Composite Tanker Trucks: Design and Fabrication

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The use of composite materials is expanding in many industries because of their light weight, corrosion resistance, and strength properties. In this paper, a summary of the design and manufacturing of an all-composite tanker truck is presented. The design is based on the U.S. Code of Federal Regulations for MC–312 tanker trucks, standard design practices for composite pressure vessels, and experience of several composite design engineers. The construction materials include E-glass and vinylester resins. Structural calculations were performed with the SAP IV finite element program for static analysis and the BOSOR IV finite element program for various buckling conditions. The composite tanker truck obtained a U.S. Department of Transportation permit to transport many different hazardous materials.

Composite materials have been successfully used for the past 50 years in a variety of industries including automotive, aerospace, aircraft, chemical processing, recreation, medical, housing, and transportation. For such industries, composites offer advantages such as light weight, high strength-to-weight ratio, high corrosion resistance, and unique mechanical properties. As in reinforced concrete for which R–bars can be placed in a direction of highest stress, fiber composites allow for even greater versatility for optimum design in relation to the type, magnitude, and direction of loading. Current widely used structural applications for composites include aircraft components, entire fiberglass ships up to 200 ft long, emission stacks *(1)*, storage tanks, pipes, and small buildings. For these applications, composites offer unique advantages not available with conventional materials.

In this paper, the basic design and fabrication parameters and the structural design of an all-fiberglass tanker truck with a 5,500-gal (20,820-liter) capacity are discussed. This tanker truck was intended for use in highly corrosive chemical environments for which stainless steel, lined carbon, or aluminum vessels are currently required. Most design parameters are derived from the 1983 U.S. Code of Federal Regulations (CFR) for Motor Carrier Specifications *(1)*. Loading conditions such as dead loads, full vacuum, acceleration, deceleration, and loading and unloading pressures are considered in the design. Because composite materials are not currently recognized in American codes or regulations for the design of tanker trucks, design criteria are presented for allowable stress and strain levels, safety factors against buckling, fatigue design considerations, and allowable displacements.

The tanker truck is manufactured by filament winding technique with the contact molded end heads wound into the shell. Stiffeners are provided on the cylindrical shell for buckling considerations. Loads are transferred from the fiberglass shell into the dual-wheel axles by means of steel saddles wound onto the shell. This article is based on the report *(2)* submitted to the U.S. Department of Transportation for approval or variance for a composite tanker truck. Only E-glass and polyester-type resins were considered in the design. The mechanical properties of composites are a function of many parameters such as fiber and resin type, fiber orientation, and fiber content. The strength of fiberglass composites can vastly exceed that of steel. Relative to bridge components, in addition to strength, fatigue, and creep, environmental degradation and long-term behavior are additional properties of composite materials that must be considered. Many fiberglass tanks, pipes, and boats have been in service up to 30 years. Some specialized structural glass or graphite composite applications such as pressure vessels or aircraft components have also been in service for over 25 years.

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ADVANTAGES OF AN ALL FIBER-REINFORCED PLASTIC (FRP) TANKER TRUCK

Although the idea of FRP tanker trucks in the United States is still in its infancy, several European countries and Canada have allowed such trucks on their highways since the early 1960s *(3, 4)*. The primary advantages of composite tanker trucks are lower costs on a life cycle basis, higher strength-to-weight ratios, and superior corrosion resistance of composite materials as compared to steel or aluminum. The light-weight FRP tanker truck results in lower unit transportation costs because of larger payloads, less wear on tires and running gears, and lower maintenance costs (because relining of the tank is not required). Composites are also considered to be thermally insulating materials with thermal conductivity coefficients of 30 to 50 times less than that of steel. Such thermal insulating properties prevent FRP tank contents from reaching their flash point much more effectively than steel or aluminum and allow FRP tankers to maintain their structural integrity much longer under short-duration high-intensity fires that may occur under highway transportation conditions.

