ANALYSIS for DESIGN of FIBER REINFORCED PLASTIC VESSELS and PIPINGS

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PREFACE

This book is intended to be used by designers of fiber reinforced plastic tanks, vessels and pipings, particularly those in the chemical processing industry. Fiber reinforced plastic vessels and pipings in this particular industry have been used mainly for corrosion applications. For containing many chemicals, fiber reinforced plastic vessels and pipings provide better corrosion resistance than metallic vessels. As chemical processing equipment, these vessels and pipings have many discontinuous regions in their structures such as manhole connections, nozzles, supports, joints, etc. They are also subjected to different loadings such as internal pressure, external pressure, thermal loads, lateral loads, etc. This makes the structure of these vessels much more complicated than vessels used in aerospace applications where only one or two openings at the ends are required for filling purposes. For this reason, the construction of chemical processing vessels and pipings requires both continuous and discontinuous fibers involving a combination of techniques such as contact molded and filament winding. In spite of the fact that these structures are complicated, little effort has been spent in studying the mechanical behaviour of these structures. Lacking the knowledge on the directional dependence of the mechanical properties of the materials, while at the same time having to construct the containers required, designers almost constantly have to utilize equations developed for isotropic metallic vessels to design anisotropic fiber reinforced plastic vessels. Realizing this weakness, the new section 10 (1989) of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code included the use of laminate theory for the analysis for design of fiber reinforced plastic vessels.

In more than the last two decades, the aircraft and aerospace industry has been pushing rapidly the advance of knowledge on composite materials. These consist of graphite/epoxy, Kevlar/epoxy, boron/epoxy, glass/epoxy, etc. Although these materials are different in composition from the glass/polyester materials usually used in the chemical processing vessels, their anisotropic mechanical behaviour is similar. It is, therefore, the intention of this book to utilize the principles that have already been developed for composite materials in the aircraft industry and apply these principles for the analysis for design of fiber reinforced plastic vessels and piping in the chemical processing industry.

This book consists of seven chapters. Chapter 1 gives an introduction to fiber reinforced plastic vessels, tanks and pipings. In Chapter 2, properties of the constituent layers making up the wall thickness of FRP vessels and tanks will be presented. Failure theories designed to predict the failure strains or loads of these layers will be examined. The laminate analysis will be done in Chapter 3. Laminate theory will be used to derive the properties of the laminate from different combinations and stacking sequences of the constituent layers. Different failure theories for situations where laminates are subjected to different loadings are examined. The case where the vessels or tanks are subjected to internal pressure is presented in Chapter 4. Shell theory will be used to calculate the strains and stresses in the wall material. Failure theories and failure modes are also examined. Examples of a few typical designs are presented. Stability of the vessels and tanks under external pressure and axial loads is examined in Chapter 5. Design equations from different codes and standards will be compared to formulation using shell theory using examples. In Chapter 6, thermal stresses in the wall materials will be examined. Finally, in Chapter 7, works done on the effect of discontinuities such as manhole or nozzle openings and the effect of saddle support on horizontal vessels will be examined.

The culmination of this work is the result of efforts of many co-workers, for which I would like to express my sincere appreciation. Among them I would like to particularly thank Mr. J.A. Kidd at CPF Dualam Ltd. for providing vessels, samples and technical guidance concerning the relevance of the research work, many of my graduate students and research associates and assistants who have carried out research and testing work, Patricia Stewart for typing the first version of the manuscript and Sophie Mérineau for typing this manuscript.

Montreal, February 1991

CONTENTS

1. INTRODUCTION

1.1. General

There are many reasons why fiber reinforced plastics (composites) have been used to make vessels and storage tanks. The first reason is the good corrosion resistance of fiber reinforced plastics. In corrosive environments such as in many acids, fiberglass reinforced vinyl ester composites outlast many steel counterparts. The second reason is the low weight but high strength, high stiffness of the advanced composites such as glass/epoxy, graphite/epoxy or kevlar/epoxy materials. In situations where transportation is important, light weight can offer a great advantage. The range of properties of composites varies greatly. One can go from the low end composites of glass mat/polyester with a tensile modulus of about 8 GPa (1.17 msi*)[1] and tensile strength of about 103 MPa (15000 psi) to an advanced composite of graphite epoxy with a tensile modulus of 181 GPa (26.5 msi) and a tensile strength of 1500 MPa (220 ksi*)[2]. The degree of material and process control for the different materials also varies in the same proportion. Needless to say, the material cost is of similar variation. Depending on the type of composites that is used, different types of composite vessels are produced.

