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Comparison of the shell design methods for cylindrical liquid storage tanks

Eyas Azzuni, Sukru Guzey *

Lyles School of Civil Engineering, Purdue University, West Lafayette, IN 47907, USA

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ABSTRACT

The three methods for determining the shell thickness of steel cylindrical liquid storage tanks designed in conformance with API Standard 650, Welded Tanks for Oil Storage (API 650) are: (1) one-foot method (1FM), (2) variable-design-point method (VDM) and (3) linear analysis. We compared the shell designs based on these three methods for different tank properties: diameter, height and allowable stress. For linear analysis, we developed a stiffness–flexibility matrix method based on thin shell theory that gives the theoretical displacements and stresses at each shell course without any approximation or simplification. Results show that shell designs using VDM may produce overstressed shell courses for some of the large steel liquid storage tanks when VDM is permissible to use. Linear analysis would give more accurate shell designs for those cases.

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1. Introduction

API 650 is an industry standard used for the design and construction of large cylindrical storage tanks for liquid products [1–3]. API 650 storage tanks are vertical, cylindrical, closed- and open-top welded tanks with uniformly supported flat bottom. They are used to store petroleum, petroleum products, and other liquid products [1].

Recently, considerable research effort has been devoted to the analysis, design, and evaluation of the liquid storage tanks [4]. Much of the research conducted has focused on the buckling of and wind effects on the storage tanks [5–8]. Some researchers worked on dynamic effects related to earthquakes [9–11]. Chen et al. worked on developing a simple method to calculate shell stress [12].

A typical storage tank has a number of shell courses of uniform plate thickness. The thickest course is at the bottom and each shell course above is typically thinner than the previous one. See Fig. 1 for a typical storage tank shell cross-section.

There are three methods allowed by API 650 to determine the required plate thickness of the shell. The first method is the one-foot-method (1FM) which is based on the “membrane theory”. The required shell plate thickness for each shell course is calculated using the circumferential stress at a point 0.3 m (1-ft) above the lower horizontal weld seam of the shell course due to hydrostatic pressure of the stored liquid. The reasoning behind this assumption is that the tank bottom plates provide restraint to reduce circumferential stress due to hydrostatic pressure at the bottom 0.3 m (1-ft) of the lowest shell course. Similarly, a shell course other than the lowest shell course, has generally thicker shell plates below. The plate below provides some restraint at the lower portion of the shell course in consideration. The 1FM is used successfully for the majority of the tanks. However, the designs based on the 1FM may become conservative and cost prohibitive for larger diameter tanks. Therefore, API 650 limits the applicability of this method to tanks up to 61 m (200-ft) in diameter.

The second method to calculate the required shell plate thickness is the variable-design-point method (VDM) that is also based on the “membrane theory”. The VDM was proposed by Zick and McGrath in 1968 [13] and later adopted by API 650 as a refined method to calculate the required shell plate thickness especially for tanks more than 61 m (200-ft) in diameter. The VDM takes into consideration the restraint provided by the tank bottom plates to the first shell course and the restraint provided by each lower shell course to the upper shell course. The VDM uses a variable distance instead of fixed distance of 0.3 m (1-ft), as used in 1FM, above the circumferential seam for each shell course to calculate the maximum stress due to hydrostatic pressure. The variable distance in VDM is a function of the shell plate thickness above and below

* Corresponding author.
E-mail addresses: eazzuni@purdue.edu (E. Azzuni), guzey@purdue.edu (S. Guzey).