However, the resistance to corrosion of composite materials under exposure to various chemicals is the most significant advantage of FRP tanker trucks. Because of the inherent corrosion resistance of composite materials, FRP tanker trucks can be designed to carry most chemicals without the danger of perhaps rapid and undetected degradation or corrosion that can cause potentially dangerous problems in lined or unlined steel tanker trucks. For highly corrosive chemicals, steel tanker trucks are normally relined with rubber, epoxies, or fiberglass at a regular frequency of between 1 and 5 years. Based on past performance of above-ground and underground fiberglass tanks and European fiberglass tanker trucks, an all-FRP tanker truck should be able to perform satisfactorily without repair for much longer periods, hence reducing the long-term costs of the FRP tanker truck.

TEMPERATURE AND FIRE EFFECTS

There are two ranges of temperature to which a composite tanker truck may be exposed. The first range is due to ordinary environmental exposure and is taken as around 0°F to 160°F. The second range is due to the significant possibility of fire exposure because of a mishap in the transport of some highly flammable substance such as gasoline or polymers.

Concerning the typical thermal fluctuations of the environment, most mechanical properties of E-glass polyester laminates are not significantly affected. This conclusion is substantiated by numerous research publications *(2)*. However, available experimental test data on the behavior of composite structural components under fire exposure are limited to several reports *(1, 2)*. Numerous test reports are available on the flame spread rate and the nature of the gaseous substances emitted during several standard ASTM tests. None of these tests, however, provide any indication as to the strength properties of composites under fire exposure.

E-glass laminates, although slightly inferior in material properties to other composites, perform well at elevated temperatures. In long-term testing at 225°F, the retention of flexural strength is practically total. In short-term testing, up to 160°F, the retention of tensile strength is total *(2)*. There may be a moderate drop in the tensile modulus of elasticity depending on the particular polyester-type matrix under consideration. Manufacturers' literature indicates that almost all heat distortion temperatures for E-glass composites are greater than 200°F so that heat distortion of E-glass composites in a natural environment should not be a problem for such tanker truck applications.

Limited amounts of experimental data (excluding ASTM D–635 and ASTM E–84 tests) on the behavior of composite structural components under fire exposure are available. However, the available data *(2)* do provide certain generalities that can be extended to composite tanker trucks under fire exposure.

First, short-fiber noncontinuous type of composites (chopped fibers) are severely affected by fire. As the fire burns and the resin pyrolysis process occurs around the short fiber, the fibers may eventually fall off, exposing the short fiber beneath and causing further pyrolysis of the resin. Fortunately, a single woven roving within the laminate can virtually stop this burning process as can continuous-filament construction. In fact, composites manufactured with continuous filaments behave as self-extinguishing materials. In one test, a continuous-filament-wound composite tank of E-glass and isothalic polyester resin subjected to a fire for 30 min was self-extinguished within 5 min. After the resin is pyrolyzed on the surface and to the depth of the exterior glass filament thickness (about 0.020 in.), this exterior fiber acts as an insulator and virtually eliminates the pyrolysis of resin within the composite interior *(2)*.

Second, the resin content of the composite significantly affects the extent and rate of resin pyrolysis within composites, especially for all-chopped-fiber composite construction. The rate of flame spread and pyrolysis appear to increase dramatically when fiber content is less than 30 percent by weight for all-chopped-fiber laminate construction *(20)*. Because filament-wound construction typically contains more than 50 to 60 percent of fiber by weight, the rate and extent of matrix pyrolysis in this type of construction may not be influenced by the percentage of resin content.

Third, most composite materials are thermal insulators, as illustrated by the relative behavior of steel, aluminum, and fiberglass tanker truck tests *(2)*. In the experimental tests, aluminum, steel, and fiberglass vessels were subjected to fire exposure *(1)*. The vessels were filled with gasoline before exposure to fire. Because of the thermally insulating properties of fiberglass, the heat transferred into the vessels was least for the fiberglass vessel. Hence, the aluminum and steel vessels exploded before the fiberglass vessel.

Fourth, glass fibers are considered fireproof materials, that is, they do not support combustion. Also, the melting point of glass exceeds that of steel and aluminum.