1.2. Types of Fiber Reinforced Plastic Vessels

The end uses of fiber reinforced composite pressure vessels fall into three relatively distinct markets (industrial, military and aerospace/aeronautical) each governed by their own design and qualification procedures. For instance, standard industrial vessels require a design (or burst) pressure of at least six times the maximum anticipated operating pressure to alow for fatigue situations and less stringent quality control procedures [1.1]*[3]. Vessels for the military and aerospace sectors are generally manufactured from higher quality materials with tighter manufacturing control and are allowed a safety factor of two or three depending upon the situation. Low pressure service (up to 3.5 MPa (500 psi)) is common in the chemical process industries where the corrosion resistant properties of polyesters or vinyl esters are combined with the low cost of the E-glass fibers to produce pressure vessels with economic advantages over their metal counterparts. Advanced composites such as kevlar 49, carbon, and S2 glass fibers combined with an epoxy matrix see service in the low presssure military and aeronautical sectors as storage containers for rocket fuel and oxidants. The increased cost of these materials and the higher level of technical expertise required for their effective use has limited the penetration of these composites into the industrial sector. Increasing service pressures sees the elimination of the polyester resin family in favor of epoxy resins. E-glass as a structural fiber is also replaced by the more advanced fibers. Table 1.1 summarizes the vessels according to service pressure as well as target markets.

1 * 1 msi = 10^6 psi

2 * 1 ksi = 10^3 psi

3 * Numbers in bracket refers to references at the end of the chapter.

Service Pressure MPa (psi)	Industrial Market	Military Market	Aerospace/Aeronautical Market	Remaining Challenges
Low	E glass/polyester		S glass, Kevlar, Carbon/Epoxy	
0 - 3.5 (0 - 500)	- compressor tanks - chemical storage/ processing - filtration tanks		- rocket fuel/oxidizer storage	manufacturing economics
Moderate	E glass, S glass/epoxy		S glass, Kevlar, Carbon/Epoxy	
3.5 - 14 (500 - 2000)	- chemical storage/ processing - salt water desalination		- rocket fuel/oxidizer storage - nitrogen storage for spacecraft	manufacturing economics
High	S glass, Kevlar/epoxy	S glass, Kevlar, Carbon/epoxy	Kevlar/epoxy	
14 - 70 (2000 - 10000)	- compressed natural gas - compressed air back pack	- rocket launching tubes	- compressed air (Boeing 747) - compressed helium (shuttle) - air tanks/space suits - hydrogen storage (Venus probe)	- liner buckling - liner weight - manufacturing variability
Ultra-High	Metals	S glass/Kevlar/ Carbon Hybrids	S glass, Kevlar, Carbon hybrids	
70+ (10000+)	- high pressure processing - material research - detonation tanks	- compressed helium/missile systems	- compressed helium/spacecraft	- composite material properties - liner problems

Table 1-1: Composite Pressure Vessel End Uses [1.2]

A simplified view on the relationship between internal pressure p, inside vessel diameter D and thickness t would indicate that the larger is the internal pressure, the larger should be the thickness and the smaller should be the diameter of the vessel to contain that pressure. Vessels for high internal pressures (above 14 MPa (2000 psi)) are usually small (about 254 mm (10 inches) or smaller in diameter) and thick (can be up to 50.8 mm (2 inches) thick). Vessels for lower pressures (less than 14 MPa (2000 psi)) are usually large (can be up to 1 m (39.4 inches) in diameter) and thin (several milimeters or fractions of an inch).

