# COMPOSITE MATERIALS FOR PRESSURE VESSELS AND PIPES

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**Contents**

## Summary

Composite pipes and vessels are used in many environments due to their special properties such as high strength-to-weight ratio, corrosion resistance and the ability to be tailored to specific design requirements. As properties of the constituent materials and fabrication methods have improved, the use of composite pipe and vessels has increased accordingly. A brief history of the introduction of composite materials to industry and the subsequent development of composite vessels and pipes is presented. Also, the design, analysis and application of composite pipe and vessels is briefing outlined in this article.


## 1. Introduction

The use of composite piping and vessels has increased in industry as composite materials have improved and fabrication techniques have evolved. This section contains a brief description of the application of composite piping and vessels. Four areas will be covered. Section 2 is a brief historical background of the growth of the use of composite materials will be discussed. Section 3is a brief survey of the composite materials mechanics needed for design and analysis of composite piping and vessels. This material will be needed to understand the design and analysis presented in the last two sections. Section 4 describes the design and analysis of composite piping systems. This will include the type of information that an engineer will need to collect prior to starting design of a piping system. Section 5 is a brief introduction to the design and use of composite vessels. The information needed for design is similar to what is need for piping design. The arrangement of the four sections is shown schematically in Figure 1.

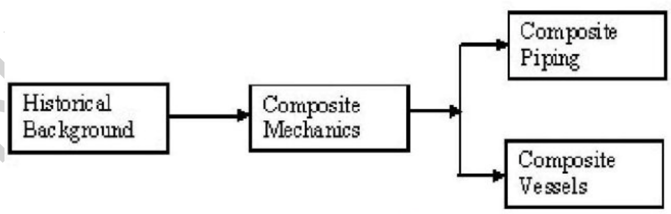


Figure 1. Outline of Sections

## 2. Historical Background

Man has known that two or more materials could be combined to form a new material with enhanced material properties for a long time. Ancient Jewish slaves used straw to enhance the structural integrity of the bricks they molded for the Pharaohs. The Egyptians wrapped human bodies in cloth saturated with natural resins as part of the mummification process. Japanese Samurai warriors used special laminating techniques to forge swords that had desirable physical properties. Around the Mediterranean and in the Far East, artisans used a type of composite technology to mold artwork using layers of paper cut to appropriate shapes. Composite materials also occur in nature, for instance, bone is a composite of the mineral apatite and the protein collagen, and wood is a composite of cellulose and lignin.

For purposes of this chapter, a composite material may be defined as the combination of two or materials on a macroscopic scale to form another useful material. Many examples exist today. A wooden pencil is a good example. Another very common example would be steel reinforced concrete that is used to construct buildings and roadways. The steel reinforcing bars act as tensile reinforcement for the brittle concrete matrix. In fact, almost all engineering materials are composites of one type or another. For example ordinary steel is painted to prevent corrosion and the two components work together to meet the design goals.

The development of fiberglass started in the 1920s, but fiberglass composite materials were not commercialized until after they were exhibited at the 1939 New York World's Fair. Grade E and C glass fibers are the most commonly used, but there are other grades available. Other reinforcing fibers that span a wide range of strengths and chemical resistance are also used when needed, a few examples are boron nitride fibers, carbon fibers, ceramic fibers, graphite fibers and jute.

The field of fiberglass reinforced plastics (FRP) began after World War II when fiberglass reinforced plastic radomes were first fabricated to house radar sets. The boating industry was the first to widely embrace the use of fiberglass reinforced plastics. The light weight of fiberglass reinforced plastic and the ability to mold it to complex shapes made fiberglass composites ideal materials of construction for boat fabrication. The first fiberglass boats produced suffered serious delamination problems early in their useful life. There was very little design data available for engineers to use in designing the boats. The boat manufacturers were forced to develop the necessary data through trial and error, and testing. The initial data that they accumulated and developed has been vastly expanded as the use of fiberglass reinforced plastics has moved into other industries.