Fifth, most unfilled epoxy and polyester resins begin pyrolytic decomposition at temperatures less than 350°F, with rapid decomposition occurring at temperatures greater than 400°F. High-temperature resins (over 600°F) exist, but are not currently used in the composite manufacturing industry because of higher costs or more difficult manufacturing. Pyrolytic decomposition of epoxies or polyesters usually results in the evolution of gases and solids. The gases range from harmless hydrogen to highly toxic carbon monoxide and methane.

At elevated temperatures, the addition of fillers and flame retardants changes the characteristics of resin matrices in a variety of ways such as cost, color, strength, thermal properties, and flame spread. Addition of most fillers results in reduction of strength. Addition of flame retardants reduces the flame spread rate but does not necessarily increase the strength of the resin or composite at elevated temperatures. Because most additives or fillers reduce the critical properties of composites, their use should be limited if possible to several exterior laminas. Selective addition of fillers or additives is feasible in filament-wound or contact molding fabrication techniques.

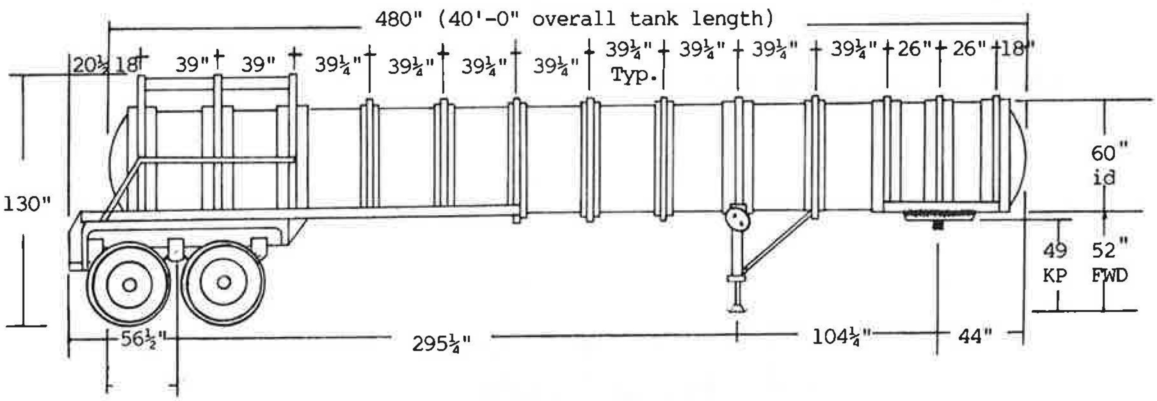
DESIGN SPECIFICATIONS

Design requirements are provided in the U.S. Code of Federal Regulations (CFR) for various types of motor tanker truck carriers. Well-defined design requirements have been developed from stress and buckling analysis of metals such as steel or aluminum, which are ductile. However, these same requirements cannot be used in the analysis and design of FRP tanker trucks because composite materials are brittle, their stress-strain curves often providing little or no warning of impending failure, and their ductility ratio being close to 1.0. Therefore, the design of the structural members of the FRP tanker truck is based on allowable strain limits included in the following guides:

MAIN STRUCTURE

Capacity: 5,683 gallons
Size: 60" inside dia. x 40' overall length
Shape: straight cylinder, clean bore
Compartments: one (Compartment hds. optional)
Code: MC-312, 35 psi operating pressure
Construction:

Construction:
Shell: ½" filament wound to ASTM D3299 ASME Chapter X
Heads: semi-elliptical, 48" crown radius 8½" knuckle radius, 5/8" solid FRP integral with shell
Ribs: (13) 4" x 3" rect. foam filled



	Trailer Tandem Axles	Tractor Tandem Axles	Steering Axle	Total
Tractor	---	7400	7600	15000
Tank & Gear	7000	2600	400	10000
Payload	27000	24000	4000	55000
TOTAL	34000	34000	12000	80000

FIGURE 1 Design specifications for the FRP tanker truck.

1. ASTM D3299 specification for filament-wound fiberglass tanks *(5)*.
2. NBS PS 15–69 specification for hand-layup fiberglass tanks, pipes, etc. *(6)*.
3. ASME Boiler Code Section X.
4. Design experience with FRP pressure vessels.

