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Research Paper

STUDY OF THE EFFECT OF LIQUID LEVEL ON THE STATIC BEHAVIOR OF A TANK WAGON

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In this research the stresses and deformations encountered in the structure of a railroad Tank-Wagon as a result of the content liquid level are analyzed. The study is conducted by means of a computational Finite Element Model, whose design is the product of a literature study about cylindrical tank cars for transporting liquid fuels. In this sense, four different liquid levels in static state were analyzed using ANSYS®, hydrostatic pressure on the inner walls of the container was applied in order to simulate the presence of the fluid. The project also deals with evaluating the bending stress in filled tank conditions. The material properties and design recommendations were taken from AAR-MSRP which is intended to be used for the analysis and construction of freight cars. The final results of this analysis can be used to improve the designs safety.

Keywords: Liquid level, Tank-Wagon, Finite Element Method, Stresses, Deformations

INTRODUCTION

A tank car is a type of railroad freight car designed to transport chemicals, petroleum products, and other bulk liquids and compressed gases.

Today thousands of different commodities are carried in tank cars. The AAR (2013) indicates that the North American tank wagons fleet consists of about 335,000 cars, of which around 92,000 are used to transport crude oil and other flammable liquids. A typical carload of liquid fuel contains around 30,000 gallons.

According to Trejo *et al.* (2014) the design of railroad tank cars is subject to structural and performance requirements and constrained by weight. In this sense and according to the geometric configuration of the wagons, the level of transported liquid may directly influence the structural mechanical behavior of the units.

Previous both static and dynamic studies were mostly conducted under the condition of full liquid level, assuming that this it is the critical condition. Miele and Rice (1993) used the Finite Element Method (FEM) to find the stress distribution in

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different models of tank cars. They indicate that any force occurring in service is transmitted through the tank shell. Fahy and Tiernan (2001) model a ISO tank container statically and dynamically for rail, road and sea conditions using ANSYS, with the objective of produce a more efficient and safer design, the areas of high stress in the tank and support structure were identified. Years later, Domagala and Lisowski (2011) indicate that fluid structure interaction simulation represents a very efficient tool to design mobile tanks, especially under dynamic loading. Shortly after, Zhang (2012) indicates that the difference of the liquid volume in tank has great influence to the structural stress and strain. When the tank is not filled with liquid, the liquid has large-scale amplitude sloshing, and the stress and strain are much bigger than the static condition.

The main objective of this paper is to analyze the effect of liquid level in static state of a railroad tank wagon using the FEM and allow the improvement of future designs.

MATERIALS AND METHODS

Methodology

The proposed methodology to achieve the objective of this research is listed below:

- Definition and modelling of geometry using a CAD software.
- Perform analytical analysis for reactions in supports and maximum bending stress of the tank wagon at maximum capacity.
- Importing geometry to ANSYS Workbench platform.
- Defining materials and contact configuration between the elements of the 3D model.
- Discretization of geometry into a FEM.
- Perform structural static analysis to calculate stress and deformations in the tank filled to 100%, 80%, 75% and 50% of its capacity.
- Finally, from the results obtained, evaluate the static behavior of the unit for each level of fluid analyzed.

3D Modelling of Tank-Wagon

According to the literature study performed, a non-pressure stub sill tank-car with cylindrical body was modelled. The principal components of the model created can be seen in Figure 1. Note that the trucks were not explicitly modelled because of the scope of this study are not necessary.

In Table 1 are listed the principal characteristics of the constructed model.