Modern composite materials have found wide use in the chemical process, petrochemical, and pulp and paper industries primarily because of their corrosion resistance compared to steel and other metals. The class of fiber reinforced plastics includes many combinations of matrix and reinforcement materials. A number of resins have been widely used in these industries; including polyesters, vinyl esters, epoxies and furans. Each of the resins can be combined with an appropriate fiber reinforcement of the types mentioned above. The choice of a combination of matrix material and reinforcement material can be complicated and must be based on design goals, environment, and other factors such as physical testing, both in the laboratory and in actual plant service, and historical data. In weight sensitive applications such as off-shore oil platforms, the primary attribute of interest is the weight savings when compared to exotic metal alloys that would otherwise be required to contain corrosive liquids.

This limited definition of composite materials is in no way complete as there are many other composite materials in use. Metal-matrix composites are used where special temperature environments and load requirements make the use of plastic based composites unacceptable. But polymer composites have found applications in the chemical process industry, petrochemicals, oil, aerospace, and shipboard applications due to the many attributes of this type of composite materials. They have a high-strength-to-weight ratio, overall light weight when compared to metals, and good corrosion resistance.

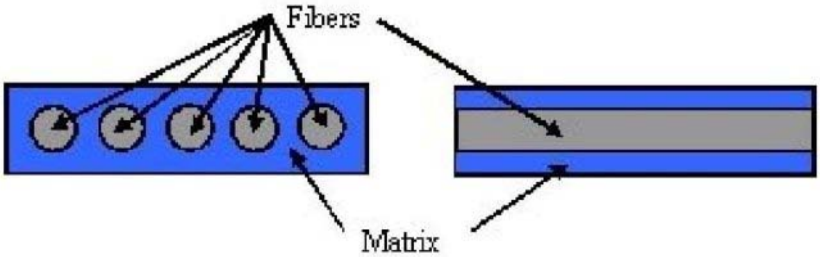


Figure 2. Single Lamina

Figure 2 shows two views of a single lamina, or layer, or ply, of a composite material. The sketch on the left is looking into the fiber direction and the gray fibers are perpendicular to the plane of the paper. The blue color represents the matrix material. In an actual composite laminate, several layers are stacked, often with different orientations for the fiber axis in different plys. The ability to tailor the strength of a laminate to particular design criteria is another advantage of composite materials. The sketch of a cut section on the right is at 90º to the first sketch, and shows the long axis of the fibers. The matrix is usually some type of polymer and its primary purposes are to provide dimensional stability and physical protection for the fibers. The fibers are considerably stronger in tension than the matrix material, but must be restrained against buckling for any compressive loading along the fiber direction. Fibers can be one of several types of glass, carbon, or other specialty fibers.

For applications in very corrosive services composite pipes can be produced with plastic and fluoroplastic liners, such as Teflon and PVDF (polyvinylidene fluoride). Plastic and fluroplastic lined composite pipes, fittings and other items are referred to as dual laminates. Dual laminated pipe, components, and vessels are necessarily more expensive than standard fiberglass pipe and components, but they are often still less expensive exotic metal alloy pipe, components, and vessels.

There are several options for valves used in fiberglass piping systems. Plastic lined metal valves are in common use. Lined metal lined valves are heavy and must often be supported externally to prevent overloading the composite piping or vessels. There are also valves fabricated of plastic or fiberglass reinforced plastics.

## 2.1. Fiberglass Piping

In 1950 fiberglass piping first became a viable alternative to more expensive coated steel, stainless steels and other exotic metal alloy piping. Centrifugally cast fiberglass pipe was offered that year to the oil industry as a solution to corrosion problems. Perrault Fibercast Corporation of Oklahoma used a patented process to manufacture the first pipe constructed of fiberglass reinforced polyester resin. The company was sold and later became Fibercast, Inc. The name change also involved a new focus for the business, and the piping material was also changed to epoxy resins that were more suitable to the chemical process industry. This expanded the use of fiberglass pipe significantly.

AmericoatBondstrand also started manufacturing pipe in the early 1950's in southern California. They produced filament-wound pipe for the chemical, industrial and military pipe markets.

