\Delta = \frac{\partial U}{\partial Q} \quad \text{Equation 19}$$

where:

U = total energy

Q = applied force

Δ = deflection of arch under top roller

When Equation 15 is implemented in the energy analysis the results are given by Equation 20. It includes the substitution of $P/2$ for both P and Q . This allows for the calculation of deflection under either roller due to the total applied load. Equation 20 provides the initial load deflection behavior for the arch.

$$\Delta = 0.1208 \frac{PR^3}{EI} \quad \text{Equation 20}$$

where:

R = the radius to the centroid of the specimen's cross-section

E = elastic modulus

I = moment of inertia

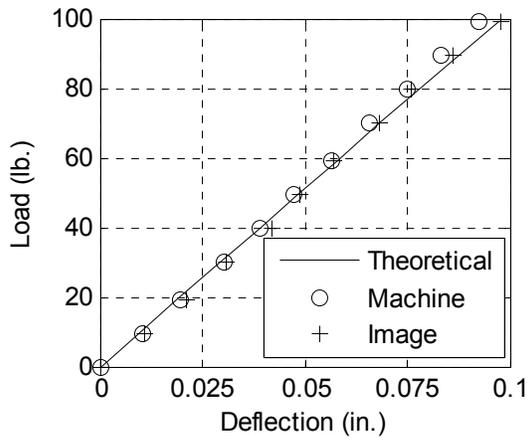
Validation of Image Measurements

Tracking the deformation of the arch specimen with traditional transducers is a complicated process. The arch deforms in both the horizontal and vertical direction all while changing its contact point with the roller bearings. In order to capture this behavior, geometric deformations were measured using digital images. In order to validate the image capture and measurement process, validation was performed on the flexural specimens FA and FS. The geometry of the test specimens are given in Table 26. Load and deflection data was recorded with a universal testing machine. This data was compared to deflection data measured from successive images. The images were scaled and measured using the software ImageJ. ImageJ is a public domain image processing program developed by the National Institutes of Health. The data from the testing machine and the images are plotted in Figure 23. Also shown in Figure 23 is the theoretical deflection calculated as the deflection under the applied load for a simply supported beam with a point load located at mid-span. Figure 23 shows good agreement between the theoretical load deflection behaviors, the load deflection behavior measured using the universal testing machine, and the deflection determined using image analysis.

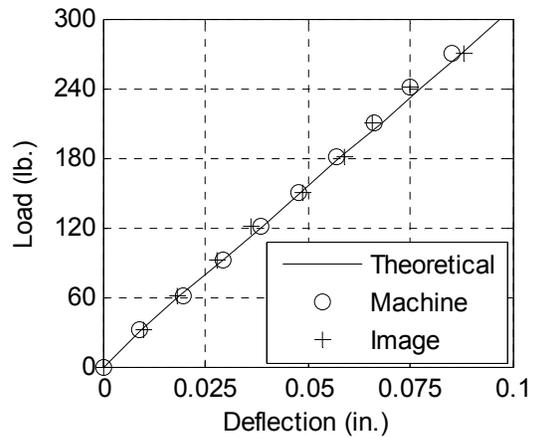
Deformation of the Arch

The deformation of an aluminum arch specimen is given in Figure 24; it is identified as Specimen A2 in the subsequent sections. The load deflection curve in Figure 24a shows two nonlinear portions. The first nonlinear portion is a function of changes in the geometry, and the second nonlinear portion is due to yield of the aluminum accompanied with change in geometry. FRP materials are generally considered to

experience only linear elastic material behavior, and this makes the second concave up portion of the curve of less interest. The initial concave up portion of the load-deflection curve, due to nonlinear geometry, shows progressive spring behavior. As the deflection increases, the spring becomes stiffer. The increased stiffness occurs due to changes in geometry.

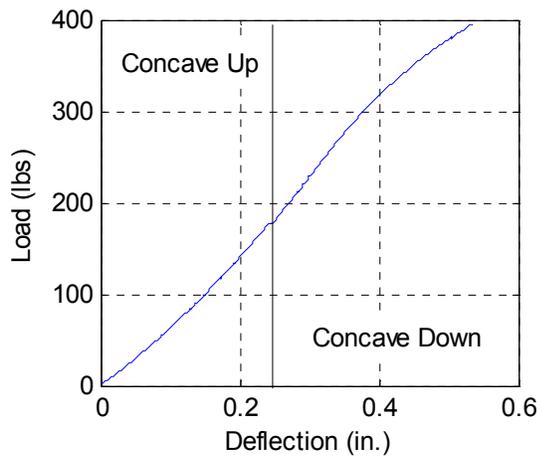


a) Aluminum Beam

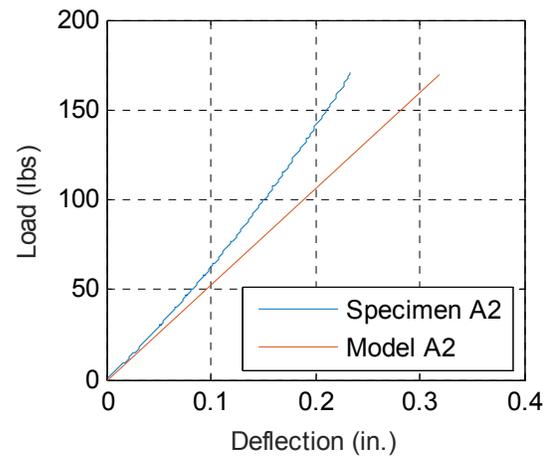


b) Steel Beam

Figure 23. Image measurement validation



a) Load deflection curve of aluminum arch A2



b) Concave up portion of A2 and Deflection Model (Equation 20)

Figure 24. Load-deflection behavior of aluminum specimen

During the testing of the arch specimen, images were taken and tied to a load and deflection measurement. At each given load and deflection, the images were used to determine the current geometry. When the images were analyzed, it was found that each pixel in the image scaled to approximately 0.01 in. Figure 25 shows the standard grid overlaid on each image, and moments were calculated at eight specific grid points (A-H). These points were then used to construct moment diagrams.

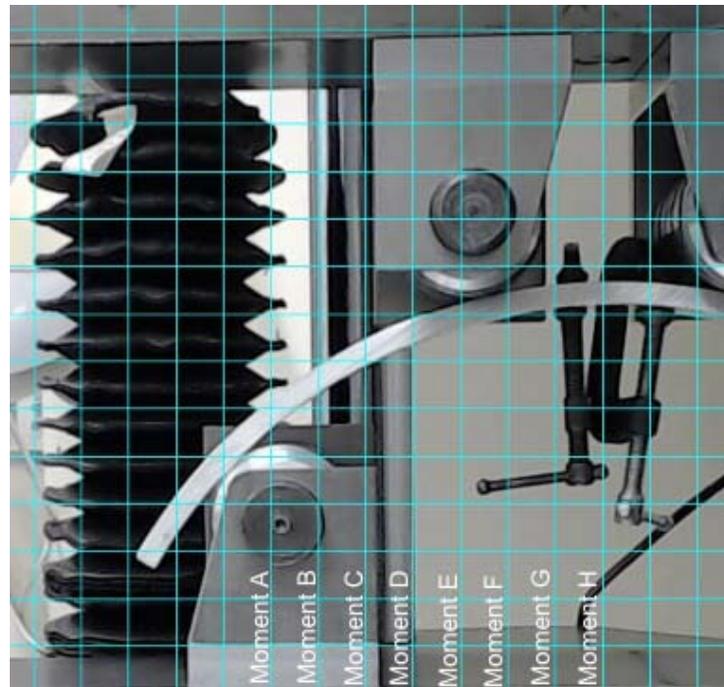
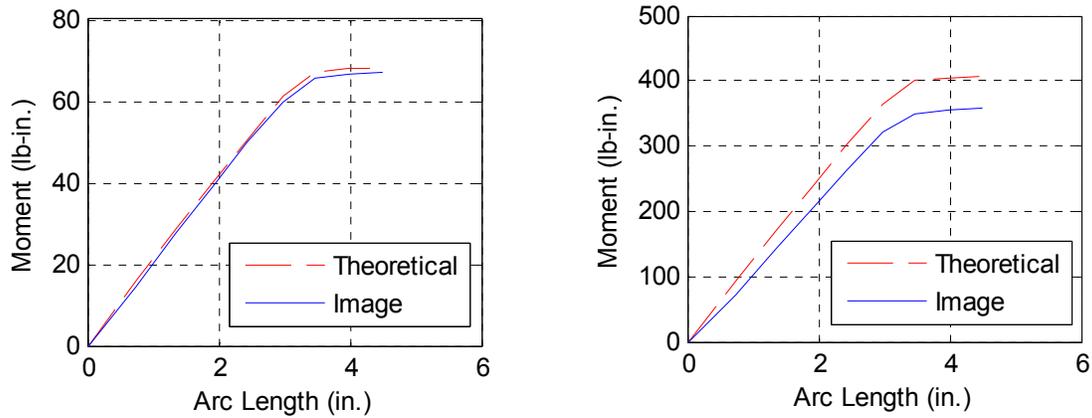


Figure 25. Grid and moment locations for Specimen A2

Figure 26 gives the moment diagram for the aluminum arch specimen under 30.2 lbs. and 180.4 lbs. In the figure, the moment diagrams developed from the image analysis are compared to the theoretical moment given by Equation 13. At 30.2 lb. there is good agreement between the image analysis and the theoretical moment, but at a load of 180.4 lbs. the theoretical moment exceeds the moment from image analysis. From Figure 26b there appears to be a scalar factor relating the moment diagram from the image analysis to the theoretical moment. Figure 27 shows the theoretical moment from Equation 13 normalized over the moment calculated from the geometry taken from the images. This ratio is then plotted versus the deflection. Figure 27a shows the ratio taken at points between deflections 0 and 0.25 in. At small deflections it is hard to determine

any relationship; it is difficult to distinguish change from the original geometry. When the ratios are examined at deflections greater than 0.05 in., as seen in Figure 27b, the relationship between the ratio of moments and deflection take on an approximately linear relationship. It can also be seen that the lines appear to be approximately parallel.



a) Moment due to a 30.2 lb. load

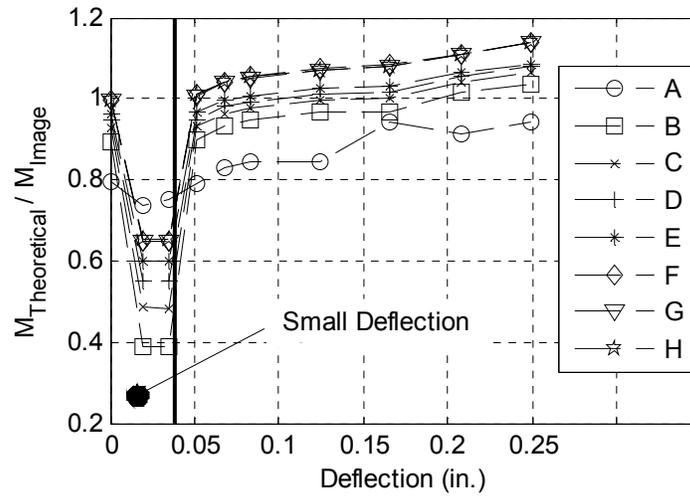
b) Moment due to a 180.4 lb. load

Figure 26. Moment diagrams for half of aluminum arch specimen

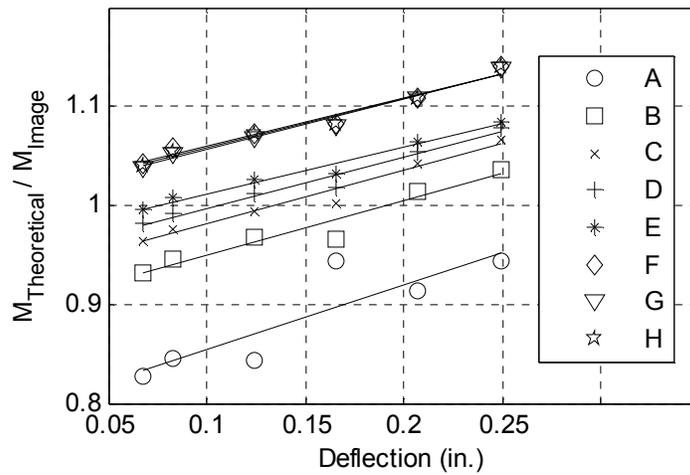
Table 30 shows the results of linear regressions performed on the data represented in Figure 27b. The coefficient of determination for point A is significantly lower than for the other points. From Figure 25 it can be seen that point A is located close to the roller support. Due to its proximity to the support, the arch will experience less deflection at point A. This reduces the ability to determine change from the image analysis. If the average is taken for the slope and y-intercept for points B to H they are 0.51 and 0.96 respectively. The simplified relationship shown in Equation 21 can be justified based on these values.