A partial list of CFR specifications and dimensions for the FRP tanker truck are provided in Figure 1. The view from the rear of the first prototype is shown in Figure 2. The weight distribution is based on the bridge gross weight formula mandated by the FHWA in 1982. This formula allows for a maximum dual-axle load of 34,000 lb (151,000 N) and a total payload of 55,000 lb (245,000 N). The length and diameter of the tanker truck and the wheel spacings are mandated by this bridge formula. From the viewpoint of structural design, the optimum tanker truck dimensions would result in a tanker truck with a larger diameter and shorter length.

FIGURE 2 End view of the first prototype.

LAMINAR CONSTRUCTIONS

The laminar construction of the shell for the tanker truck is shown in Figure 3 with an interior veil of 0.010 in. (0.025 cm), a chopped glass liner of 0.10 in. (0.25 cm), and filament winding consisting of seven helix cycles and eight laminas of unidirectional fibers in the axial direction. A gel coat was used as a nonstructural exterior surface for environmental and ultraviolet light protection. The end dome heads are of spheroidal geometry with contact-molded laminar construction consisting of 1½-oz (0.417 N) mat and 24-oz (6.67 N) woven roving. As shown in Figure 4, the heads were integrally wound with the shell. The laminar constructions were chosen on the basis of optimum strain and buckling conditions. Premium polyesters and E-glass were used for all laminar constructions. The helical winding angles were optimized with respect to various pressure and flexural load conditions imposed on the shell. The unidirectional fibers were located in the longitudinal directions of the shell to provide increased strength and stiffness for flexural and pressure load conditions. The combination of helical and

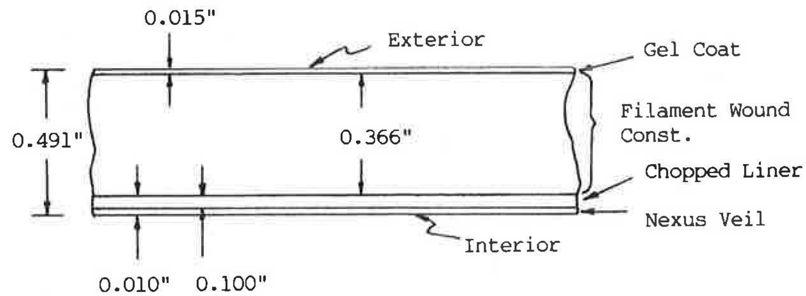


FIGURE 3 Laminar construction for the shell.

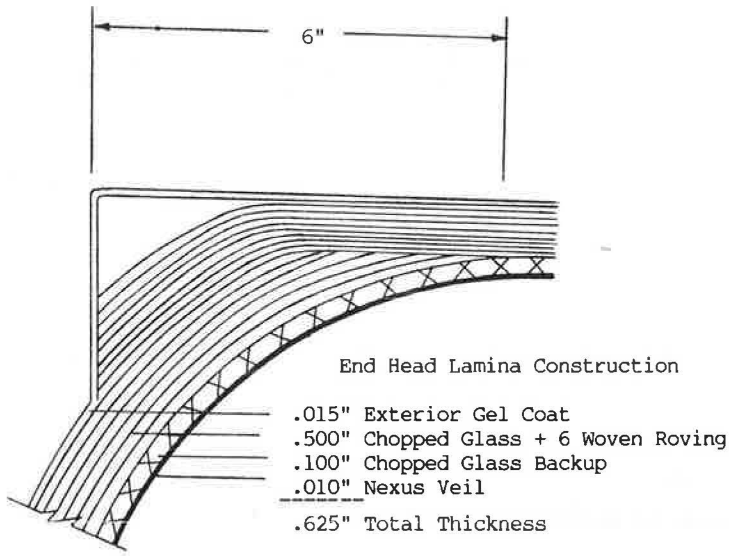


FIGURE 4 End heads wound into shell.