The American Society of Mechanical Engineers Boiler and Pressure Vessel Code, Section X, Fiberglass Reinforced Plastic Vessels [1.1] distinguishes two classes of vessels: class I and class II. Class I designs based on the qualification of a prototype vessel require that the minimum burst pressure of the prototype be at least six times the design pressure. The maximum design pressure is limited to 1.03 MPa (150 psi) for bag-molded, centrifugally cast, and contact molded vessels; 10.3 MPa (1500 psi) for filament-wound vessels with cut filaments; and 20.6 MPa (3000 psi) for filament-wound vessels with uncut filaments (ports on axis of rotation only).

Class II designs based on mandatory rules and acceptance testing are for one of a kind vessels (low volume production). The maximum design pressure and inside diameter of class II vessels are restricted as follows:

a. Vessels designed in accordance with Method A (Design Rules) are limited to a maximum internal pressure of 0.51 MPa (75 psi) and a maximum inside diameter of 2438 mm (96 in).

b. Vessels designed in accordance with Method B (Discontinuity Analysis) have pressure and diameter restrictions as follows.

   i) the algebraic product of the internal pressure (psi) and the inside diameter (in) shall not exceed 7200 (PD = 7200)

   ii) the maximum internal pressure shall not exceed 1.37 MPa (200 psi)

   iii) the maximum inside diameter shall not exceed 3658 mm (144 in)

c. Vessels may be designed using a combination of Methods A and B. For such vessels the maximum design pressure shall be limited to 0.51 MPa (75 psi) with a maximum inside diameter of 2438 mm (96 in).

d. Vessels designed by either Method A or B shall be limited to an external pressure of 0.1 MPa (15 psig).

Even though the design method can be applicable to vessels containing internal pressure from zero, the American Boiler and Pressure Vessel Code, Section X [1.1] restricts its jurisdiction to above 0.1 MPa (15 psig). For vessels containing internal pressure below 0.1 MPa (15 psig), the jurisdiction falls under the Reinforced Thermoset Plastic Corrosion Resistant Equipment, ASME/ANSI [1.3]. The technical reason for this distinction is not clear.

Filament wound vessels with uncut fibers can contain high pressures and have found applications in solid rocket motor cases, fireman's breathing systems, fire extinguishers, emergency actuation power, airplane escape slide inflation cylinders, over the highway trailer tubes for compressed gas, etc. [1.4.]. These high pressure vessels usually have a metallic liner (aluminium or titanium) overwrapped with high strength glass, graphite or kevlar fibers [1.5], [1.6]. This mode of manufacture produces uncut fibers and the only area of discontinuity is at the end port. Since these vessels are relatively thick, thin walled formulas are no longer applicable and many attempts have been made for the calculation of stresses in these vessels [1.2, 1.7 to 1.9].

High pressure composite pressure vessels are undergoing rapid development particularly for applications for containers of compressed natural gas or liquified natural gas for commercial vehicles. It is not the intention of this book to go into deep details on the design and analysis of these vessels. The reader is recommended to refer to the cited references for further study.

1.3. Fiber Reinforced Plastic Vessels in the Chemical Processing Industry

Due to their good corrosion resistance, fiberglass reinforced plastic materials have been used in making chemical processing tanks, vessels, and in making pipes for transporting these chemicals. These tanks and vessels are usually large. The diameters of storage tanks can be up to 3048 mm (10 ft). Figure 1.1 shows an acid storage tank. Figures 1.2 and 1.3 show a long and two short pressure vessels. It can be seen that these tanks and vessels have openings for nozzles, manholes, etc. and therefore the filaments are cut. These openings create discontinuities in the structure. The large size combining with the discontinuities limit the operating pressure of these vessels. Also due to their large sizes, these vessels and tanks are not commonly mass produced. Each tank or vessel is different and they are usually custom made. Economic consideration does not allow manufacturers to destructively test one vessel to prove that another identical one meets the design requirements. These vessels therefore fall under the class II category of the ASME code [1.1].