Table 30. Linear Regression to Normalized Moments vs. Deflection

Moment Location	Slope	Y-intercept	Coefficient of Determination (R^2)
A	0.66	0.79	0.70
B	0.55	0.90	0.92
C	0.54	0.93	0.95
D	0.52	0.94	0.96
E	0.47	0.96	0.97
F	0.49	1.01	0.97
G	0.51	1.00	0.96
H	0.51	1.01	0.96



a) Normalized moment vs. deflection



b) Normalized moment vs. deflection- linear regression

Figure 27. Normalized moment vs. deflection

$$\frac{M_{Theoretical}}{M_{Calculated}} = \Delta C + 1$$

Equation 21

where:

Δ = deflection

C= constant relating deflection to normalized moment

$M_{theoretical}$ = moment from Equation 13

$M_{calculated}$ = moment based on load and current geometry

The calculated moment can then be based on the theoretical moment and the current deflection (Equation 22). When deflection is small the theoretical and calculated moment are equal. This is the case when small deflection theory holds.

$$\frac{M_{Theoretical}}{(\Delta C + 1)} = M_{Calculated}$$

Equation 22

where:

Δ = deflection

C= constant relating deflection to normalized moment

$M_{theoretical}$ = moment from Equation 13

$M_{calculated}$ = moment based on load and current geometry

The relationship given in Equation 22 can then be carried over to the energy equation given in Equation 20. The $(\Delta+1)$ factor is a constant through the integration, and the integration results in the deflection under the roller due to the moment given by Equation 23.

$$\Delta = 0.1208 \frac{PR^3}{EI(C\Delta + 1)^2}$$

Equation 23

where:

Δ =deflection

R= the radius to the centroid of the specimen's cross-section

E= elastic modulus

I= moment of inertia

C= constant relating deflection to normalized moment

Equation 23 can be solved for load and expressed in terms of a spring as shown in Equation 24. When the amount of deflection is very small, Equation 24 simplifies to a linear spring relationship $P=\Delta k$. This linear spring is the model expressed in Equation 20.

$$\Delta k(C\Delta + 1)^2 = P$$

Equation 24

where:

$$k = \frac{EI}{0.1208R^3}$$

R = Radius to centroid of cross-section

E =apparent flexural modulus

I = moment of inertia

Δ = deflection

C = constant relating deflection to normalized moment

In Equation 24, k is the initial stiffness. It is composed of both geometric and material properties, and gives an initial slope to the load-deflection curve. R is the radius to the centroid of the cross-section that was used to initially space the roller supports. It is the equivalent of the span in a straight beam. The moment of inertia, I , is based on the cross-section of the specimen. E represents the apparent elastic material property. For isotropic materials this will be the elastic modulus, but for anisotropic materials, this is an elastic property based on assumed isotropy. The term $(C\Delta + 1)^2$ modifies this initial stiffness; it controls the concavity of the curve. The term accounts for the geometric nonlinearity; it transforms the measured load to the corresponding load in the linear model given in Equation 23. The constant C is a factor which accounts for differences between the current and initial geometry.

If the vertical load-deflection behavior under either of the top rollers is known, two data points can be used to solve for both C and E . In this fashion an apparent flexural modulus can be determined from measured load-deflection behavior.

Apparent Stress at Outer Surface

When the ratio of the radius to the thickness exceeds 5 the circumferential stress in a curved beam can be determined using Equation 25 (Boresi and Schmidt, 2003).

$$\sigma_{\theta\theta} = \frac{N}{A} + \frac{Mt}{2I}$$

Equation 25

where:

$\sigma_{\theta\theta}$ = circumferential stress

M = moment

N = normal force

I = moment of inertia

t =thickness

A = cross-sectional area

With the measured load and the current geometry determined from image analysis, the maximum moment and axial force can be determined. With these values circumferential stress can be calculated. This stress calculation assumes isotropy and that the centroid is located at the center of the cross-section.

Validation Testing and Results

The validation of the apparent modulus was determined using both metallic and composite specimen. The validation of the apparent stress was only validated against yield in the metallic specimen. The composite specimens did not undergo any distinguishable type of yield or failure in their loading. They provided no value for a comparison of stress.

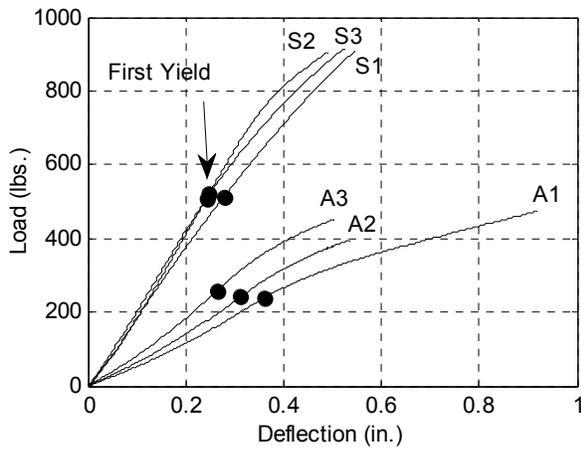
Apparent Modulus

Three tests were performed on aluminum specimens, three tests were performed on steel specimens, and twelve tests were performed on composite specimens. The geometric properties of these coupons are given in Table 31, and their load deflection behavior is shown in Figure 28. The thickness of the composite arches was highly variable, and the thickness values reported in Table 31 are the average of 17 measurements taken approximately every 0.5 in. Two points were then taken from each set of load-deflection data and the apparent flexural modulus (E) was determined using Equation 24. The points used, C value, and E are given in Table 32.

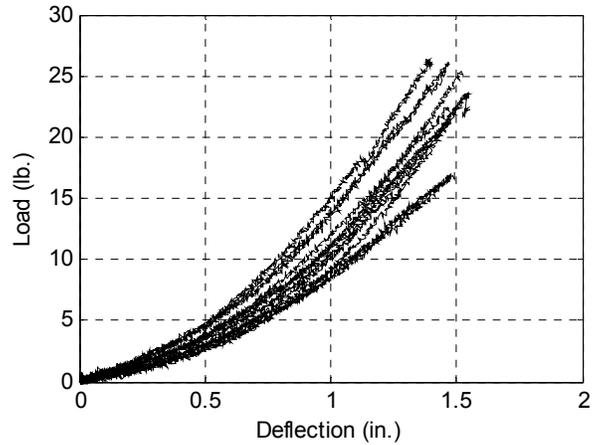
Table 32 gives the ratio of the apparent modulus calculated through the arch test over both the tension modulus and flexural modulus. The average ratios of the modulus determined through the ring test to the tension modulus and flexural modulus are 1.03 and 1.13, respectively.

Table 31. Geometric Properties of Validation Specimen

Specimen	Nominal Values		Measured Values	
	Inner Radius	Thickness	Avg. Width	Avg. Thickness
	in.	in.	in.	in.
A-A1	5.75	0.25	1.13	0.248
A-A2	5.75	0.25	1.13	0.247
A-A3	5.75	0.25	1.11	0.261
A-S1	5.75	0.25	1.07	0.249
A-S2	5.75	0.25	1.07	0.25
A-S3	5.75	0.25	1.07	0.249
A-C1	5.5	0.0431	1.13	0.0467
A-C2	5.5	0.0431	1.04	0.0455
A-C3	5.5	0.0431	1.04	0.0428
A-C4	5.5	0.0431	1.07	0.0521
A-C5	5.5	0.0431	1.11	0.0426
A-C6	5.5	0.0431	1.2	0.0439
A-C7	5.5	0.0431	1.13	0.0411
A-C8	5.5	0.0431	1.08	0.0507
A-C9	5.5	0.0431	1.05	0.0425
A-C10	5.5	0.0431	1.21	0.0429
A-C11	5.5	0.0431	1.16	0.048
A-C12	5.5	0.0431	1.2	0.0449



a) Metallic specimen



b) Carbon composite specimen

Figure 28. Load-deflection plots for arch specimen

Table 32. Apparent Flexural Modulus Calculations

Specimen	Point 1		Point 2		C	E _{Arch} ksi	E _{Tension} ksi	E _{Flex} ksi	E _{Arch} / E _{Tension}	E _{Arch} / E _{Flex}
	Load	Deflection	Load	Deflection						
	lb.	in.	lb.	in.						
A-A1	114.7	0.2	150	0.25	0.5	8,569	9,992	10,947	0.86	0.78
A-A2	114	0.17	150	0.21	0.58	10,442	9,992	10,947	1.05	0.95
A-A3	113.8	0.14	151	0.17	0.66	10,926	9,992	10,947	1.09	1.00
A-S1	180.6	0.1	301	0.16	0.25	29,327	29,323	30,885	1.00	0.95
A-S2	179	0.1	300	0.15	0.83	25,954	29,323	30,885	0.89	0.84
A-S3	180.4	0.09	301	0.15	0.36	31,887	29,323	30,885	1.09	1.03
A-C1	8.15	0.89	17.5	1.33	0.74	7,128	10,498	9,011	0.68	0.79
A-C2	7.22	0.89	13.9	1.32	0.41	10,889	10,498	9,011	1.04	1.21
A-C3	6.74	0.89	14.2	1.33	0.69	8,777	10,498	9,011	0.84	0.97
A-C4	11.2	0.89	22	1.33	0.48	9,998	10,498	9,011	0.95	1.11
A-C5	2.63	0.51	9.88	1.03	1.04	6,369	10,498	9,011	0.61	0.71
A-C6	11.18	0.89	22	1.33	0.45	15,407	10,498	9,011	1.47	1.71
A-C7	7.34	0.87	14.2	1.33	0.38	14,585	10,498	9,011	1.39	1.62
A-C8	9.89	0.89	19.3	1.33	0.45	9,948	10,498	9,011	0.95	1.10
A-C9	3.55	0.5	10.5	1.00	0.56	12,921	10,498	9,011	1.23	1.43
A-C10	9.19	0.88	18.3	1.33	0.48	13,045	10,498	9,011	1.24	1.45
A-C11	11.74	0.88	14.8	1.00	0.73	9,359	10,498	9,011	0.89	1.04
A-C12	4.00	0.5	11	1.00	0.42	12,246	10,498	9,011	1.17	1.36

Apparent Flexural Stress at Outer Fiber

The point where first yield occurs at the outer fiber of the metallic specimens is shown in Figure 28a. The stress at the outer fiber was determined using geometric measurements from image analysis and correlated load measurements. Figure 29 gives the critical dimensions needed for determining the maximum moments in the arch specimen. The dimensions are then given for each metallic specimen in Table 33. Table 34 gives the computed axial force and moment when the stress at the extreme outer fiber of the arch specimen reaches the yield stress. Given the information in Table 34, the stress can be computed using Equation 25. Also, given in Table 34 are the deflection values measured at the roller supports recorded from the testing machine and measured with the image analysis. The average percent difference between the two measurements was 1.2 percent. This comparison was performed to build confidence in the geometry measured using image analysis. From Figure 28a, it can be seen that yield at the extreme outer fiber occurs at a transition point in the load-deflection curve.

