STRUCTURAL BEHAVIOR OF FILAMENT WINDING TANKS

Jorge Nasseh (1), Jeniffer Kopetski (2) and Bárbara Vital (2)

(1) Barracuda Advanced Composites

(2) Marine Composites

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Abstract

As communities, businesses and industries are increasingly being held accountable for meeting environmental requirements for liquids that require safe and design-proven storage, wastewater composite tanks have become the solution for a wide range of issues. Filament winding tanks built with fiberglass, by virtue of its materials and design, is naturally the superior choice for safe, structurally reliable, cost-effective option for long-term storage and treatment of wastewater. A numerical analysis using the finite element method was developed to predict stress, strain and safety factors of the composite structure as well as comparative structural performance regarding the change of winding angle. Internal workloads and external environmental loads were both applied to the model. This work aims to evaluate the structural behavior of a vertical and horizontal 100m^3 wastewater tank.

Keywords: Wastewater Tank. Filament Winding. FEA.

1. INTRODUCTION

Large wastewater treatment tanks are subjected to relevant stresses. Thus, their structural design must account for the effects of both internal and external loads, in order to enable the selection of appropriate materials and manufacturing processes.

The composites industry is in constant development of new technologies that aim to offer high-quality, low-maintenance products, driving itself to create innovative solutions that increase productivity and reduce manufacturing costs. It is in this context that filament winding process is presented as an engineering solution to the issues arising from the construction of fiberglass wastewater treatment tanks.

During the past years, the use of filament winding process has greatly contributed to the large-scale production of wastewater tanks, as well as to the development of more efficient effluent treatment plants (ETP). This has enabled cost-effective solutions for the construction of lighter, stronger tanks, with superior durability.

Considering that fiber reinforcement direction significantly affects the structural strength of the laminate, a case study was developed to evaluate stresses and strains variation according to the winding angle of the tank. This case study analyzes a 100m^3 tank using the Finite Element Method.

1.1 Filament winding process

Filament Winding is a fully automated manufacturing process, used in the production of pipes, cylinders, tanks and pressure vessels. During this process, continuous fibers are impregnated with resin and wrapped around a cylindrical mold (mandrel), until the latter's surface is covered up to the required thickness.

The horizontal movement of the carriage and the rotation of the mandrel create a helical pattern of the reinforcements. These combined movements enable the manufacturing of parts with chosen angle patterns that are controlled by the pitch, creating a $+\theta$ angle on the first ply and returning on a $-\theta$ angle in the second ply. The components of the filament winding process are shown in Figure 1.

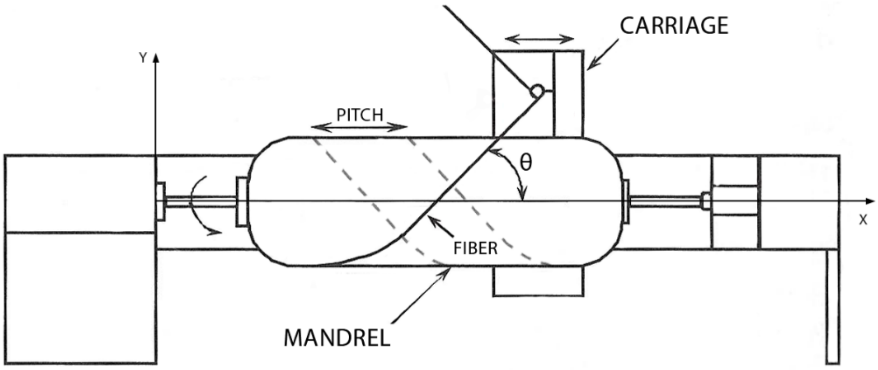

Figure 1: Winding angle

Some of the main advantages of filament winding process are the reduction of production time and the increase of fiber content, which enable the construction of extremely resistant tubular structures.

In order to meet the chemical and structural requirements of the wastewater treatment tank, the laminate is divided into three different parts: (a) the liner, (b) the chemical barrier, and (c) the structural layers. The parts are identified in Figure 2.

a. The liner is a very thin layer with high resin content that avoids liquid absorption and possible chemical attacks. The liner also provides a smooth internal surface and good cosmetics. The use of the surface veil is recommended to ensure the uniform thickness of the liner, to increase wear resistance and to minimize the propagation of surface cracks.
b. The chemical barrier is produced with chopped glass fibers with an average of 30% of fiber content. The chemical barrier aims to reinforce the liner, protecting the structural layers of possible chemical attacks. Usually, the amount of chopped strand mat ranges from 900g/m² to 1500g/m².
c. The structural layers are built by the continuous roving laid in the direction of the chosen angle, with high fiber content. The structural layers must support the structure weight and withstand the internal and external loads.