Figure 1: Principal Parts of the Performed Model

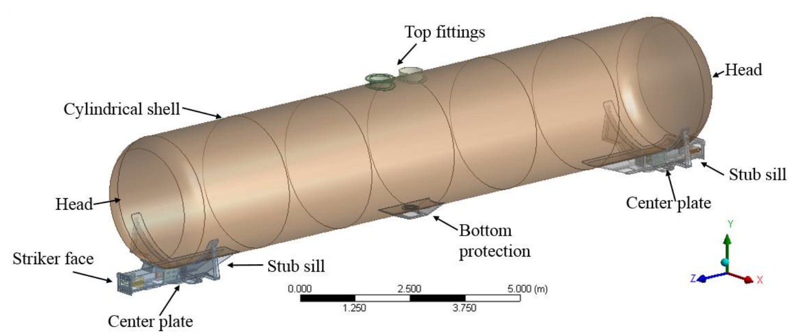


Table 1: Principal Geometric Characteristics of the Model

Shell length	14.83 m
Diameter of head	3 m
Thickness of shell and heads	0.0127 m
Stub length	3.07 m
Distance between center plates	14 m
Maximum capacity	150,000 l
Gross rail load	129,727 kg

Bending Stress Calculation

The weight of the charged unit without considering the trucks is of 135,453 kg, this value is the result of the sum of the weights of the components, whose distribution can be seen in the free body diagram shown in Figure 2.

Calculating the reaction at the supports:

$$R_A = R_B = \frac{W_{total}}{2} =$$

$$\frac{1328252.118N}{2} = 664{,}126.06\,N \quad ...(1)$$

In Figure 3 the respective shear and moment diagrams for the case study are shown.

Considering the moment of inertia of a cylinder:

$$1 = \frac{\pi}{4}\left(r_e^4 - r_i^4\right) \quad ...(2)$$

$$1 = \frac{\pi}{4}\left(1.5^4 - 1.4873^4\right) = 0.1329m^4 \quad ...(3)$$

Finally the maximum bending stress is given by:

$$\sigma_{\max} = \frac{M_c}{l} \quad ...(4)$$

$$\sigma_{\max} = \frac{(2021003.62)(1.5)}{0.13296}$$

$$\sigma_{\max} = 22.80MPa \quad ...(5)$$

Definition of Materials

According to Cai *et al*. (2015) most tank cars are made with ASTM TC-128B steel, whose properties are shown in Table 2. For this reason this steel was selected as the material of the entire structure.

Meshing

According to Leyva *et al.* (2014), the solving time of the model is dependent on the number of