Prior to yield in the extreme compression fiber the load-deflection curve is concave-up. After the point, the curve transitions to concave-down.

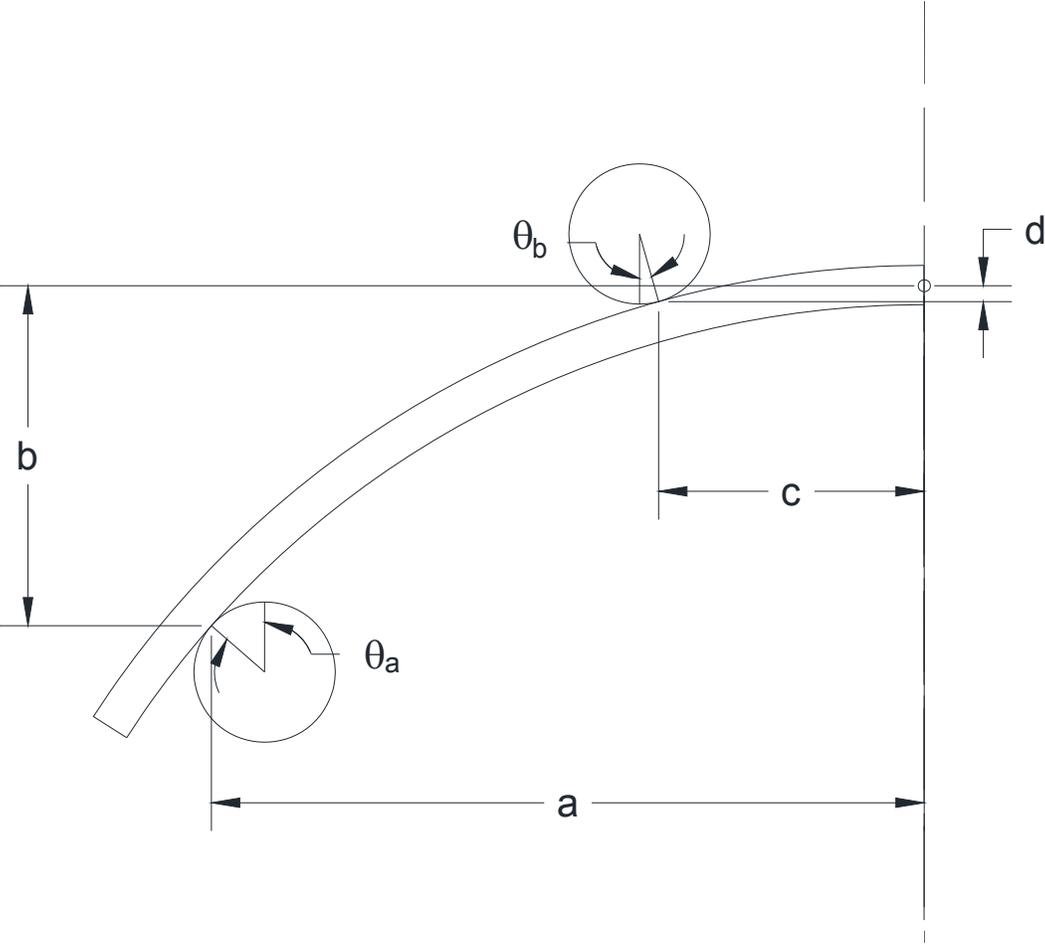


Figure 29. Geometry of deformed arches

Table 33. Geometry of Metallic Arches at Yield of the Extremem Outer Fiber Determined through Image Analysis

Specimen	a in.	b in.	c in.	D in.	θ_a Degree	θ_b Degree
A1	4.04	1.42	1.48	0.018	37.7	5.27
A2	3.96	1.46	1.43	0.026	33.3	4.00
A3	3.98	1.54	1.38	0.013	38.7	4.95
S1	4.07	1.42	1.47	0.035	36.5	7.13
S2	4.13	1.54	1.52	0.024	37.7	7.85
S3	4.09	1.44	1.45	0.006	35.1	10.8

Table 34. Moment and Axial Force at Yield of Extrememe Fiber of Metallic Arches

	Load	Deflection Machine	Deflection Image	% Difference Deflection	Axial	Moment
Specimen	lb.	in.	in.		lb.	lb-in
A1	239	0.362	0.367	1.38%	81.4	438
A2	241	0.313	0.311	0.67%	70.7	420
A3	258	0.265	0.268	0.98%	92.2	495
S1	514	0.279	0.281	0.65%	158	937
S2	519	0.246	0.251	1.97%	165	985
S3	509	0.243	0.240	1.28%	130	927

The use of yield is less than ideal for validation purposes. It does not provide a definitive point for comparison. The results of the analysis did indicate that yield of the outer fiber of the arch did occur at the point where there was a change in the concavity of the load-deflection curve. This is a positive indication, but further testing is required to validate the determination of an apparent stress.

Summary of Validation Results and Test Recommendation

Table 35 summarizes the results of the validation testing for the ring and arch tests. It shows that both of the methods developed worked well for determining the modulus of the metallic specimen. There is a larger variation for the composite material. Composite, itself, is a more variable material, and the small thickness of the test specimen can cause variation due to difficulty in measurement. Ultimately, there is still good agreement for both of the tests.

Table 35. Summary of Validation Testing for Arch and Ring Tests

Material	$E_{Arch}/E_{Tension}$	E_{Arch}/E_{Flex}	$E_{Ring}/E_{Tension}$	E_{Ring}/E_{Flex}
Aluminum	1.00	0.91	0.95	0.87
Steel	0.99	0.94	1.00	0.95
Hand Lay-up Carbon Composite	1.04	1.21	0.88	1.02

Of the two tests, the ring test was selected for inclusion in the redeveloped specification. The ring apparatus is simpler to construct, and the ring test is a less complicated test. A test standard for the Ring Test is given in Appendix C.

DEVELOPMENT OF NEW JERSEY DEPARTEMT OF TRANSPORTATION SPECIFICATION

The main purpose of a material specification is to prevent the use of materials which cannot be successfully designed for an appropriate life-span or whose use incorporates excessive uncertainty in a design. The main goal of redeveloping Section 916 of the NJDOT Standard Specification is to make it more economically competitive. The most economically competitive specification will allow the largest number of products to be qualified. Based on their composition four types of polymer based pile products are currently being manufactured. They are:

- Thermoset circular structural tubing
- Thermoset polygonal structural tubing
- Thermoplastic rectangular and circular structural members
- Thermoplastic rectangular and circular structural members reinforced with solid glass fiber-reinforced polymer bars

Material Requirements

The material specifications were primarily based on those developed over the past 15 years (Zureick , 2002; Zureick et al. , 2010) and adopted by both the AASHTO Subcommittee on Bridges and Structures (AASHTO FRPS-1, 2012) and the AASHTO Subcommittee on Materials (AASHTO MP22-13). However, it should be noted that currently proposed NJDOT specifications address additional requirements, beyond those covered in MP22, related to thermoplastic materials that NJDOT has used in the past.

It is important to note that the thermoplastic in Thermoplastic rectangular and circular structural members reinforced with solid glass fiber-reinforced polymer bars is exempt from the requirements for glass transition temperature. The performance of thermoplastic reinforced with glass-fiber reinforcing bars is entirely dependent on the mechanical properties of the reinforcing bars under the specified loading conditions. Figure 30 shows the flexural stress strain curve of the FRP reinforcing bars along with the flexural stress strain curve of the thermoplastic layer surrounding the reinforcing bars. These curves were developed from tests conducted, following ASTM D790 for the

thermoplastic layer and ASTM D4476, for the reinforcing bar. The secant modulus values corresponding to a 1 percent strain can be shown to be 110 ksi. and 3,696ksi for the thermoplastic and FRP reinforcing bars, respectively. That is a modular ratio of more than 30. With the reinforcing bars distributed near the outer surface of the pile, the flexural rigidity of the pile in question is essentially due to the reinforcing bars. For example, in a 13-in diameter thermoplastic pile reinforced with twelve glass reinforced polymer bars of 1 5/8 in, the contribution of the HDPE to the flexural rigidity of the pile will be less than 10 percent.

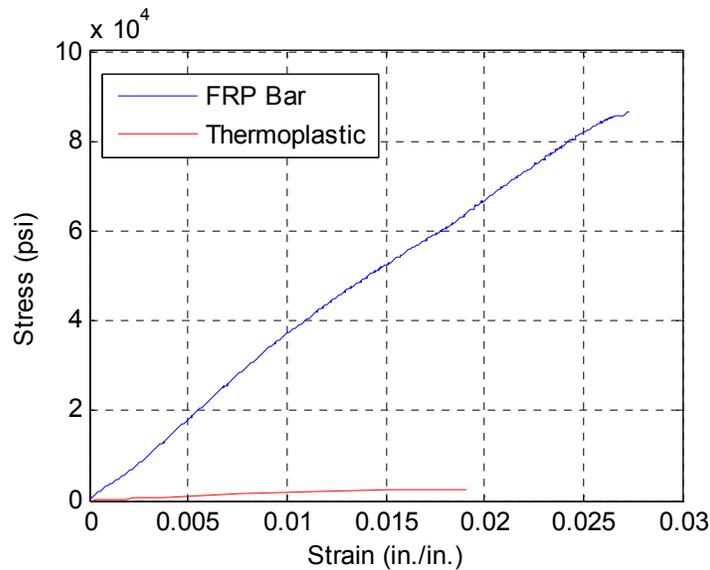


Figure 30. Stress-strain comparison for FRP reinforcing bar and thermoplastic

MP-22 uses ASTM D3039 as the test method used to determine compliance, but ASTM D3039 is only applicable to thermoset polygonal structural tubing. This being the case, alternate test methods were required for each material. Appropriate flexural tests were chosen for each material, including the new ring test for thermoset circular structural tubing. Flexural testing is generally one of the simplest types of tests to run. The material type and test methods used are given in Table 36.

Table 36. Test Method for Polymer Materials

Materials	Standard Test
Thermoset circular structural tubing	NJDOT Ring Test
Thermoset polygonal structural tubing	ASTM D790
Thermoplastic rectangular and circular structural members	ASTM D790
Thermoplastic rectangular and circular structural members reinforced with solid glass fiber-reinforced polymer bars	ASTM D4476

Structural Requirements

After the review of the existing literature, structural requirements incorporating provisions found in Section 1710 “Preconstruction Load Tests” of the 2012 International Building Code (IBC) were created. The goal of these requirements was to limit excessive creep. Otherwise, no explicit nominal values are set for the structural properties.

Revised Specifications

The full revised NJDOT specification can be found in Appendix D. The revision includes revisions in Section 511, and a completely revised Section 916. Also included are requirements for the entry of products into the Qualified Product List (QPL). All changes have been highlighted for clarity.

CONCLUSIONS AND FUTURE WORK

Conclusions

The main goal of this work was to develop Section 916 of the New Jersey Department of Transportation into an economically competitive specification. The current state of the specification allows only for two proprietary products. Currently, Section 916 covers fiberglass composite materials intended for use as pile supported bridge fender systems, bulkheads, and pile foundations for light structures. There are four distinct types of polymer products currently being produced for these uses. They are: Thermoset circular structural tubing, Thermoset polygonal structural tubing, Thermoplastic rectangular and circular structural members, and Thermoplastic rectangular and circular structural members reinforced with solid glass fiber-reinforced polymer bars.