Codes, standards and guides for fiber reinforced plastic vessels and tanks

Over the years there have been many codes and standards formulated to provide guidelines for the design, manufacturing and quality control of fiber reinforced plastic vessels and tanks. In 1960, Gibbs & Cox Inc. produced a Marine Design Manual [1.10]. This design manual provides basic engineering properties of reinforced laminates such as specific gravity, strength, moduli, Poisson's ratio, creep, resistance to impact, etc. Laminates are made of mat and/or woven roving reinforcements and polyester resins by contact molded method of manufacture. Variation of properties with respect to direction of loading was also provided for these materials. As its title implies, this manual is for the manufacture of boats and marine structures. However, since the materials are similar, this manual has been useful to manufacturers of fiberglass reinforced polyester tanks, vessels and piping.

Figure 1.1: Fiber reinforced plastic acid storage tanks

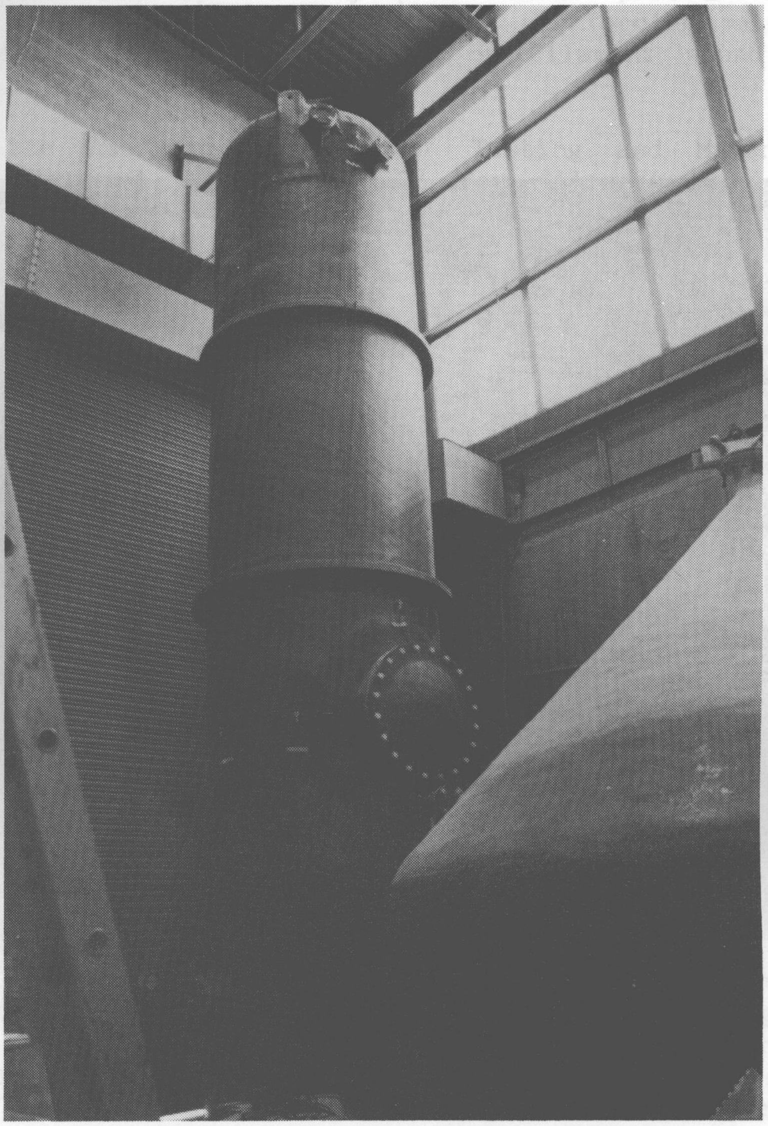

Figure 1.2: A fiber reinforced plastic vessel under hydrostatic test

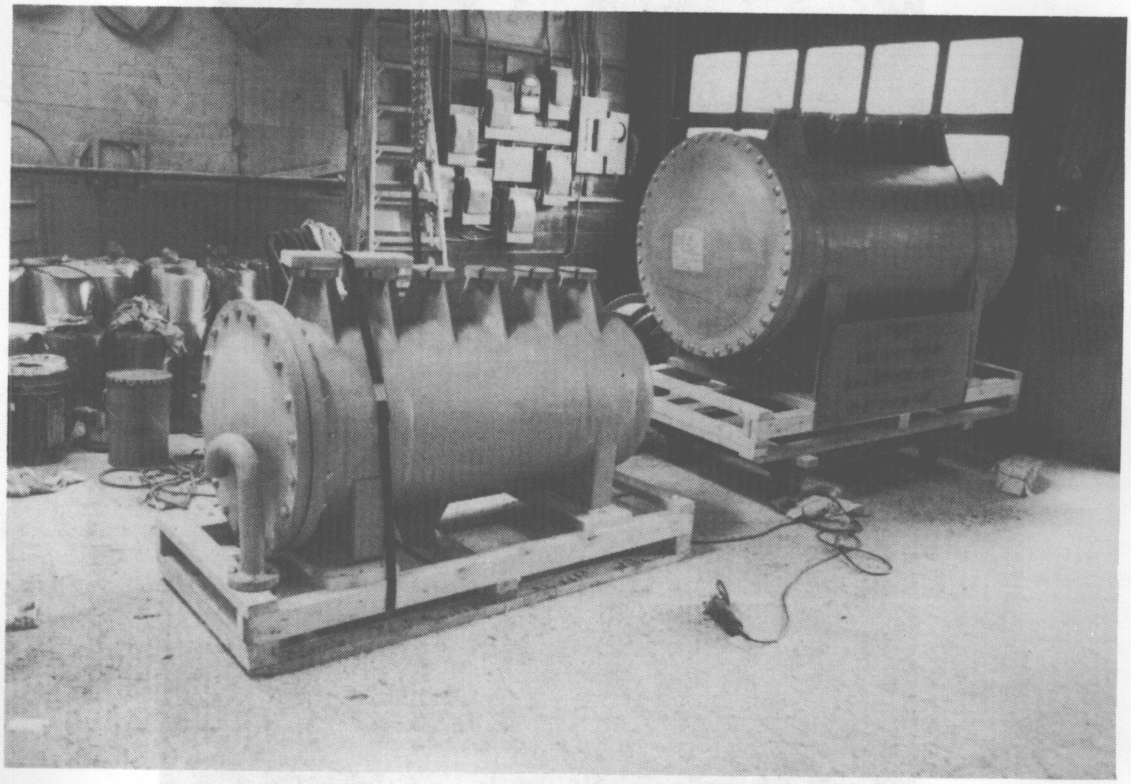

Figure 1.3: Small fiber reinforced plastic vessels

In 1969, the US Department of Commerce, National Bureau of Standards produced the NBS Voluntary Product Standard PS 15-69 [1.11]. This is a Voluntary Standard developed by producers, distributors and users with the cooperation of the National Bureau of Standards. This product standard covers materials, construction and workmanship, physical properties, and methods of testing reinforced