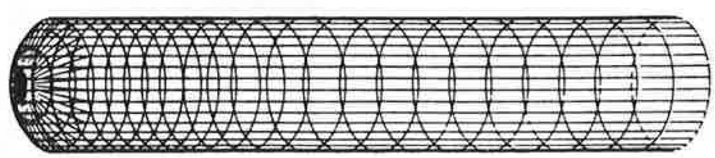


FIGURE 5 Finite element model of half the tanker shell and without saddles.

unidirectional laminas must result in a composite shell with the required strength, stiffness, and most important resistance to the millions of fatigue cycles throughout the life of the tanker truck. The material properties such as moduli, tensile and shear strengths, and ultimate elongations were determined from appropriate ASTM tests on test samples obtained from simulated tanker truck cutouts. These strength values were used in the final design of the tanker truck.

LOAD CONDITIONS AND ANALYSIS TECHNIQUES

The CFR outlines the minimum required design loads for all tanker trucks designed to carry hazardous materials. The design of the FRP tanker truck was based on all of the loads required by the CFR including the following design conditions:

1. Strain and stress levels and buckling for full vacuum.
2. Strain and stress levels and buckling for loading or unloading pressures of 35 psi (241 kPa).
3. Dynamic strains and stresses under horizontal acceleration and deceleration.
4. Dynamic strains and stresses under vertical accelerations.
5. Dynamic strains and stresses generated by surging loads because baffles were not used.

The complete tanker truck assembly was analyzed with several finite element models. The finite element model of half the tanker shell is shown in Figure 5 without the saddles or the axle supports. For the design condition of a fully loaded tanker truck and horizontal accelerations such as collisions, the tanker truck is designed to survive an impact acceleration of 20 g [1 g = 32.2 ft/sec^2 (9.81 m/sec^2)]. The fully loaded tanker truck is also designed to withstand vertical accelerations due to depressions or bumps of up to 9 g before shell buckling occurs. If the tanker truck is fully loaded and under full vacuum conditions, the safety factor against buckling is only 1.85. Hence, it is recommended that the tanker trucks not be under vacuum condition while on the road. Circumferential ribs were designed for control of buckling and postbuckling behavior as illustrated. The tanker truck has also been designed to withstand the rollover condition (the tanker rolls 180 degrees on its top surface). Sixteen other load and design conditions were also evaluated, with the full vacuum condition the most critical. The stress analysis was performed with the SAP-IV finite element computer program and closed form shell solutions for stress and strains. The buckling analysis was performed with the aid of the BOSOR IV finite element computer program and conventional shell buckling formulas and tabular solutions.

In addition to strain and stress levels and buckling of the various tanker truck components, the fatigue effects on the shell, dome, and bond laminates must also be considered. Fatigue tensile test specimens were fabricated according to ASTM D638 Type III and tested at a stress ratio $R = 0.175$. The tests were performed to 1,000,000 haversine load cycles for specimens in both the hoop and axial directions. The maximum stress level for all fatigue cycles was 10 percent greater than the maximum design stress level. Because of curvature of the hoop direction specimens, these samples were modified so as to avoid large flexural stresses. On completion of the 1,000,000 load cycles, only minor surface cracks were visible without any failure. With regard to the actual number of load cycles that may be experienced by such a tanker truck during its projected lifespan of 10 to 20 years, only a rough estimation is possible. Hence, for safety consideration, the endurance limit of the shell laminar construction should be considered as the highest stress level allowed for load conditions during travel.

CONCLUSIONS

Fiberglass tanker trucks can be designed for extremely complex load and environmental conditions that must be anticipated for transportation of hazardous chemicals on highways. Due to lower dead weights, the payloads for composite tanker trucks are about 8 percent greater than for conventional steel or aluminum tanker trucks. Due to fatigue sensitivity of nonunidirectional composites, the strain limits and the fiber orientations must be optimized to withstand the repeated cyclic loadings and the chemical attack from the various payloads. It is also recommended that the composite tanker trucks be designed at stress levels below the endurance limit because the total number of load cycles at a critical load condition cannot be accurately established.

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Publication of this paper sponsored by Structures Section.