Figure 2: Free Body Diagram

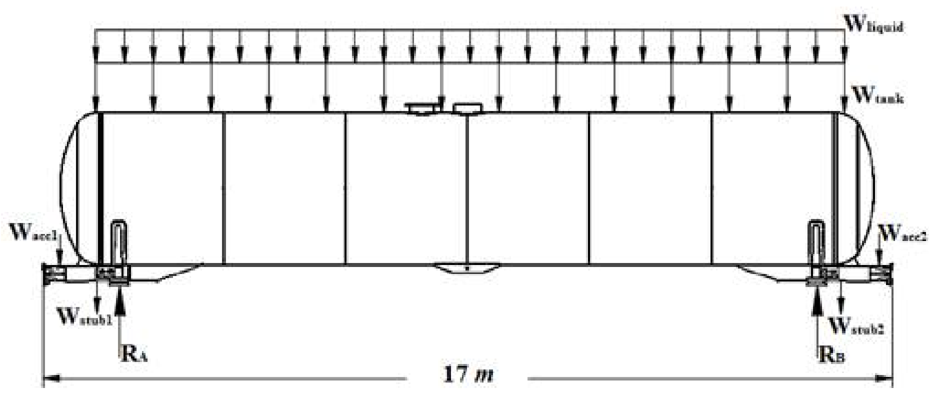


Figure 3: Shear and Moment Diagrams

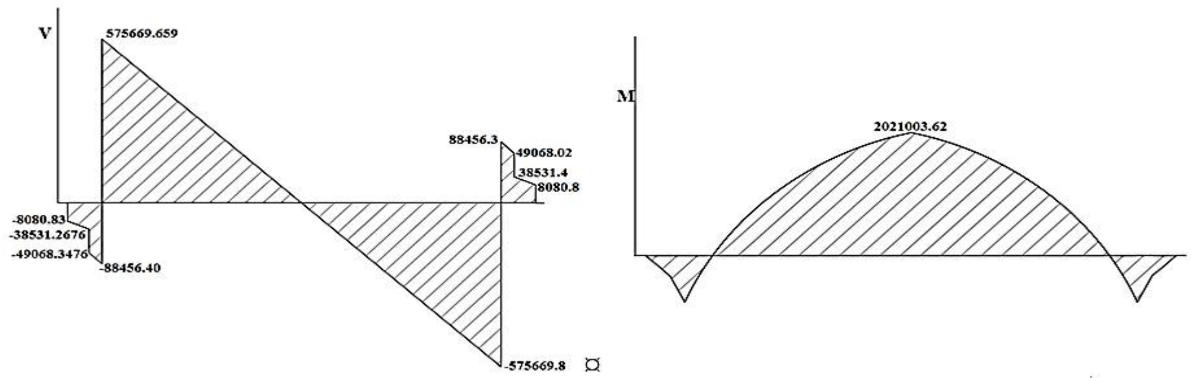


Table 2: TC-128B Steel Properties

Mechanical Property	Value
Young's modulus,	206,842.773 MPa
Poisson's ratio,	0.3
Yield strength	344.738 MPa
Tensile strength	558.475 MPa
Weight density	7,916.453 kg/m^3

elements, which is determined by the mesh density. In this sense, the Hex Dominant Method was selected as the method of meshing to achieve a more orderly and better distributed mesh, the Figure 4 show the finite element model of the tank wagon.

In Table 3 the final results of the Finite Element Model are shown.

Boundary Conditions

Hydrostatic pressure was used to simulate the

Table 3: Final characteristics of finite element mesh

Nodes	424,456
Elements	106,209
Skewness average	0.39 (Very Good)

Figure 4: Section View of the Tank Wagon Discretized in Finite Elements

presence of the fluid, the pressure was directly applied to the inner walls of the shell with a fluid density of 1000 kg/m^3, which is slightly larger than of the tank cars intended for the transportation of hydrocarbons. The boundary conditions provided by the trucks were simulated by using simple supports at each end. This configuration can be seen in the diagram of Figure 5.

The following equation is taken for hydrostatic pressure calculation.

$$P_h = \rho g h \quad ...(6)$$

Varying the value of h for different fluid levels, the results shown in Table 4 was obtained.

Table 4: Hydrostatic Pressure Values at Different Liquid Levels

h values [m]	Hydrostatic pressure [Pa]
2.932 (100%)	28,751.19
2.3456 (80%)	23,000.95
2.199 (75%)	21,563.39
1.466 (50%)	14,375.59

RESULTS AND DISCUSSION

Support Reactions

The first action taken was the calculation of support reactions (center plate and side bearings at both ends of the unit) through the ANSYS software for comparison with the analytical results presented above. The results are shown in Table 5 can be seen that there is considerable consistency in both cases, so it can be argued that the finite element model works properly.

Stress Distribution Along the Tank (Shell)

Figure 6 shows the distribution of maximum principal stresses along the tank shell in the case of a 100% loaded tank. It is observed that the maximum concentration occurs at the ends of the bolster, in which the tank rests.

In the graph of Figure 7 can be seen as varying the stresses in the tank bottom relative to the distance between both heads.

Figure 5: Schematic Representation of the Boundary Conditions

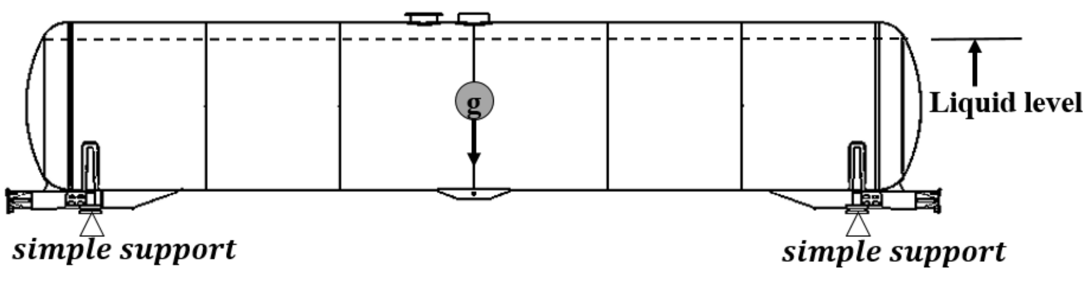


Table 5: Comparative analysis of the results of reactions with full tank

	FEA by ANSYS	Analiticalvalidation
Force reaction at end A	664.74 kN	664.13 kN
Force reaction at end B	664.71 kN	664.13 kN

The variation of the stresses in the bottom of the tank as result of the liquid level can be seen in Figure 8.