polyester materials for process equipment and auxiliaries intended for use in agressive chemical environments, including but not limited to pipe, ducts and tanks. The standard is based on the technology of fabrication by hand lay-up or contact pressure molding. It does not cover resins other than polyesters, reinforcing materials other than glass-fibers, laminate constructions or filament wound fabrication methods.

In 1974, the American Society for Testing and Materials (ASTM) published ASTM Standard D3299-74 [1.12] for filament-wound glass-fiber reinforced polyester chemical-resistant tanks. This standard specification covers the composition, performance requirements, construction practices and workmanship, design, and methods of testing filament-wound glass-fiber reinforced polyester tanks for use in aggressive chemical environments. It is limited to atmospheric pressure, vented, vertical, above ground cylindrical tanks, and is not to be used for vessels intended for pressure operation, for heating liquids above their flash points, or for vacuum conditions. It recommends a maximum service temperature of 82°C (180°F).

In 1976, the Commission Chaudronnerie Génie Chimique du Syndicat Général de l'Industrie du Plastique Armé (France) published a "Code de construction des appareils chaudronnés en plastique armé" [1.13]. This code covers materials and construction of vessels made of fiberglass reinforced thermosets, with or without thermoplastic liners. The construction of the vessel can be by contact molding or filament winding. The vessel can be subjected to internal pressure and external pressure.