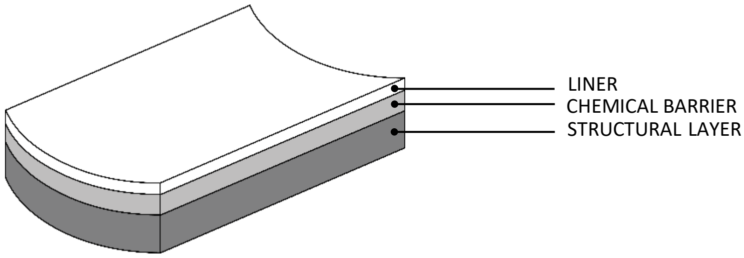

Figure 2: Plies

2. MATERIALS

The following table shows the typical mechanical properties of the composites stack used in most of filament winding tanks [4].

Table 1: Typical Ply Mechanical Properties

Components	Young's modulus, E (MPa)		Poisson's ratio, υ	Shear modulus, G (MPa)
	Ex	Ey		
Fiberglass roving	40.000	10.000	0.25	4500
Fiberglass Fabric	20.000	20.000	0.25	4500
Chopped Mat	7.000	7.000	0.30	3500
Surfacing Veil	7.000	7.000	0.30	3500

3. FAILURE CRITERION

The Tsai-Wu criterion is a failure indicator widely applied to orthotropic composite material shells. Since it analyzes tensile and compression strengths independently, it provides more reliable results. However, the Tsai-Wu criterion cannot predict different failure modes, such as matrix failure, and fibre-matrix interface failure.

The following equation demonstrates the calculation of the safety factor according to the properties of the material. SF is the coefficient by which all the stress components of the laminate must be multiplied to achieve the failure according to the Tsai-Wu criterion.

$$SF^2 (F_{11}\,\sigma_1^2 + F_{22}\,\sigma_2^2 + F_{66}\,\tau_{12}^2 + 2F_{12}\,\sigma_1\,\sigma_2) + SF\,(F_1\,\sigma_1 + F_2\,\sigma_2 + F_6\,\tau_{12}) = 1{,}00 \qquad (1)$$

The equation (1), elaborated by Tsai and Wu [1], represents the general resistance theory for anisotropic materials. The coefficients Fij, are determined from the resistance properties of the lamina in the directions 1 and 2, which represent the direction of the orientation of the layer and the direction transverse to the orientation of the layer, respectively.

The complex part of the criterion is to obtain F_{12}, since it is necessary to perform a biaxial test [1], while the other coefficients are obtained from standardized uniaxial tests. Thus, Tsai and Hahn [2] proposed a direct and approximate formula for this value, based on existing experimental data:

$$F_{12} = 0{,}5\,(F_{11}\,F_{12})^{0{,}5} \qquad (2)$$

4. LOAD STUDY

Simplified theoretical calculation procedures were applied in order to define the loads acting on the tanks during their operation, while the wind pressure was determined according to ABNT –Brazilian Standards [3] and the structure weight was determined by the composite laminate stack.

The loading conditions to which the tank is subjected during operation were estimated by the following formulation.

4.1 Hydrostatic pressure

$$p_h = (rho)gh \quad (3)$$

p_h – Hydrostatic pressure (Pa);
ρ – Fluid density in kg/m³;
h – Liquid height in meters.

The liquid heights considered for the vertical tank 9.7m and for the horizontal was 2.8m.

4.2 Wind loads

The wind load was estimated according to ABNT-Brazilian Standards NBR 6123 and the characteristic speed was determined by the following formula:

$$V_k = S_1 S_2 S_3 V_0 \quad (4)$$

V_k – Characteristic wind speed in m/s;
S_1 – Topographic Factor;
S_2 - Factor that considers the influence of the terrain roughness, the dimensions of the tank, and its height on the ground;
V_o – Basic wind speed: which was based on the basic speed isopleths in Brazil.

Using the characteristic wind speed, it is possible to determine the dynamic pressure, by the expression:

$$q_{wind} = 0,613 V_k^2 \quad (5)$$

q_{vento} – Dynamic wind pressure, corresponding to the characteristic speed V_k, under normal conditions of pressure and temperature;
Vk - Characteristic wind speed in m/s.