In order to determine the required material and structural properties a thorough evaluation of the AASHTO Specifications, the Standard Specifications of each state, and other national standards, namely, ASTM D7258-14 Standard Specification for Polymeric Piles, the ASCE Pre-Standard for Load & Resistance Factor Design (LRFD) of Pultruded Fiber Reinforced Polymer (FRP) Structures, and the AASHTO LRFD Guide Specifications for Design of Concrete-Filled FRP Tubes for Flexural and Axial Members, were evaluated. A review of the existing literature on polymer materials used as piles was conducted. The major finding of the evaluation of existing standards and literature search were:

- 1) Creep is a considerable issue when dealing with polymer based materials
- 2) All of the national standards reviewed have limitations in the proper assessment of the strength of the materials being produced
- 3) Due to their complex nature, the nominal design properties in axial, shear, moment, and torsion must be evaluated from full-scale tests of actual specimen
- 4) There is no coupon level test that can be performed on any part of thermoset circular structural tube

In order to provide a coupon level test for thermoset circular structural tubing, two tests were developed and verified. These tests involve either the testing of a full ring cut from the cross-section of the tube or an arc cut from the ring. Existing coupon level tests were identified for thermoset polygonal structural tubing, thermoplastic rectangular and circular structural members, and thermoplastic rectangular and circular structural members reinforced with solid glass fiber-reinforced polymer bars. These coupon level tests were then used for degradation testing, qualification, and acceptance testing of the polymer based materials.

An engineering assessment was performed on the feasibility of use of currently marketed thermoset circular structural tubing and thermoplastic rectangular and circular structural members reinforced with solid glass fiber-reinforced polymer bars. The results of the analysis showed, that based on manufacturer reported properties, each of the products could successfully be used in design.

A specification designed to limit the amount of degradation of materials and creep was developed. The degradation requirements were based on those found in *AASHTO MP-22 Standard Specification for Fiber-Reinforced Polymer Composite Materials for Highway and Bridge Structures*. Structural adequacy was based on load testing procedures for materials with no applicable standard tests found in the International Building Code. The goal of the structural adequacy requirements was to limit the amount of acceptable creep. No specific nominal value was set on the strength or stiffness of the materials. The specification will accept all materials which show an appropriate level of resistance to creep and degradation. The specification is based on the current state of knowledge; as experience and the knowledge base grows the specification should be updated.

Survey on Use of FRP Materials

A survey on the use of FRP materials was electronically distributed as part of Phase I. The intent of the survey was to determine how FRP materials are currently being used, and how they may be used in the future. A summary of some pertinent details follows.

Currently, the survey has been completed 107 times and the responders practice in 19 of the 50 states. States with the highest response rate were New Jersey, Pennsylvania, and Delaware. The survey respondents were asked to identify their profession, and 95 did so. Figure 31 gives the breakdown by percentage of the 95 respondents.

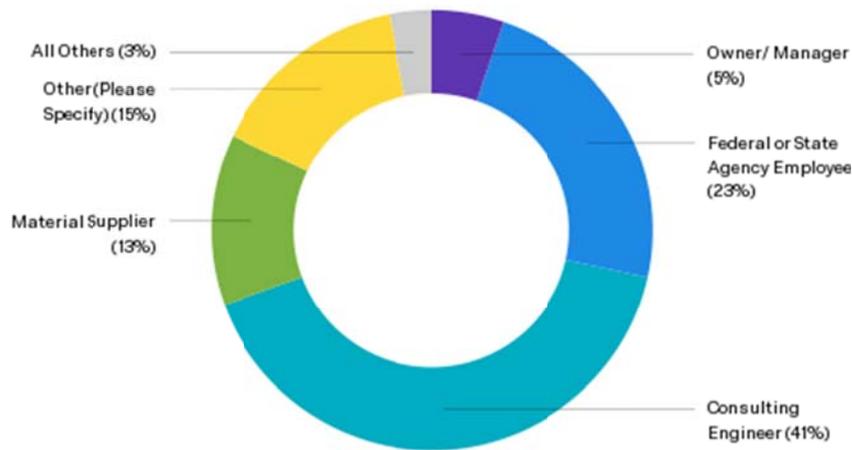


Figure 31. Survey Respondents

When all professions other than materials suppliers were asked if they designed, specified or implemented FRP materials, 25 respondents indicated yes, while 52 indicated no. When FRP had been used or specified, it was mostly used for external and internal concrete reinforcement. When the 52 respondents who indicated they had not implemented FRP were asked if they had ever consider the use of these materials, 21 responded yes while 31 responded no. The largest reason given for deciding not to use composite materials was lack of design procedures and examples.

The majority of materials suppliers deal with internal concrete reinforcement. The suppliers feel that the biggest obstacle in the implementation of their products is lack of familiarity with FRP materials. Based on the survey results and looking forward, the next major polymer based structural component being widely considered for use is internal concrete reinforcement.

Recommendations for Further Research

Based on the findings of this research project, the following topics are proposed for further research:

- 1) Structural Properties.** Structural members, in almost all cases, are exposed to forces in three dimensions (axial, shear, torsion, and flexure). In order to perform a complete structural design their strength and stability limit states under all of these loading conditions must be understood. The literature search revealed none of the products being currently implemented have had complete and thorough evaluation of their limit states performed.
- 2) Long Term Behavior.** The amount of creep experienced by polymer materials can be great. The creep properties of the polymer structural members currently being implemented must be understood.
- 3) Field Experimentation.** Section 916 deals with polymer structural members used as pile foundations. A critical aspect of designing pile foundations is understanding the interaction between the pile and the soil. Not all of the products being currently implemented have been installed in the field and tested both axially and laterally. The lateral design of piles involves the implementation of P-y curves which model the soil as springs. The spring behavior takes into account the shape of the pile and the friction between the pile and the soil. These curves have not been developed for the polymer materials being implemented.
- 4) System Level Behavior.** When the polymer structural members are constructed into fender systems they require connections. The total behavior of fender systems constructed from polymer materials has never been evaluated. A critical part of the evaluation of the system will be the influence of the connections. The connection detail dictates how the forces are transferred and ultimately what limit states will govern the capacity of the structural members.

- 5) Effect of shear deformation on design of fenders.** Shear deformations can be sizable for polymer structural members. Currently, shear deformations are not always considered in the analysis of polymer structural members. It must be understood what conditions make the shear deformations negligible for design.
- 6) Life cycle analysis on use of polymer structural members.** The advantage that polymer based materials have over traditional materials (timber, steel, and concrete) is their resistance to the marine environment. In order to make the most economical decision the life cycle costs of the different polymer based materials must be compared to one another and traditional materials.

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APPENDIX A- HARDESTY AND HANOVER MEMO DATED 12/10/2015

Date: December 10, 2015

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**Re: NJDOT Bureau of Research: Fiberglass Composite Materials Specification Redevelopment
Project No. 2014-15-02**

Dear Dr. Bechtel,

This memo summarizes our findings to date and it focus on the state of the current issues. Future research will be targeting some of the solutions of the issues. After reviewing current section 916.01 - Fiberglass Composite Materials of NJDOT's 2007 Standard Specifications for Road and Bridge Construction, we have identified the following issues:

Proprietary Based Specification: Current specifications for Fiberglass Reinforced Plastic Lumber (FRPL), Fiberglass Reinforced Plastic Piles (FRPP) and Fiberglass-Concrete Composite Piles (FCCP) are typically based on proprietary systems such as those manufactured by Bedford Technology (SeaPile and SeaTimber) and Lancaster Composite (Composite Pile 40, CP40). Because this approach has favored a limited number of manufacturers of the proprietary-based products it has eliminated competition from other equivalent products by other manufacturers.

On a few occasions, the current specification has even encouraged high bids from supplier of proprietary products. A few years ago, the Federal Government suspended primary east coast supplier of Fiberglass Reinforced Plastic Piling from performing work on Federally Funded Projects on the charges of bid-rigging and customer allocation conspiracies. This suspension affected some of the projects construction cost and time significantly, and procurement of similar substitution product proved to be a very difficult task.

Value Engineering: As a value engineering measure contractors will often request substitution of Fiberglass Composite Materials (FCM) products by other manufacturers to offset the high cost of procuring proprietary based products. This often creates confusion and results in costly delays, since the current specifications are based on manufacturing practices specific to the proprietary based products, and the substitute FCM having performance standards equal to or greater than the proprietary based product, cannot meet these practices.

Proprietary Properties: Section 916 of the NJDOT Standard Specifications dictates a general set of parameters that FCM products must meet on any given project, independent of the project requirements. These parameters are viewed by other FCM manufacturers as being too restrictive and/or specified to cater to particular proprietary based products. The table below presents parameters that have generally created concern for the general contractor/other manufacturer on past projects:

Table 1: Proprietary Properties

Product Type	Parameter	Remark by other manufacturers
FRPL & FRPP	Density i.e., Skin (Component)	Note 1
	Density i.e., Core (Component)	Note 1
	Reinforcement Manufacturing: - Using fiberglass reinforcement rods - Fiberglass reinforcement rods parameters - Interior voids	Note 1
	Member Size	Note 2
FCCP	manufacturing requirements: - Resin type - Type of filament - Glass fiber Grade	Note 3
	Coating - Ultraviolet resistant coating to portions of piles remaining exposed after installation.	Note 4
	Wall Thickness	Note 5
	Member Size	Note 2

Note:

1. Proprietary based product requirement not applicable for the substitution material.
2. Can alternate FCM products of different member sizes with similar or higher stiffness be used? If not provide reasoning.
3. Can alternate FCM product of different wall thicknesses with similar or higher stiffness be used? If not provide reasoning.
4. Unable to apply coating to portions of the piles in tidal fluctuation Zone
5. Substituted FCM product far exceeds the material and structural properties, however does not meet specified manufacturing requirements. Advise if substituted FCM product is not acceptable with reasoning.

Types of Composite Products: FCM fabrication is done by several manufacturing methods. Typically FCM structural shapes use recycled plastics in combination with steel members, or fiber reinforced materials such as wound or pultruded fiberglass or other type of fiber glass reinforced plastics. The current specification only speaks on the Fiberglass Reinforced Plastic (FRP) and Fiberglass-Concrete Composite

products (FCCP), though there are several different types of composite products that are currently available in the U.S. market. Refer to below Table 2 for available composite product types.

Table 2: Composite Product Types

Product Type	Description	Meet Current Specification
Steel Pipe Core Pile	Steel pipe pile encased by plastic shell	No
Structurally Reinforced Plastic Pile	Plastic pile reinforced with fiberglass or steel rebar	Yes: Fiberglass reinforcement No: Steel reinforcement
Fiberglass-Concrete Composite Pile	Fiberglass pipe pile filled with concrete	Yes
Fiberglass Pultruded Pile	Fiberglass cross-section filled with fiberglass grid inserts	No
Fiberglass Reinforced Plastic Pile	Plastic matrix with fiberglass	No
Hallow FRP Pile	Fiber Reinforced Polymer Shell	No

As detailed in the above table, the majority of available FRP products either does not meet current specification requirements or are not recognized as viable FRP products.

Structural Properties: The composite products are extensively used in marine applications such as fender and dolphin systems. A typical FCM fender system is composed of plumb FCM piles that are driven into the riverbed and are horizontally connected by FCM lumber. An FCM dolphin is composed of a cluster of FCM piles that are driven into the riverbed, extend above the water, and are connected above the waterline with wire rope. See below Figure 1 for details of each.



1(a): Dolphin



1(b): Fender

Figure 1: FCM Marine Application

Fender and dolphin design uses computer program(s) (e.g., LPILE or FM-MultiPier) that incorporate soil strengths using P-Y curves and pile and/or pile-to-wale properties to determine the system's potential energy available to redirect or possibly bring errant vessel to rest upon impact. The structural properties of pile-to-wale considered in analyses include unit weight, Young's Modulus, Torsional Modulus, Moment of Inertia, Shear Modulus, Poisson's ratio, etc. The current specification requires conformance to certain minimum structural properties (such as unit weight, Young's Modulus and Moment of Inertia), however it does not require conformance to other properties such as Torsional Modulus, Shear Modulus and Poisson's ratio that are essential to the design of fender and dolphin systems.