Fibercast and AmericoatBondstrand purchased fittings from the Conley Corporation of TulsaOklahoma. The Conley Corporation patented the molding process and methodology used in the production of fiberglass fittings in 1954.

In the mid-1950's several new players entered the market place. Rock Island Oil and Refining Company introduced a filament wound high pressure fiberglass line pipe and downhole tubing product line that had threaded connections for use in oil field applications. Rock Island later became KOCH Fiberglass Products. A. O. Smith Corporation began field testing filament-wound, low-pressure fiberglass piping in 1955. This product line was introduced to the oil industry in 1960. During the period of 1955 to the mid-1960's, additional products and manufacturers entered the market place. By the mid-1960's fiberglass products began to be used in the municipal water and sewerage treatment markets.

It was also during this time frame that manufacturers began a concentrated effort to develop nationally recognized standards and test methods for fiberglass piping systems. The first specification that was developed was ASTM D1694, "Standard Specification for Threads (60˚ Stub) for Glass Fiber Reinforced Thermosetting Resin Pipe" was issued in 1959. In 1962 ASTM D1599, "Standard Test Method for Short-Time Hydraulic Failure of Plastic Pipe, Tubing and Fittings" was issued. Many nationally recognized standards have been developed since these initial efforts were completed.

Many organizations exist today that are involved in developing nationally recognized standards and specifications. These include the American Society of Testing and Materials (ASTM), American Petroleum Institute (API), American Water Works Association (AWWA), American Society of Mechanical Engineers (ASME), National Sanitation Foundation (NSF), Underwriters Laboratory, Inc. (UL), Factory Mutual Research (FM), and the military (MIL).

During the 1980'sReinforced Thermosetting-Resin Pipe (RTRP) became known simply as fiberglass piping. Several names are now in common usage. Fiberglass Reinforced Plastic (FRP), Fiberglass Reinforced Epoxy (FRE), and Glass Reinforced Plastic (GRP) are a few of the many terms in use.

### 2.2. Fiberglass Tanks and Vessels

The oil industry was one of the first to use fiberglass tanks. When a well is being drilled, or maintained, small atmospheric storage tanks are used to contain various liquids including brines and drilling mud. These tanks are moved from site to site by truck. Fiberglass tanks were an obvious choice due to their light weight and corrosion resistance as compared to carbon steel tanks. Fiberglass tanks are fairly robust and can handle the rough treatment they endure during transport by gin-pole truck or on flatbeds trailers.

The earliest tanks were formed one half at a time on plywood forms by hand lay-up techniques. Two halves were then welded together with a butt and strap joint to form the tanks. General purpose tanks often had stainless steel couplings placed into holes in the shell and were then over-laid with fiberglass resin and fiber reinforcement mats to form the connections for liquid hoses.

As tank usage increased and moved into the chemical process industry and paper industry, design and fabrication methods evolved. Filament winding was developed to form one-piece vessel shells. And nozzles replaced couplings for tank connections. Filament winding enabled tighter control over tank wall thickness and other dimensions and reduced the chances of unwanted gaps in the laminate where liquids could get inside the laminated tank wall and attack the wall structure. This provided improved tank integrity and improved corrosion resistance. There are obvious size limitations associated with filament winding equipment, and transportation of filament wound tanks produced in a fabrication shop. Tankinetics, Inc. has developed the capability of filament winding larger tanks up to eighty-two foot diameter on a customer's foundation. Also sections or rings of larger diameter tanks can be folded and shipped to a customer's site for on-site assembly by welding a sequence of rings to form the tank wall.

Higher pressure applications led to composite pressure vessels. Early pressure vessels were fabricated with one extra vessel fabricated for destructive testing. As fabrication techniques and materials improved, design methods were developed to eliminate the destructive testing requirement. The most notable pressure vessel construction standard is Section X of the ASME Boiler and Pressure Vessel Code.