With the above results it can be argued that while fuller is the tank, the more concentrated stresses occur in the lateral areas (joining the ends of the bolsters to the tank) and with less fluid, the concentration will occur at the bottom of the tank near the center. To see if this is true, the stress distribution along a lateral line of the shell are plotted in Figure 9.

Total Deformation

Due to 100% of load capacity, the structure is deformed 6.30 mm which for the reasons identified above is presented on the side of the tank, the vector representation of this deformation can be seen in Figure 10.

With the measuring the deformations from the top of the tank to five filling levels. It is noted that for cases of little liquid (less than 50%), the deformations are concentrated inward along the side of the tank causing it to elongate slightly upward. As shown in Figure 11.

Figure 6: Stress Distribution Along the Shell with The Tank Filled to 100%

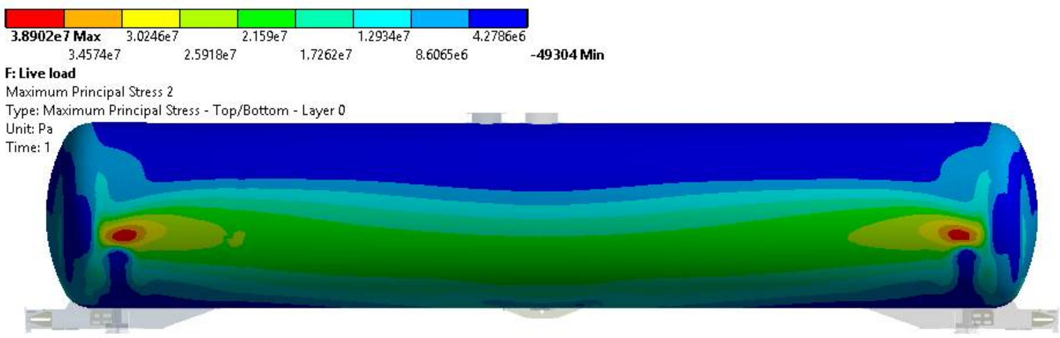


Figure 7. Stress Distribution Along the Bottom of the Tank Filled to 100%

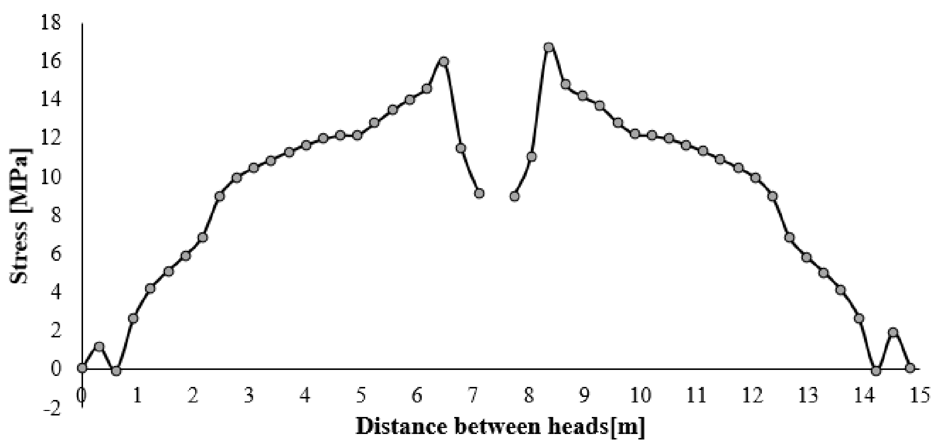


Figure 8: Stress Distribution Along the Bottom of the Tank Accord to Liquid Level