To further complicate this issue the minimum structural properties that require conformance are established based on a survey of limited proprietary products available at the time of specification development rather than through independent structural criteria. The later would be advisable since it would be based on the actual requirement of the fender and dolphin to redirect or possibly bring errant vessel to rest rather than just a summary of minimum structural properties.

FCM Pile Drivability: The integrity/durability of the pile during installation is commonly assessed using the Pile Driving Analyzer (PDA) test. The damage to the pile is prevented by limiting driving stress subjected to the pile during installation within acceptable stresses limit. The AASHTO LRFD Bridge Design Specifications provide guidance on the acceptable driving stresses that conventional piles can sustain during installation without sustaining damage. The suggested guidance is not applicable to FCM piles. At present, little to no information/guidance is available to the practicing engineer to assess the durability of FCM piles during installation.

Pile and Hammer system: The FCM piles are driven to target depth and/or to the required capacity using vibratory and/or impact pile driving hammers, however installing the piles without damaging them is problematic on most job sites. On past projects we have observed that the clamps of a vibratory hammer have an articulating jaw that applies force to opposing faces of the pile. The teeth on the clamp are uneven and result in localized damage at the top of FCM piling during installation as shown in Figure 2.



2(a): Localized Damage



2(b): Vibratory Hammer's Clamp

Figure 2: Vibratory Hammer Induced Damage

Similar observations of localized damage at the tops of FCM piling were noted when an impact hammer was used to drive the piles. We attributed this to the concave surface of the hammer's anvil block, which is suited for driving timber/concrete/steel piles. See Figure 3 for details.



Figure 3: Impact

Hammer Induced Damage

As shown in Figures 2 and 3, the tops of the FCM piles are susceptible to damage during pile driving. One of the short comings of the current specification's approach in ensuring integrity of pile top is that it does not address the observed drivability issues related to a standard Pile and Hammer systems.

Plastic Sheet Piling: In recent years, the use of plastic sheet pile for earth retaining structures has increased in the United States as an alternative to conventional steel sheet pile. The shift in utilization of plastic sheet piling is due to the material's resistance to degradation, aesthetics and a smoother permit process. An additional benefit is the ecology associated with recycling of PVC waste product.

Although plastic sheet piling is available in the market for grade separation structures, current specifications do not provide information/guidance to the practicing engineer and/or contractor on material and structural properties.

Summary: The current specifications are based on proprietary products and as such do not encourage competitive material product of equal quality by other manufacturers. Contractor's request for substitution of a proprietary product often results in confusion, since substitution product shall meet requirement of proprietary based products that are irrelevant for civil engineering application. Also, specification fails to aid design engineer and/or contractor with regard to establishing structural properties.

Sincerely,



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APPENDIX B- HARDESTY AND HANOVER MEMO DATED 7/26/2016

Date: July 26, 2016

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**Re: NJDOT Bureau of Research: Fiberglass Composite Materials Specification Redevelopment
Project No. 2014-15-02**

Dear Dr. Bechtel,

We have concluded our study to investigate the feasibility of using different types of composite products that are currently available in the U.S. market for marine structures such as fender and dolphin systems. The following summarizes the conclusions.

Background: The New Jersey Department of Transportation (NJDOT) Bureau of Research wishes to redevelop Section 916 of their Standard Specifications. The current NJDOT specifications for Fiberglass Reinforced Plastic Lumber (FRPL), Fiberglass Reinforced Plastic Piles (FRPP) and Fiberglass-Concrete Composite Pile (FCCP) covered under section 916 are proprietary based. The project objective is to redevelop the specification in a generic format to encourage an economically competitive market.

The NJDOT Bureau of Research selected The College of New Jersey (TCNJ) to redevelop Section 916 of the Standard Specification. Hardesty & Hanover, LLC (H&H) is a subconsultant to TCNJ and H&H's scope of work includes the following subtasks:

- 1) Provide input on the current state of engineering practice on Fiberglass Composite Material and identify areas of proposed change to the current Section 916 of the Standard Specification.
- 2) Identify mechanical properties of Fiberglass Composite Structural Shapes.

Purpose and Scope: The purpose of this memorandum is to document mechanical (structural) properties of Fiberglass Composite Material (FCM) structural shapes that may be critical for civil engineering applications in the NJDOT construction projects. The H&H memorandum dated March 15, 2016 provides our input on the current state of engineering practice on FCM and areas of proposed change to the current section 916 of the Standard Specifications.

Previous NJDOT information suggests that FCM structural shapes are primarily used in marine applications such as fenders and dolphins in the NJDOT bridge projects. Therefore the scope of our study

focused on assessing the suitability of FCM structural shapes that are commercially available in the U.S. market for use in fender and dolphin applications, and to identify essential mechanical properties for marine applications.

FCM Product Types: The FCM structural shapes (Pile and Lumber) are currently fabricated through various methods such as pultrusion, filament winding, and vacuum infusion, although additional new fabrication methods are evolving rapidly. There are several different types of FCM structural shape that are currently available in the U.S. market. The FCM structural shapes that are commercially available in the U.S. market vary significantly in material composition and structural properties depending on the fabrication method and/or the product’s material composition. Table 1 provides information on available sources and FCM structural shapes.

Table 1: Composite Product Types

Manufacturer/Distributor	Product Type
Bedford Technology	Solid plastic pile and lumber
Harbor Technology	Hollow FCM pipe pile
Creative Pultrusion	
Pearson Fiberglass Piling	
Lancaster Composite	Hollow FCM pipe pile filled with unreinforced concrete

Additional FCM products are available in the market however those products are not discussed due to the lack of response from the Manufacturer/Distributor during the preparation of this memorandum.

Marine Structures: FCM composite products are extensively used in marine applications such as fender and dolphin systems in NJDOT projects. A typical FCM fender system is composed of plumb FCM piles that are driven into the subsurface materials and are horizontally connected by FCM lumber. An FCM dolphin is composed of a cluster of FCM piles that are driven in clusters into the subsurface, extend above the water, and are connected above the waterline with wire rope. Refer to Figure 1 for details of each.



1(a): Dolphin



1(b): Fender

Figure 1: FCM Marine Applications

Design of Marine Structures: All marine structures protecting bridges against collision are designed in accordance with AASHTO's Vessel Collision Design of Highway Bridges guidelines. The design approach is based on a kinetic energy method, which determines the amount of energy that needs to be absorbed by the marine structure. The marine structure is sized to absorb the impact energy represented by the area below the characteristic load-deflection curve illustrated in Figure 2 while sustaining acceptable deformation.

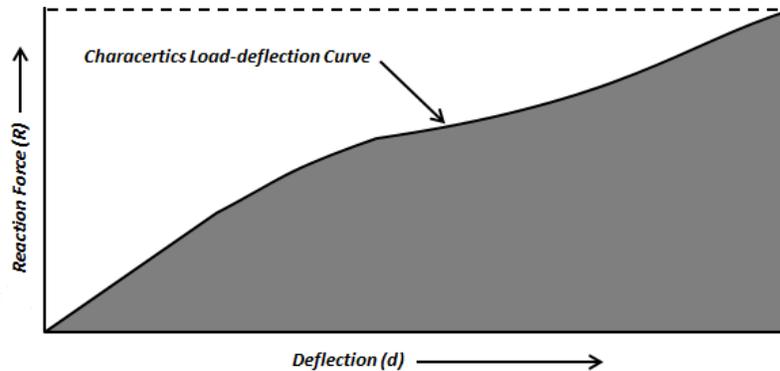


Figure 2: Energy absorption of a marine structure.

Acceptable deformation is the maximum permissible deflection a marine structure can sustain while maintaining minimum clearance distance between the marine structure and the pier to avoid contact during ship impact and/or a deflection marine structure can sustain without experiencing permanent deformation (failure). The estimated marine structure's energy absorption capacity is the area under the load- displacement curve which is simply force times displacement divided by two.

Finite element programs such as LPILE, GROUP and FB-MultiPier that incorporate soil resistance using P-Y curves and pile-to-waler properties can be used to generate a characteristic load-deflection curve. This curve is then used to determine a marine system's potential energy absorption capacity to redirect or possibly bring an errant vessel to rest upon impact. The characteristic load-deflection curve depends on soil resistance, lateral load and structure response. The structure response to a lateral loading is function of soil resistance and structure (pile-to-waler) stiffness. Therefore, this study focused on sensitivity of soil resistance and structure response to the mechanical properties of FCM structure shape types.

Soil Resistance: The soil resistance needed to generate characteristic load-deflection curves is based on P-Y models which are the most widely accepted definition to quantify soil resistance in substructure design. These models have been developed from the results of full scale lateral load tests on conventional piles (steel and concrete). The mobilized soil resistance (P) at any depth is obtained by integrating the stress around the pile cross section as function of deformation Y.

The soil resistance (P) is a function of depth, soil type, soil strength and modulus, pile dimension and deformation, and the soil resistance (P) is independent of pile stiffness. Table 2 summarizes the P-Y

models developed for different soils currently accepted by federal and state design guidelines that are applicable to New Jersey Soils, table below do not present criteria for rock since composite pile socketed into rock is not a preferred option.

Table 2: P-Y applicable to New Jersey Soils

Soil Type	P-Y models*
Soft Clay	Matlock (1970)
Stiff Clay with Free Water	Reese, et al. (1975)
Stiff Clay without Free Water	Welch and Reese (1972), and Reese and Welch (1975)
Sand	Reese, et al. (1974)

* Note that the listed P-Y models are a few selected models out of a large pool that are available for pile's lateral load analyses. The previously mentioned models are well accepted by the professional engineer since their long-term performance is proven.

Therefore, it can be concluded that soil resistance is independent of a composite pile's unique fabrication method and/or manufacturer's material composition. This conclusion is further supported by FHWA-HRT-04-043: A Laboratory and Field Study of Composite Piles for Bridge Substructures (Pando et al., 2006) where P-Y models criteria listed in Table 2 showed reasonably good agreement with the field measurements.

Structure Response: The characteristic load-deflection curve can be generated using Soil Structure Interaction (SSI) analyses. The structure response is a function of soil resistance, and the soil resistance, in turn is a function of structure response (pile deformation). The structure response also depends on head and toe conditions, and the stiffness (mechanical properties) of structure's element. Therefore, mechanical properties of FCM structural shapes that are a function of fabrication method and/or manufacturer's material composition will influence structure response and/or the characteristics load-deflection curve of a given structure.

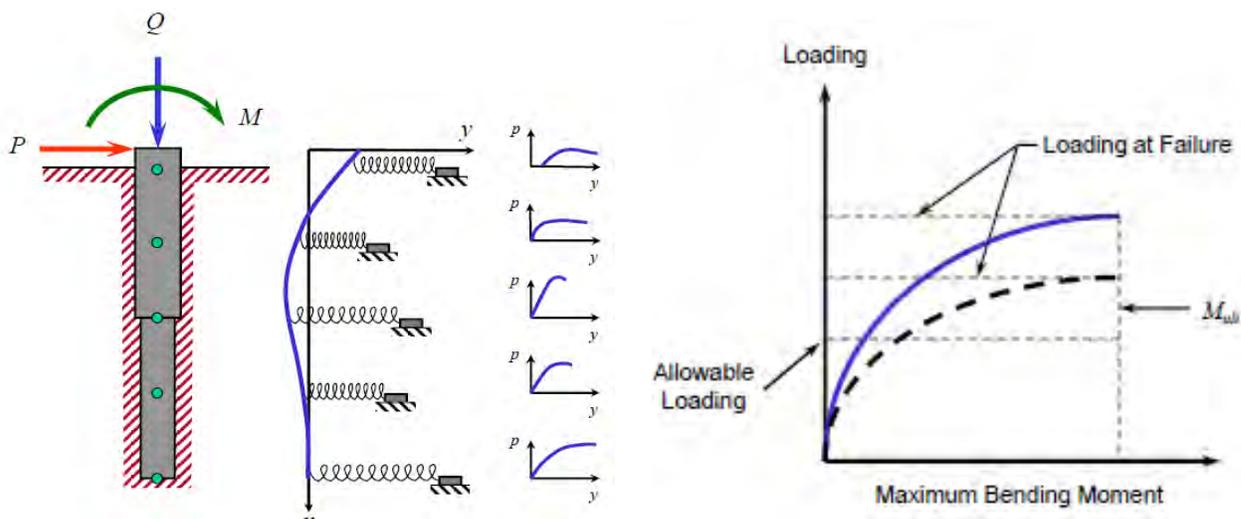


Figure 3: Modeling of Pile under Lateral Load and P-Y Curves (Ref., LPILE Technical Manual)

Hence SSI analyses were conducted by incorporating variations in mechanical properties of FCM structure shape types to determine if the readily available structural shapes meet the requirements for use in marine application and/or yield desirable load-deflection curve characteristics for marine structures. The SSI analyses model the soil around a pile as nonlinear springs representing soil resistance P as a nonlinear function of pile deflection Y (P - Y Criteria). The SSI analyses estimate the structure response the mobilized soil resistance, structure's stiffness and head and toe conditions. Analyses were performed for known soil information, loading and boundary conditions to capture the influence of variation in mechanical properties on characteristics load-deflection curve, refer to Figure 3 for SSI details.