In 1973, the British Standards Institution published the "Specification for vessels and tanks in reinforced plastics" BS4994-1973 [1.14]. In 1987, the Institution withdrew the BS4994-1973 version and published a 1987 version with a different title of "Specification for design and construction of vessels and tanks in reinforced plastics," BS4994-1987 [1.15]. This standard is the most commonly used to date. The standard specifies requirements for the design, materials, construction, inspection, testing and erection of vessels and tanks in reinforced plastics, consisting of a polyester, epoxy or furane resin system reinforced with glass-fibers, manufactured by the wet lay-up process. Constructions both with and without a liner of thermoplastics are included. The standard has some limited provision for filament winding in that the directional properties of the filament wound layers are discretized into a few angles. It does recommend the use of laminate theory for more accurate design calculations. This standard uses the concept of unit loading rather than stress. For example, the ultimate tensile unit strength is defined as the strength of a reinforcement type, expressed as a force per unit width, per unit mass of the reinforcement (N/mm per Kg/m^2 glass). The use of this concept facilitates the strength calculation in laminates having added or deleted number of layers. However, in calculations such as for stability under external pressure, unit modulus is not sufficient and the normally defined modulus values have to be calculated. Further details on this are explained in Chapter 2.

In 1989, the American Society of Mechanical Engineers (ASME), Boiler and Pressure Vessel code, Section X, published its revised code on fiberglass reinforced plastic pressure vessels [1.1]. It establishes the minimum requirements for the fabrication of fiber reinforced thermosetting plastic pressure vessels for general service, sets limitations on the permissible service conditions, and defines the types of vessels to which these rules are not applicable. It uses laminate theory to account for the anisotropic properties in different layers. It divides the vessels into two classes. Class I is for vessels that have high volume production and class II is for one of a kind, custom made vessels. It also imposes acoustic emission as a qualification test for class II vessels. The ASME code limits its jurisdiction to internal pressure above 0.1 MPa (15 psig). For vessels containing internal pressure less than 0.1 MPa (15 psig), the jurisdiction falls under the ASME/ANSI RTP - Standard called Reinforced Thermoset Plastic Corrosion Resistant Equipment [1.3]. This standard also uses laminate theory to account for the anisotropic properties of different layers.

There are also standards from other countries. The Canadian Standard CGSB41G22 [1.16] has been in existence over several years. This standard covers the general requirements common to all fiberglass reinforced plastic (FRP) products intended for use in corrosive industrial applications. These requirements outline the minimum acceptable parameters for materials, laminates, design and fabrication and levels of compliance for quality control and inspection.

The Germans also have developed their own specifications for fiber reinforced plastic vessels [1.17]. The specifications in the form of leaflet N1 contains methods for calculation for internal pressure and external pressure.

Apart from the standards and codes, guidelines for the construction and design of storage tanks and pressure vessels have been given by Mallinson [1.18].

The common feature of all codes, standards and guidelines for fiber reinforced plastic vessels is that they have been formulated based on experiences on vessels made by hand lay-up (mat and woven roving) materials. More often than not, the materials are assumed to be quasi-isotropic. This asumption is made because of the availability of isotropic design formulas for metallic materials. Two examples of the commonly used sources by designers of fiberglass reinforced vessels are the book of Roark and Young [1.19] and of Brownell and Young [1.20]. However, except for the case of randomly distributed mat, fiber reinforced plastics such as woven roving and filament winding are anisotropic, i.e. their properties are directionally dependent. It is not that equations treating anisotropic materials are not available. Anisotropic materials such as wood have been with us ever since the beginning of time. Documentation on the mechanics of anisotropic materials was provided by Lekhnitskii [1.21]. Also recent rapid advances in the advanced composites field have produced voluminous amount of literature on composites [1.22 to 1.25]. Because of the lack of training in dealing with anisotropic materials, many manufacturers do not handle these materials properly. This resulted in many failures [1.26]. Also many manufacturers tend to shy away from using filament winding. This can result in disadvantages in competition because filament winding is less labor