The wind load

4.3 Load combinations

Some conditions where different loads are combined should be analyzed such as superposition of the tank weight and hydrostatic pressure and superposition of the tank weight, hydrostatic pressure and wind loads.

The load cases must consider the least favourable loads to which the tank will be subjected. For this study, the loads were applied as follows and listed in Table 2.

- Vertical Tank: subjected to the pressure of the liquid, wind load and its own weight.
- Horizontal Tank: subjected to the pressure of the liquid and its own weight;

Table 2: Load cases

Load Case	Loads[a] (kPa)	
	Hydrostatic Pressure	Wind Load
1 (Vertical Tank)	114	1,5

2 (Horizontal Tank)	33	-

[a] All analyzes have considered the acceleration of gravity

The hydrostatic pressure was applied in the tank length and it is proportional to the tank height, according to Equation 3. Wind pressure was applied to the vertical tank in the transverse direction of the surface.

5. FINITE ELEMENT ANALYSIS

Computational methods to predict stress and strain can be efficiently applied to a vast range of problems. Elasticity relations can be used to generate a complex system of equilibrium equations in order to obtain displacements and stresses of the structure.

As we move away from simple situations, such as a plain rectangular plate, the equations system become increasingly complicated to solve using classical methods, requiring sophisticated mathematical techniques to analyze structures with complex geometries.

The Finite Element Method (FEM) is an alternative approach to produce an approximated solution of a system of complex equations in a structural problem. Hence, if correctly applied, both methods, FEM and classical methods, should produce similar results for the same problem.

The Finite Element Method consists of discretizing the structure by subdividing its domain into a finite number of elements connected to each other by nodes, such a way as to represent the distortion of the structure under the specified loads.

This subdivision is the Finite Element Mesh and the solution is presented through the values of displacements at the mesh nodes. The method was initially developed for isotropic materials and the majority of elements available and to apply the technique to composite materials it requires different element formulations that adequately represent their orthotropic stiffness and strength nature.

After the mesh generation using forms that best represent the phenomena and geometry, it is necessary to inform the characteristics of the material, the boundary conditions and the loads which the model is subjected.

5.1 Model

Two different 3D models were developed to run the analysis: the vertical tank with a 7.5mm thick structural layer and the horizontal tank with a 5mm thick structural layer. The laminate is balanced so, for each ply with +θ angle there should be another one with -θ angle.

The horizontal tank beds were considered simple supported as well the bottom of the vertical tank. The vertical tank brackets were considered fixed. The mesh uses 6 degree of freedom orthotropic shell elements on the SolidWorks package.

5.2 Stress analysis

Structural analysis focus on the tank body. Below the results for both load cases and graphics showing results variations due to winding angle.

Table 3: Results of load case 1 (Vertical Tank)

Parameters	55°	70°	90°
Stress (MPa)	29.5	26.4	24.4
Displacement (mm)	18.6	23.1	26.0
Strain	0.0014	0.0013	0.0013

Safety Factor	3.6	4.7	6.0

Table 4: Results of load case 2 (Horizontal Tank)

Parameters	55°	70°	90°
Stress (MPa)	15.0	16.5	18.0
Displacement (mm)	25.0	25.5	26.4
Strain	0.0056	0.0053	0.0052
Safety Factor	1.6	1.8	1.6