The SSI analyses were performed on readily available FCM structural shapes and product types for both single and cluster cases.

Single Pile Analyses: Single pile analyses using Test runs on an assumed water/soil profile using LPILE software were performed to evaluate the expected behavior of FCM piles and to assess the suitability of commercially available composite product types as viable alternatives to timber piles in marine construction.

A typical marine structure is expected to absorb kinetic energy while sustaining acceptable deformations depending on the project constraints, therefore our test analyses focused on two performance aspects of FCM pile; 1) deformation characteristic, and 2) energy absorption capacity. Figure 4 and Table 3 present the boundary conditions and a summary of the analyses. The analyses considered 16" diameter circular piles because these were available from all the composite manufacturers. The analyses considered pile as an elastic section with defined bending stiffness.

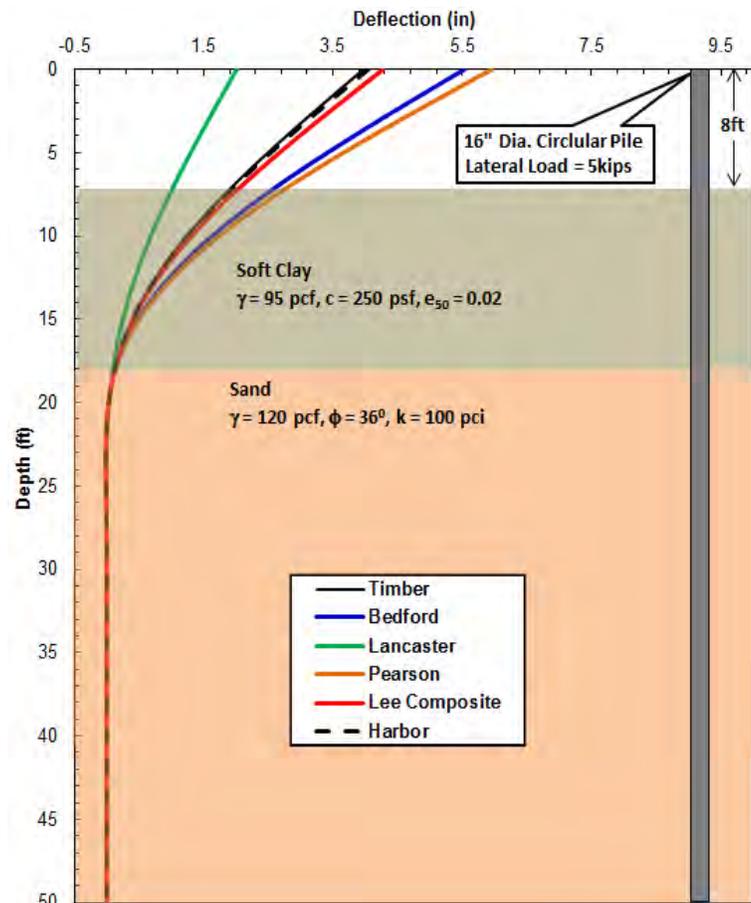


Figure 4: Pile and soil information

Table 3: Summary of Single Pile Analyses

Product	Circular Pile Properties				Deformation Characteristic		Energy Absorption Capacity		
	Dia.	Wall Thickness	Stiffness (EI)	Moment Capacity (kip-ft.)	Lateral Load (lb.) ¹	Deflection (Inch)	Impact Load (lb.) ²	Deflection (Inch)	Kip-ft. ⁴
Timber	16"	N/A	4.82E+09	80	5000	3.96	8000	1.69	0.56
HarborPile		1.125"	4.70E+09	411		4.05	31000	9.96	12.9
SUPERPILE		0.500"	4.38E+09	437		4.27	32000	11.0	14.7
Bedford		N/A	3.18E+09	550		5.53	40000	20.4	34.0
Pearson		0.500"	2.51E+09	404		5.96	30000	14.6	18.3
Lancaster		0.205"	1.98E+09	200		1.76	18000	17.0	12.5 ³

Note: 1) Free Head condition

2) Fixed head condition chosen for energy absorption since marine structure's piles head are connected at the top.

3) Concrete core allowed to crack and pile wall does not buckle at that loading

4) Energy Absorption Capacity of 0.56 kips-ft. = $(0.5 \times 8000 \times 1.69) / (1000 \times 12)$

The results indicate that the energy absorption capacity of each of the composite piles under our assumed conditions exceeded that of timber piles, whereas deformation characteristics indicate composite piles are more flexible compared to timber piles with the exception of the Lancaster pile. A flexible pile is often an attractive option for marine structures since energy-absorption capacity of the system is proportional to the deformation. Therefore it may be concluded that the readily available composite products are suitable alternatives to timber piles.

Pile Group Analyses: Pile group analyses using FB-Multiplier (FBMP) software was performed to assess the feasibility of using readily available composite products in marine applications and to identify threshold values of structural/mechanical properties that may be essential.

A composite product can be used in marine structures, provided the structure can absorb impact energy of the errant vessel to redirect or possibly bring errant vessel to rest upon impact while sustaining acceptable deformation. To investigate suitability of using a composite product in a marine application, a fictitious bridge dolphin system that required absorbing kinetic impact energy of 100 kip-ft. while sustaining no more than 9ft of deformation was evaluated. Deformation criteria of 9-ft is a representative "upper bound" criteria allowed by the state agency where contact between the marine structure and the pier during ship impact is not a concern.

The dolphin pile group model was prepared using a trial pile layout and assumed soil information as shown in Figure 4. The model included a pile nonlinear analysis with pinned head condition and the pile properties defined using User Defined Stress Strain Curves) applicable to each composite product type. The Stress Strain Curves is the relationship between the stress and strain that is unique for each composite product type found by recording the amount of deformation (strain) at distinct intervals of tensile or compressive loading (stress). In addition the analyses also considered the self-weight of the piles and a buoyancy factor of zero to ignore P-Delta effects since most of the dolphins will have minimal self-weight. The P-Delta effect is a destabilizing moment equal to the force of gravity multiplied by the

horizontal displacement a structure undergoes when loaded laterally. Refer to Table 4 for a summary of the analyses results.

Table 4: Summary of Pile Group Analyses

I.D	Diameter	Thickness (inch)	Stiffness (EI)	Moment Capacity (kip-ft.)	Target Energy Absorption (Kips-ft.)	Dolphins Options				
						No of Piles	Impact Load (kips)	Deflection (Inch)	Energy Absorption Capacity Kip-ft.	
BEDFORD Technology (SEAPILE)										
1	10" dia.	5.0	1.81E+08	48	100	17	35.0	70.9	103	
2	13" dia.	6.5	7.88E+08	177		5	28.0	85.1	100	
3	16" dia.	8.0	1.29E+09	226		3	27.5	88.5	101	
HarborPile™										
4	10" dia.	0.500	6.40E+08	82	100	17	52.0	52.5	114	
5	12" dia.	0.625	1.30E+09	144		9	50.0	51.3	107	
5	14" dia.	0.625	2.00E+09	189		7	63.0	40.7	107	
6	16" dia.	0.875	3.70E+09	327		5	60.0	40.7	102	
7	18" dia.	0.625	3.90E+09	303		4	53.0	46.2	102	
8	20" dia.	1.000	8.80E+09	593		3	65.0	41.7	113	
9	24" dia.	1.500	2.10E+10	1198		2	80.0	33.1	110	
10	36" dia.	1.500	6.70E+10	2645		1	79.0	39.4	130	
Creative Pultrusions, Inc. (SUPERPILE)										
11	12" dia.	0.375	1.22E+09	167		100	9	60	42.7	107
12	12" dia.	0.500	1.77E+09	289	4		50	61.3	128	
13	16" dia.	0.500	4.38E+09	437	3		48	52.4	105	
Pearson Pilings										
14	8" dia.	0.117	1.19E+08	32	100	29	38	67.1	106	
15	10" dia.	0.250	3.21E+08	78		17	45	70.1	131	
16	12" dia.	0.375	9.33E+08	112		13	52	50.5	109	
17	12HD" dia.	0.500	1.21E+09	374		3	28	98.9	115	
18	14" dia.	0.375	1.53E+09	278		4	35	72.0	105	
19	16" dia.	0.500	2.51E+09	404		3	40	67.1	112	
Lancaster Composite Pile										
20	8" dia.	0.125	2.07E+08	39	100	25	35	96.8	141	
21	10" dia.	0.145	4.76E+08	72		17	40	81.6	136	
22	12" dia.	0.175	9.44E+08	122		9	35	79.0	115	
23	14" dia.	0.185	1.33E+09	151		5	28	87.2	102	
24	16" dia.	0.205	1.98E+09	200		4	31	82.4	106	

The results indicate that each of the composite piles considered in this study are viable options for use in fender and dolphin applications. The results indicate that marine structures can be configured in numerous ways to resist the kinetic impact energy of the errant vessel while sustaining deformation with acceptable value. This result can be achieved by use of different types of composite pile from different manufacturers or using a wide range of geometries of a particular composite product.

The results also indicate that SSI relies on the stress strain curves (mechanical properties) of composite product to estimate energy absorption capacity and/or characteristics load-deflection curve of marine structure. Currently however there are no threshold limits on the stress strain curve behavior that a composite product must meet for use in marine construction. The stress strain curve represents the deformation behavior of material when it is subjected to load and this curve reflects the combined effects of several properties such as elastic constants, strength and ductility. Therefore a marine structure can be designed in a similar fashion to a fiber-reinforced plastic composite product (where an engineered product is manufactured to provide required properties) as detailed below:

- 1) Use either a composite element (pile group) that has weaker strain-strain curve characteristics or a composite element that has stronger strain-strain curve characteristics, where strict deformation criteria does not govern while achieving a design energy absorption capacity.
- 2) Use either a composite element (pile group) that has stronger strain-strain curve characteristics or a composite element that has weaker strain-strain curve characteristics, where deformation criteria govern and while achieving design energy absorption capacity.

Table 5: Feasible options to meet (assumed) required design criteria

Required Energy Absorption Capacity	Maximum Permissible Deformation	Product Type	Feasible Options I.D*
<i>Design with deformation criteria</i>			
100 kips-ft.	84	BEDFORD Technology (SEAPILE)	1
		HarborPile™	4 Through 10
		Creative Pultrusions, Inc. (SUPERPILE)	11 through 13
		Pearson Pilings	14 through 16 and 18 through 19
		Lancaster Composite Pile	21 and 24
<i>Design without deformation criteria</i>			
100 kips-ft.	None	BEDFORD Technology (SEAPILE)	1 through 3
		HarborPile™	4 Through 10
		Creative Pultrusions, Inc. (SUPERPILE)	11 through 13
		Pearson Pilings	14 through 19
		Lancaster Composite Pile	20 Through 24
* Listed feasible options are representative of few selected options considered in Table 4. It shall be noted that there are infinite feasible options possible to meet design criteria.			