For applications in very corrosive services composite tanks and vessels can be produced with in a dual laminate configuration – a fiberglass tank shell with a liner constructed of plastic. Many different plastics and fluoroplastic liners such as Teflon and PVDF (polyvinylidene fluoride) are available. Dual laminate vessels have also been fabricated for transportation service as cargo tanks, or highway trailers. Dual laminate equipment is necessarily more expensive than standard fiberglass equipment, but they are often still less expensive than exotic metal alloy tanks and components.



## 3. Mechanics of Composite Materials

### 3.1. Introduction

Design and analysis of composite piping and valves requires some preliminary mathematical analysis. There are many texts available on the analysis of isotropic and anisotropic materials. In this section, some of the pertinent results will be presented without derivation or excessive explanation. The goal of this section is to summarize the available analysis for practical application of composite materials in piping and vessels.

Analysis begins with characterizing the composite material. All practical analyses involve a smearing of the properties of the constituent parts, i.e., the matrix and reinforcement and the individual lamina. Much work has been conducted in attempts to characterize the composite material in terms of the relative amounts of matrix material and the amount and form of reinforcement without considering the interfacial geometry. The methods that have been developed range from simple rule of mixtures formulas to very complicated expressions. A survey of these micromechanics results can be found in Christensen's book. The methods can be useful in some cases, but for the structures considered in this section there are simpler methods of characterization available.

In general form, Hooke's Law can be expressed in Cartesian tensor notation as

$$\tau_{ij} = C_{ijkl} e_{kl} \qquad (1)$$

Where $\tau_{ij}$ is the stress tensor, $C_{ijkl}$ is the stiffness tensor or elasticity tensor, and $e_{kl}$ is the strain tensor. The stiffness tensor is a fourth order tensor and has 81 components. In the case of complete anisotropy, it would theoretically require 81 separate physical parameters to completely characterize the material. Fortunately, not all of the components are independent. Symmetries in *ij* and *kl* indices reduce the number of independent components to 21. Practical laminates are orthotropic and only have 9 independent constants. For plane problems, there are only 6 independent constants. The limiting case is an isotropic material where only two parameters, the modulus of elasticity $E$ and Poisson's ratio $\nu$, are required to completely characterize the linear behavior of the material.

In composite material texts and technical papers there are two types of notation used. The axes are referred as either $x, y, z$ or 1, 2, 3. The notations are interchangeable and both are used here for convenience. General equations are generally written in the 1, 2, 3 notation and specific problems may be expressed in $x, y, z$ notation. The following shorthand notation will be useful in writing stress and strain equations in the design and analysis of composite pipes and vessels.

$$\begin{aligned} &\sigma_1 = \sigma_{11}\,;\, \sigma_2 = \sigma_{22}\,;\, \sigma_3 = \sigma_{33}\,;\, \sigma_4 = \sigma_{23}\,;\, \sigma_5 = \sigma_{13}\,;\, \sigma_6 = \sigma_{12} \\ &\varepsilon_1 = \varepsilon_{11}\,;\, \varepsilon_2 = \varepsilon_{22}\,;\, \varepsilon_3 = \varepsilon_{33}\,;\, \varepsilon_4 = \varepsilon_{23}\,;\, \varepsilon_5 = \varepsilon_{13}\,;\, \varepsilon_6 = \varepsilon_{12} \end{aligned} \qquad (2)$$

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**Biographical Sketch**

**Dr. Jack E. Helms, Jr., P.E.** received his Ph.D. degree in Mechanical Engineering from Louisiana State University in 1998. He received his B.S.M.E. and M.S.M.E. degrees from the University of Arkansas in 1974 and 1975, respectively. Jack retired from the Albemarle Corporation, a specialty chemical manufacturer, in the summer of 2005 after more than 30 years of service. His career included 13 ½ years as a project engineer in a bromine chemicals plant where corrosion was a major problem, and the extensive use of composite pipe, tanks and pressure vessels were developed during his time in the plant. Since 2007 Jack has been Professional-in-Residence in the Department of Mechanical Engineering at Louisiana State University. Dr. Helms teaches both undergraduate and graduate courses, and serves as Undergraduate Program Coordinator.