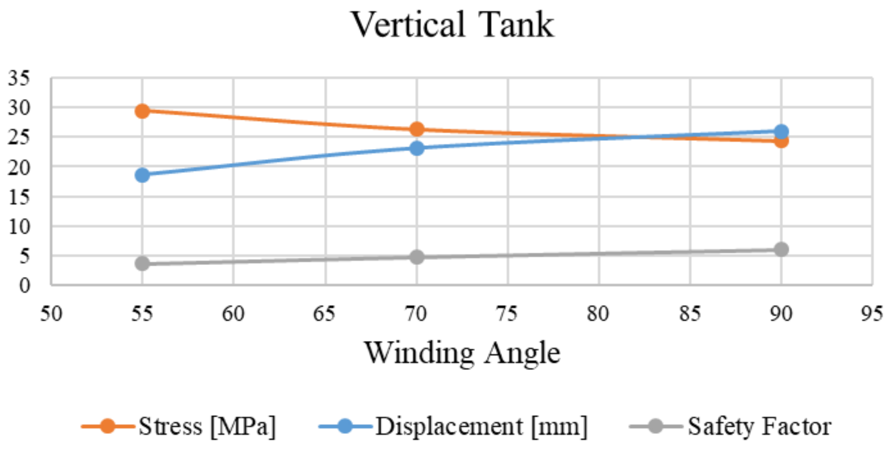

Figure 3: Vertical Tank Results

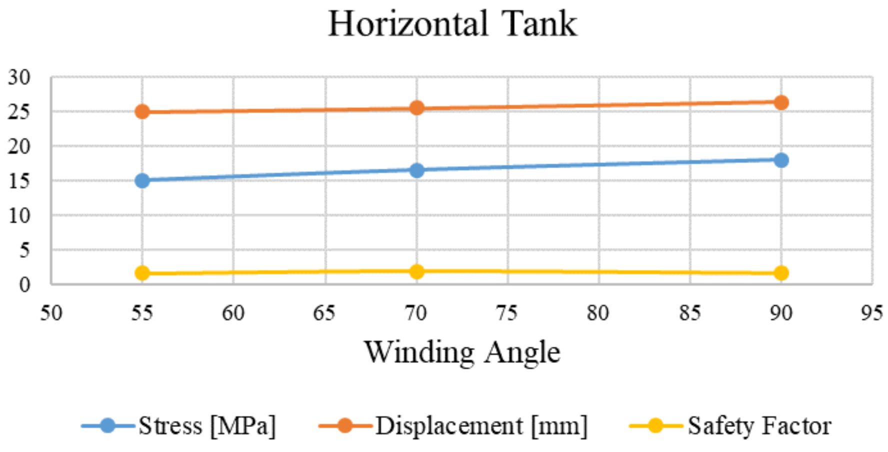

Figure 4: Horizontal Tank Results

The winding angle should be determined according to the required elastic modulus, considering that lower angles provide higher elastic modulus on x direction.

If a cylindrical structure is subjected only to circumferential loads, the axial stress is zero and the optimum winding angle is 90 degrees. In practice, the laminate should have some axial stiffness to resist handling, wind and seismic loads, therefore 70 degrees is often used.

6. RESULT COMMENTS

The following figures demonstrate the stress and displacement distribution of the evaluated structures.