Based on the analyses results, it was concluded that a variety of readily available composite piles may be suitable for the use in the construction of fenders and dolphins depending on specific project deformation and energy absorbing criteria and that pile group configurations can be designed to meet commonly applied project criteria. This conclusion is likely to extend to additional varieties of composite products that are available in the market, but which were not specifically investigated in this study.

Conclusion and Recommendations: The results of our parametric study indicate that all of composite piles considered in this study meet the requirements for use in marine structures and the current performance requirements within specification Section 916.01 - Fiberglass Composite Materials of NJDOT Standard Specifications. The current specification however, currently favors a limited number of manufacturers and does not address the technical reasoning and basis for the specification. Therefore current Specification Section 916 should be revised to encourage participation by a wider variety of composite pile manufacturers that are currently available in the market. This revision is likely to encourage a more competitive bidding environment.

Limitations: This memorandum has been prepared on behalf of and for the exclusive use of the client, The College of New Jersey (TCNJ), for the NJDOT Bureau of Research: Fiberglass Composite Materials Specification Redevelopment (Project No. 2014-15-02). The scope of our services for this project did not include revising or redevelopment of Section 916 of NJDOT standard Specification. Hardesty & Hanover, LLC (H&H) will not be responsible for any claims, damages, or liability associated with redevelopment of section 916 of NJDOT standard Specification.

H&H has attempted to conduct the services reported herein in a manner consistent with the level of care and skill ordinarily exercised by members of the profession currently practicing in design of marine structures such as fenders and dolphins using composite products. The analyses, conclusions and recommendations contained in this memorandum are based on the LPILE and FB-Multiplier (FBMP) using assumed loadings and water/soil profiles as described. These software products do not specifically consider composite product materials and the assumed water/soil profile may not apply to all project locations, therefore our conclusions and/or recommendations are somewhat interpretive. The recommendations and conclusions contained in this report are professional opinions. No other representation, expressed or implied, and no warranty or guarantee is included or intended in this document.

Sincerely,



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Calculations

Attachment 1 - FRP Product Details

Attachment 2 - Single Pile Analyses (Deformation Characteristics)

Attachment 3 - Single Pile Analyses (Energy Absorption Capacity)

Attachment 4 - Dolphins Analyses (FB-Multiplier)

See Supplementary Materials

APPENDIX C- RING TEST STANDARD

NJDOT #-# – TRANSVERSE FLEXURAL PROPERTIES OF THERMOSET STRUCTURAL MEMBERS WITH CIRCULAR CROSS-SECTIONS

1.0 Scope

This test provides a method which can be used to determine the transverse flexural modulus of thermoset structural members with circular cross-sections for use as polymer structural members in bridge fender systems, bulkheads, and light structures.

2.0 Apparatus

2.1 Testing Machine

The testing machine shall be calibrated in conformance of ASTM E4. Data of force versus displacement must be permanently recorded or stored digitally and post processed.

2.2 Ring Test Tension

The testing machine shall have the capability of applying force to a tension test fixture as shown in Figure 1. The supports for the ring shall be round.



a) Tension test apparatus

b) Specimen in tension test apparatus

Figure 1. Ring Test Tension Apparatus

3.0 Specimen Geometry

3.1 Sampling Geometry

Specimen shall be sampled directly from full-scale products. The sides of the specimen shall be machined or cut parallel to one another to produce a ring with rectangular cross-sections. The minimum ratio of width to thickness shall be 2.

3.2 Characterization of Sample Geometry

Prior to testing, the diameter, width, and thickness of each ring are determined as follows:

1. Create a mark, labeled Point A, placed on an arbitrary location on the ring circumference.
2. Trace the inner circumference and label Point A, Figure 2a.
3. Place the corner of a right-angle triangle or a carpenter square drafting tool at Point A and add marks, A' and B, Figure 2b.
4. Place the corner of the drafting tool at B and align one of its sides with line segment A-B. Marked B', Figure 2c.
5. Locate the center by intersecting line segments A-A' and B-B' (Figure 2d).
6. Using a protractor, divide the circle into twenty-four 15° degree segments and make twelve diameter measurements, Figure 2d.
7. Make width and thickness measurement every 30° from Point A, resulting in 12 measurements.

Report the mean values from the twelve measurements of diameter, width, and thickness as:

r_m = average measured inner radius
 t_m = average measured thickness
 w_m = average measured width

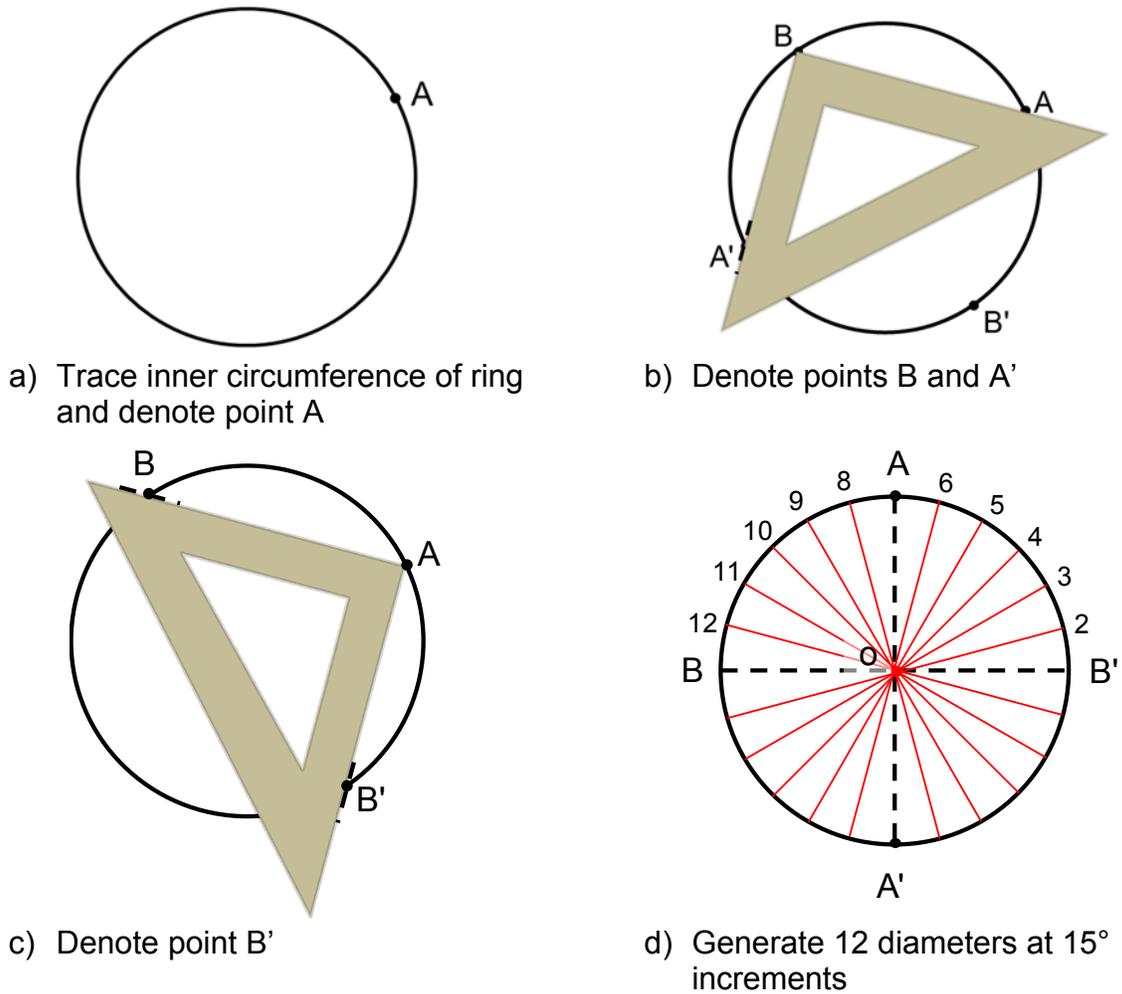


Figure 2. Measurement of rings

4.0 Installation and Testing

4.1 Fixture and Specimen Installation

Install all fixtures in the testing machines so that they are aligned vertically and horizontally. Install all specimens in the fixtures so that all loading points are contacted.

4.2 Test Speed

The maximum test speed is 0.01 in/min

5.0 Calculations

5.1 Elastic Flexural Modulus Ring Test

Equation 1 gives the flexural modulus for the ring specimens in tension.

$$E = 0.148m \frac{R_m^3}{I} \quad \text{Equation 1}$$

where:

E = elastic flexural modulus

$$R_m = r_m + \frac{t_m}{2}$$

$$I = \frac{w_m t_m^3}{12}$$

m = slope of initial linear portion of the load-deflection curve

**APPENDIX D- REVISED NEW JERSEY DEPARTMENT OF TRANSPORTATION
SPECIFICATIONS**

Section 511 – Bulkhead, Fender, and Dolphin Systems

511.01 Description

This Section describes the requirements for constructing bulkhead, fender, and dolphin systems using concrete, steel, timber, or **polymer structural members**.

511.02 Materials

511.02.01 Materials

Provide materials as specified:

Concrete	903.03
Precast Structural Concrete	904.03
Prestressed Concrete	904.04
Structural Steel	906.01
Steel Piles	906.02
Bolts and Bolting Material	908.01
Coal Tar Epoxy Paint	912.01.03
Zinc Coating on Steel	912.02.01
Sawn Timber Posts	915.01
Timber Bearing Piles	915.02
Timber Sheet Piles	915.03
Timber for Structures	915.04
Timber Treatment	915.05
Polymer Structural Members	916.01

Provide tie rods, plate washers, turnbuckles, nuts, bolts, washers, and all other hardware in bulkheads made of steel with a dual coating system consisting of zinc coating (galvanizing) and coal tar epoxy paint.

511.02.02 Equipment

Provide equipment as specified:

Impact Hammers	1004.01
Vibratory Hammers	1004.02
Leads and Followers	1004.03

511.03 Construction

511.03.01 Bulkhead, Fender, and Dolphin Systems

A. **Working Drawings.** At least 30 days before beginning work, submit working drawings for approval for steel or concrete sheet piling, and polymer structural members.

1. **Steel and Concrete Sheet Piling.** Include design calculations, member size, member location, and penetration depth.
2. **Polymer Structural Members.** When using polymer structural members include the following
 - a. Product name and manufacturer as listed in the QPL
 - b. Test results demonstrating that materials used in the manufacturing of the polymer structural members are in accordance with AASHTO MP22¹.
 - c. Location of any embedded or attached lifting devices and use of pick-up or support points.
 - d. Location of the roughened surface where skin friction is needed between the pile and the soil.
 - e. Location of detailing of any splices, shoes, and top of pile connections required.
 - f. Catalog cuts, manufacturer's recommendations, schedules, diagrams, performance charts, physical appearance, and other characteristics.
 - g. Pile driving recommendations, including recommended driving energies.

¹The thermoplastic used in thermoplastic rectangular and circular structural members reinforced with solid glass fiber-reinforced polymer bars are exempt from the requirements of Sections 4.4.1 and 4.5.1 of AASHTO MP22-13.

B. **Shipping, Storing, and Handling.** Ship, store, and handle components, including fiberglass tubes, protective coatings, and concrete to avoid damage. When pile tips are required, attach to the pile before shipping. Store piles on a minimum of 6-inch wide timber cribbing arranged to support and to maintain straightness within the specified tolerance. Store components so that they may be easily inspected. When storing components, protect from exposure to extreme heat or impact. Only use fabric slings to move composite, timber, and concrete materials.