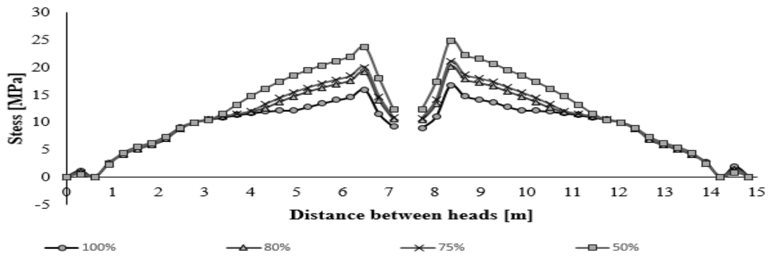


Figure 9: Stress Distribution Along a Lateral Line of the Tank Accord to Liquid Level

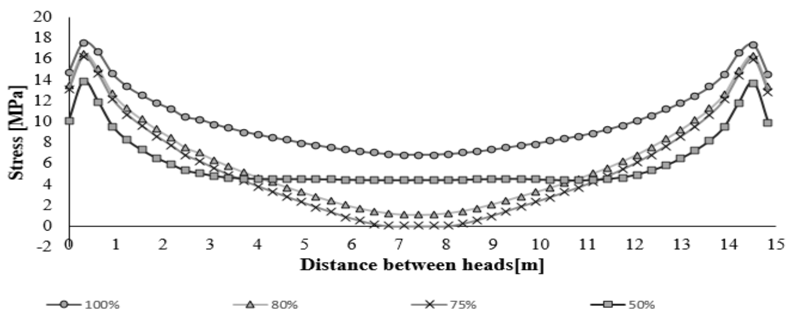


Figure 10: Total Deformation With the Tank Filled to 100% (M)

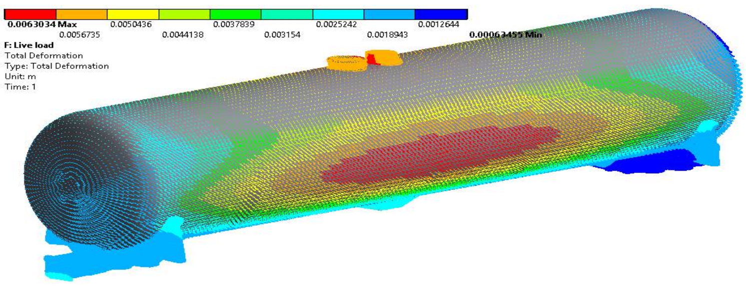
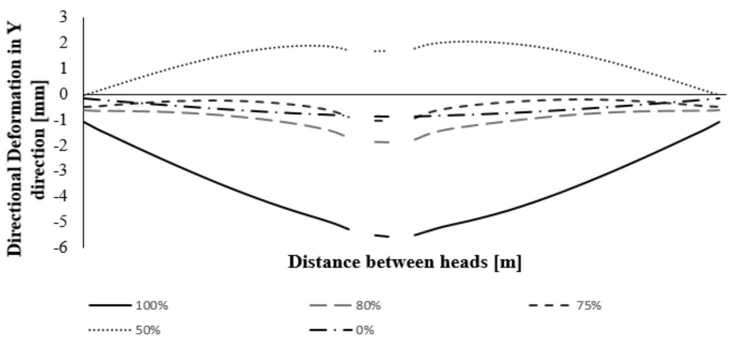


Figure 11: Directional Deformation Along the Top of the Tank Accord to Liquid Level



CONCLUSION

1. It is noteworthy that for all the cases analyzed in this article, the maximum stress permitted by the regulations (344.74 MPa) was perfectly fulfilled.
2. It can be argued that while fuller is the tank, the more concentrated stresses occur in the lateral areas (joining the ends of the bolsters to the tank) and with less fluid, the concentration will occur at the bottom of the tank near the center.
3. The finite element method represents a useful tool that allows us to experiment with computer models in a short time without investing in prototypes.
4. Finally, it is concluded that the liquid has great influence on the mechanical behavior of the vans, so it must be taken into consideration for the design of new units.

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