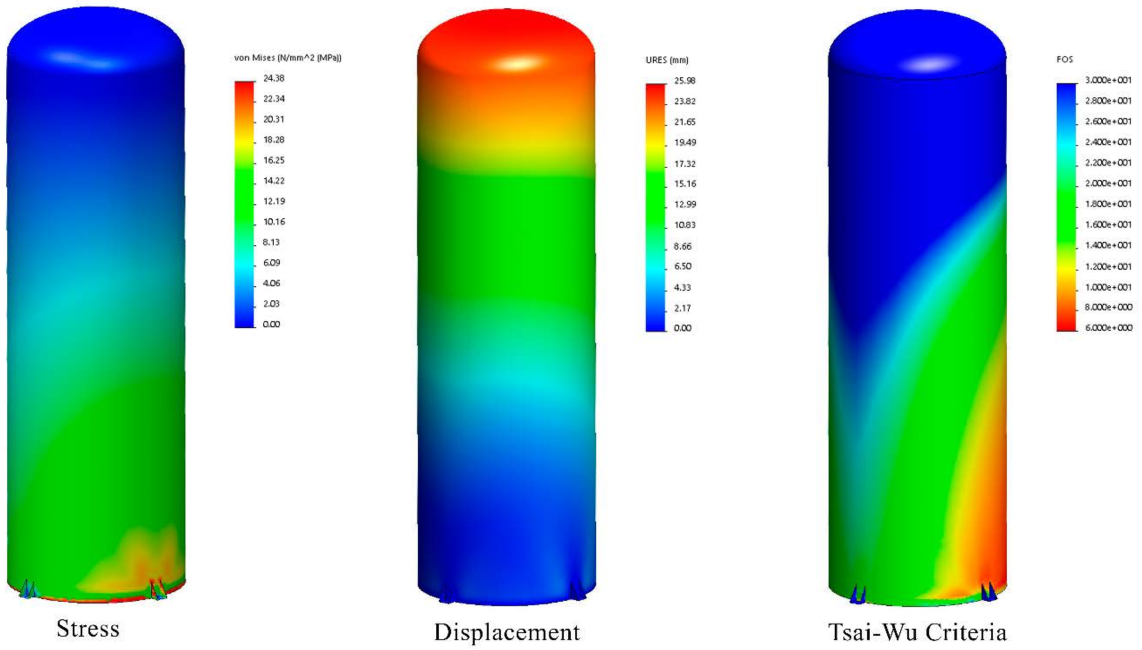

Figure 5: Vertical Tank Results

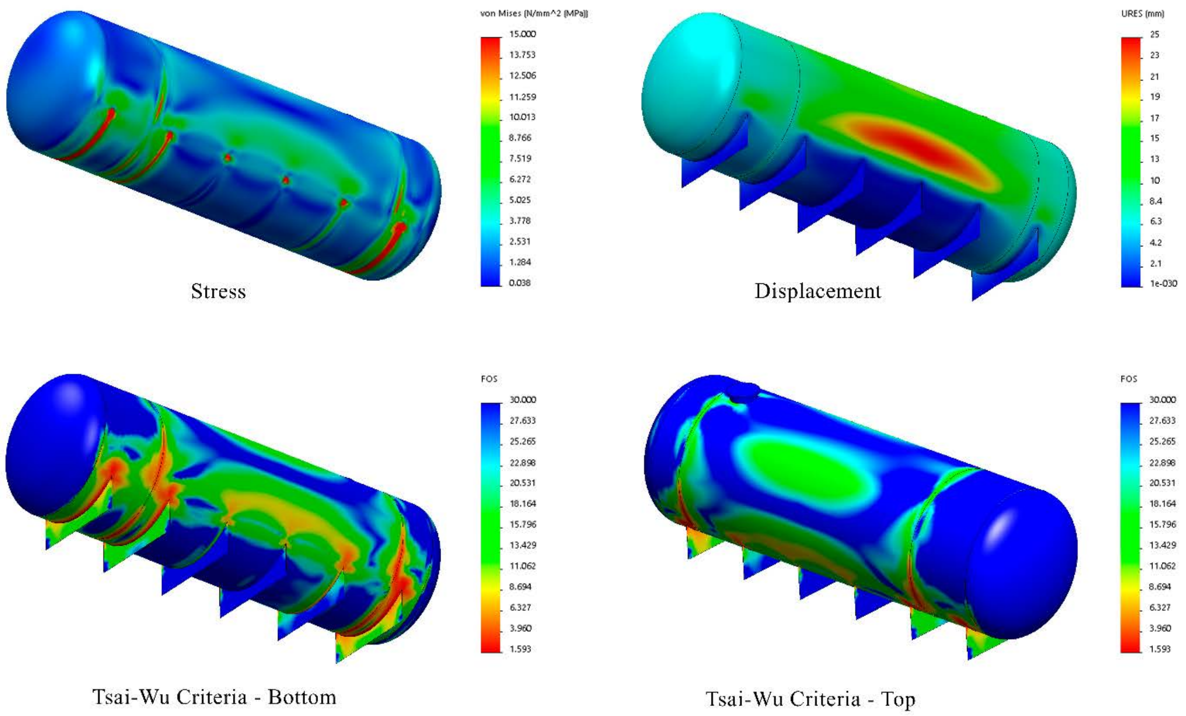

Figure 6: Horizontal Tank Results

The analysis of the vertical tank demonstrated that its stress decreased and its displacement increased with the use of higher winding angles. If a cylindrical structure is subjected only to circumferential loads, the axial stress is zero and the optimum winding angle would be near 90 degrees, however wind and handling loads may suggest that the winding angle can reach lower stress values at 70 degrees. Due to the nature of the Finite Element analysis, where an intermediate chemical layer made with quasi isotropic reinforcements is added, the result of lower stress at 90 degree wind angle is expected.

It could be noticed from the Finite Element analysis that both the stress and displacement of the horizontal tank tend to decrease with lower winding angles, reaching the same value calculated by trigonometric functions at 55 degrees winding angle. The lower winding angle also indicates the need of axial strength due to the tank ends pressure and the supports inducing flexural stress on the tank wall. This winding angle also proves to be more efficient by the Tsai-Wu failure criterion.

REFERENCES

[1] TSAI, S. W.; WU, E. M. A general theory of strength for anisotropic materials. Journal of Composite Materials, n. 1, v.5, p.58-80. Jan, 1971.
[2] TSAI, S. W.; HAHN, H. T. Introduction to composite materials. Technomic publishing, 1980.
[3] ABNT. NBR 6123: Forças devidas ao vento em edificações. Jun, 1988.
[4] CARVALHO, A. Compósitos para uso industrial. Minas Gerais: dez, 2012