C. **Coating Steel.** Apply coal tar epoxy paint immediately after the installation of all connections, except for tie rods that do not have threaded ends. Paint unthreaded tie rods at least 72 hours before installation. Clean galvanized surfaces receiving coal tar epoxy paint according to SSPC-SP 6. Ensure that galvanizing is not damaged during the cleaning process.

Blast clean surfaces of sheeting, plates, and wales according to SSPC-SP 6. Coat the surfaces with coal tar epoxy paint as follows:

1. Immediately after blast cleaning, apply 2 coats of coal tar epoxy paint at a maximum coverage rate of 125 square feet per gallon. Ensure that the total dry film thickness of the 2 coats is not less than 16 mils at any point. Apply the coating by brush, roller, or spray. First coat may be thinned with a maximum of 10 percent of solvent according to the coating manufacturer; however, the second coat may not be thinned. Allow the first coat to thoroughly dry before applying the second coat. Allow the second coat to dry and harden before handling the steel.
2. Clean damaged or rejected areas of coating of foreign or loose material and promptly recoat the area. Remove the loose or damaged coating in the surrounding area, and brush the adjacent surface of the remaining sound film with methyl isobutyl ketone to provide a good bonding surface for the new coats.
3. Allow the top coat to cure for at least 72 hours before driving.

D. Constructing Bulkhead, Fender, and Dolphin Systems. When constructing with timber, drive nails flush with the surface of the wood. Ensure that driving does not cause hammer marks in wood surfaces. Drift sharpen the lower ends of timber sheet piling to wedge against the adjacent timbers. If the tops are battered in driving, leave slightly high and then cut off at the required elevation. After cutting, coat the ends of sheeting members and wales with 2 applications of coal tar epoxy paint.

Drive piles as specified in 502.03.03.B. The Contractor may use lighter driving equipment or vibratory pile drivers. Ensure that the completed piling is vertical, in line, driven to the prescribed depth, cut off to a straight line at the shown elevation, and watertight at the joints.

Ensure that polymer structural members are assembled according to manufacturer's recommendations. All hardware located in whalers must be recessed. Set material accurately to the required levels and lines, with members plumb and true and accurately cut and fitted. Securely attach Polymer Structural Member to substrate by anchoring and fastening as shown on Plans.

E. **Extensions and Splices.** Splice piles as specified in 502.03.04.

F. **Cut-Offs and Cappings.** Cut off and cap piles as specified in 502.03.03.E.

511.04 Measurement and Payment

The Department will measure and make payment for Items as follows:

Item	Pay Unit
CONCRETE SHEET PILING	SQUARE FOOT
STEEL SHEET PILING	SQUARE FOOT
TIMBER SHEET PILING	SQUARE FOOT
POLYMER STRUCTURAL MEMBER	LINEAR FOOT

Additional Reference Material

Item Number List

Construction Details CD-551-1, CD-551-2, CD-551-3, CD-551-4

The Department will measure FIBERGLASS REINFORCED PLASTIC LUMBER (FRPL) in cubic feet computed on the basis of volume of the shortest commercially available length that is placed.

The Department will measure the square footage of CONCRETE SHEET PILING, STEEL SHEET PILING, and TIMBER SHEET PILING by multiplying the average height and length of sheeting that is driven. The Department will determine the average height by extending a line from the bottom of the excavation to a vertical plane of the top of sheeting.

Section 916 – Polymer Structural Members

Ensure that the Polymer Structural Member is listed on the QPL, and conforms to the following material requirements.

1. Material Requirements. Provide polymer structural members made from one of the following materials meeting the requirements given in Table 916-1:

- Thermoset circular structural tubing.
- Thermoset polygonal structural tubing.
- Thermoplastic rectangular and circular structural members.
- Thermoplastic rectangular and circular structural members reinforced with solid glass fiber-reinforced polymer bars.

Table 916-1 Polymer Structural Member Material Requirements

Property	Test Method	Requirement
Glass Transition Temperature ¹	ASTM E1640	<i>Characteristic Value</i> Greater than or equal to 150° F
Indentation Hardness	ASTM D2240	<i>Characteristic Value</i> Greater than 40 Shore D

¹The thermoplastic used in *Thermoplastic rectangular and circular structural members reinforced with solid glass fiber-reinforced polymer bars* are exempt from glass transition requirements

2. Degradation Requirements. After conditioning in the following environments, ensure that polymer structural members meet the requirements of Table 916-2

- *Water*- Immerse samples in distilled water having a temperature of $100 \pm 3^{\circ}\text{F}$ for 3,000, hours.
- *Alternating ultraviolet light and condensation humidity* – Condition samples in an apparatus under Cycle 1 -UV exposure condition according to ASTM G154 for 3000 hours. Samples must be tested within two hours of removal from the apparatus.
- *Alkali* –Immersed samples in a saturated solution of calcium hydroxide (pH ~12) at ambient temperature of $73 \pm 3^{\circ}\text{F}$ ($23 \pm 2^{\circ}\text{C}$) for 3000 hours.
- *Freeze-thaw*: Expose samples to 3000 repeated cycles of freezing and thawing in an apparatus meeting the requirements of AASHTO T 161.

Table 916-2 Allowable Degradation Requirements		
Property	Test Method	Maximum Allowable Loss
Glass Transition Temperature	ASTM E1640	15% of Characteristic Value
Indentation Hardness	ASTM D2240	15% of Characteristic Value
Flexural Modulus	NJDOT Test ¹	15% of Characteristic Value
	ASTM D790 ²	
	ASTM D4476 ³	

¹Use this test method exclusively on thermoset circular structural tubing.

²Use this test method on thermoset polygonal structural tubing and thermoplastic rectangular and circular structural members

³Use this test method exclusively on the reinforcement of thermoplastic rectangular and circular structural members reinforced with solid glass fiber-reinforced polymer bars

3. Steel. Use steel materials as specified in Section 905.

4. Concrete. Use Class A concrete as specified in 903.03

For each production batch, thirty days prior to delivery, provide a certification of compliance as specified in 106.07 and sufficient materials for the ME to perform the required test in Table 916.01-1

Table 916.01-1 Acceptance Testing		
Property	Test Method	Number of Tests
Glass Transition Temperature	ASTM E1640	3
Indentation Hardness	ASTM D2240	5
Flexural Modulus	NJDOT Test ¹	3
	ASTM D790 ²	
	ASTM D4476 ³	

¹Use this test method exclusively on thermoset circular structural tubing.

²Use this test method on thermoset polygonal structural tubing and thermoplastic rectangular and circular structural members

³Use this test method exclusively on the reinforcement of thermoplastic rectangular and circular structural members reinforced with solid glass fiber-reinforced polymer bars

All test results must be greater than or equal to the characteristic value of the property determined during the degradation testing for the products most current acceptance into the QPL.



Bureau of Materials: Materials Approval Procedures

MAP Number: ###-##

Effective Date: _____

Approved By: _____

PROCEDURE FOR APPROVAL OF POLYMER STRUCTURAL MEMBERS

PURPOSE:

To establish a procedure to approve Polymer Structural Members for addition to the NJDOT Bureau of Material's Qualified Products List (QPL).

REFERENCES:

New Jersey Department of Transportation Standard Specifications for Road and Bridge Construction
Section 916

NJDOT Bridges and Structures Design Manual

TERMINOLOGY:

Polymer Structural Members are defined as one of the following:

- Thermoset circular structural tubing.
- Thermoset polygonal structural tubing.
- Thermoplastic rectangular and circular structural members.
- Thermoplastic rectangular and circular structural members reinforced with solid glass fiber-reinforced polymer bars.

The terminology used: Characteristic value (ASTM D 7290), Matrix (ASTM D3878), Plastic (ASTM D883), Thermoplastic (ASTM D3878), Thermoset (ASTM D3878). When definitions of terms are conflicting, those of ASTM D 3878 shall have the precedence.

PROCEDURE:

A. Manufacturer's Request for Approval.

The manufacturer must request in writing the approval of the **Polymer Structural Member**. Include the following information in the request:

1. The name, address and contact information for the manufacturer.
2. The name or designation of the Polymer Structural Member that is to be evaluated.
3. The type of Polymer Structural Member as defined in Section 916.1
4. Certification and documentation from an independent testing facility showing the Polymer Structural Member has structural adequacy as defined in Section C.
5. Certification documentation from an independent testing facility showing the Polymer Structural Member meets the material requirements given in Section 916
6. Calculations and certifications showing the structural properties, including ultimate strength and flexural strength requirements that are specified in Section 916.02 through 916.08.
7. Catalog cuts, manufacturer's recommendations for design and construction, schedules, diagrams, performance charts, physical appearance, and other characteristics.

Mail the request for approval to the following:

Mailing Address (USPS):

Manager, Bureau of Materials (Thiokol Bldg. 4)
New Jersey Department of Transportation
P.O. Box 600
Trenton, NJ 08625-0600

Street Address (UPS, FedEx, etc.):

Manager, Bureau of Materials (Thiokol Bldg. 4)
New Jersey Department of Transportation
930 Lower Ferry Road
West Trenton, NJ 08628

B. Bureau of Structural Engineering Review.

The Bureau of Structural Engineering will review the manufacturer's submittal for completeness. If the submittal is incomplete, it will be rejected. The Bureau of Structural Engineering will review the submittal to verify that it meets Section 916.03 requirements and NJDOT design parameters. The Bureau of Structural Engineering will make the final determination on the approval of **Polymer Structural Members** for addition to the QPL.

PROJECT ACCEPTANCE REQUIREMENTS:

Qualification of the **Polymer Structural Member** and its addition to the QPL does not constitute a blanket approval. On a project to project basis, the use of the **Polymer Structural Member** must be submitted for approval according to the Working Drawing procedures of the NJDOT Standard Specifications.

DISQUALIFICATION:

The ME may remove a **Polymer Structural Member** listing from the QPL for non-conformance with design and construction specification requirements or for a documented history of poor field performance. The manufacturer must notify the ME, in writing, of any change in product formulation or design. Failure to notify the ME of changes in product formulation will result in disqualification.

REQUALIFICATION:

The ME will reevaluate a product which has been disqualified and removed from the QPL only after submission of a formal request along with acceptable evidence that the problems causing the disqualification have been resolved.

The ME may require the manufacturer to requalify the product for any of the following reasons:

1. To ensure that obsolete **Polymer Structural Member** listings are not kept on the list, the ME may request written confirmation from the manufacturer that the material is still available and has not changed formulation or design. Failure to respond to the Bureau's written request will result in the product being removed from the list.
2. If the formulation or design of the material has changed, the ME may require that the product be requalified.
3. If the NJDOT Standard Specifications or NJDOT Bridges and Structures Design Manual change or if any referenced ASTM or AASHTO specifications change, the ME may require requalification to ensure that the product meets new criteria.

C. Requirements for Structural Adequacy.

The structural adequacy of components specified is determined from center-load flexural tests with criteria established in this section.

1. Test Specimens:

The test specimens must consist of the structural component having a length greater than or equal to $16\sqrt{D/Q}$ where D and Q are the flexural and shear rigidities of the components. The flexural and shear rigidities can be estimated by rational analysis or by tests stipulated by the Registered Design Professional.

2. Loading Procedure:

The loading procedure consists of the two stages:

Stage 1: the structural component will be subjected to an increasing superimposed load equal to not less than two times the equivalent design load. The loading must be left in place for a period of 24 hours.

Stage 2: The load applied in Stage 1 is removed and the component must be reloaded and subjected to an increasing load until either: a failure occurs, the superimposed load is equal to three times the equivalent design load, or the deflection exceeds one tenth of the test span.

3. Test Passing Criteria:

A component is considered to have successfully met the test requirements if the following two criteria are satisfied:

- 1) The test component recovers not less than 75 percent of the maximum deflection within 24 hours after the removal of the test load in Stage 1-loading.
- 2) The test component reaches three times the equivalent design load without failure during Stage 2-loading.