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Nomenclature

H	distance from the maximum product level to bottom of the shell course under consideration (m)
L	$(500\ Dt)^{0.5}$ (mm)
h_1	height of the bottom shell course (m)
D	nominal tank diameter (m)
r	nominal radius of the tank (m)
G	the design specific gravity of the stored liquid
CA	corrosion allowance (mm)
S_d	allowable design condition stress (MPa)
S_t	allowable hydrostatic test condition stress (MPa)
t	thickness of the shell
t_i	thickness of a shell course
t_d	design shell thickness (mm)
t_{1d}	design shell thickness for the first shell course (mm)
t_{dx}	design shell thickness (mm)
t_t	hydrostatic test shell thickness (mm)
t_{1t}	hydrostatic test shell thickness for the first shell course (mm)
t_{tx}	hydrostatic test shell thickness (mm)
t_u	corroded thickness of the upper shell course; approximated using 1FM for the first iteration (mm)
t_L	thickness of the lower shell course (mm)
t_1	corroded thickness of the bottom shell course (mm)
t_2	minimum design thickness of the second shell course (mm)
t_{2a}	corroded thickness of the second shell course (mm) as calculated for the upper shell courses
w	radial displacement of the cylindrical shell
x	axial length coordinate of the cylindrical shell
E	modulus of elasticity
D_s	shell bending rigidity
p	pressure
ν	Poisson's ratio
β	a parameter
$C_1, \ldots, C_4$,	integration constants
$f(x)$	particular solution to the governing equation
L_i	length of a shell course
Q_1, Q_2	end shearing forces of a shell course
M_1, M_2	end bending moments of a shell course
w_1, w_2	end radial displacements of a shell course
θ_1, θ_2	end rotations of a shell course

the seam. Most of the time designs based on VDM are more economical compared with those based on the 1FM. However, for some tank geometries the VDM may become unconservative and the tank shell thicknesses designed in accordance with VDM may be overstressed. Buzek showed that the restraint provided by the tank bottom on the tank shell produces circumferential stresses of sinusoidal nature varying with the distance from the tank bottom [14]. For certain tank diameter and height proportions, this sinusoidal varying restraining stress may add to the stress due to the hydrostatic circumferential stress and the design based on VDM may become unconservative. Therefore, API 650 limits the applicability of the VDM for the tanks with L/H ratio less than 1000/6 in SI units (refer to the nomenclature for the definition of these terms). For the storage tanks where the L/H ratio is more than 1000/6, tank shell thickness should be determined using linear analysis.

The shell thickness calculation using linear analysis is the third method given in API 650. In this approach the boundary conditions for the analysis should be a plastic moment related to yielding of the plate under the shell and fully restrained radial movement at the bottom of the shell. API 650 does not describe a specific linear analysis method. In this study we developed a new method using thin shell theory to perform a linear analysis for the shell thickness calculation. In this method we are using exact stiffness–flexibility relations and exact shape functions originating from the so called "short shell" solution of the governing equations from the thin elastic shell theory. Therefore, we do not have any approximations or simplifications. The displacements, section forces and stresses obtained from this method are exactly matching the theoretical solution of thin shell theory. Overwhelming majority of texts employ only a single course solution of shell cylinder without extension to multiple shell courses with stepwise thicknesses. One can find very few references dealing with multiple shell courses in which only approximate solutions were obtained. In our treatment, we present an attractive and easy to implement formulation that renders analytical solution without any approximation.

We shall investigate the efficiency and limitations of each method described above. The efficiency is defined in terms of minimum required shell thickness for each shell course and corresponding total weight of steel for the shell plates. A decrease in the weight of steel can be achieved by reducing the shell thickness, which will lead to a decrease in cost. Achieving a smaller design thickness is important for large diameter tanks because tank fabricators in North America typically order a plate thickness with 0.01 in. (0.25 mm) increments as well as commercially available 1/16 in. (1.59 mm) increments directly from a steel mill for sufficiently large weight of steel, about 20 tons. Another reason to achieve a smaller thickness may be to comply with the maximum thickness limit of 1 in. (25.4 mm) to avoid stress relieving requirement. Therefore, even a reduction of 0.01 in. (0.25 mm) in design thickness would be significant for large diameter tanks. Our main objective is to investigate the accuracy of 1FM and VDM and possibility of obtaining an economical result by using the linear analysis for the required shell thickness for storage tanks.

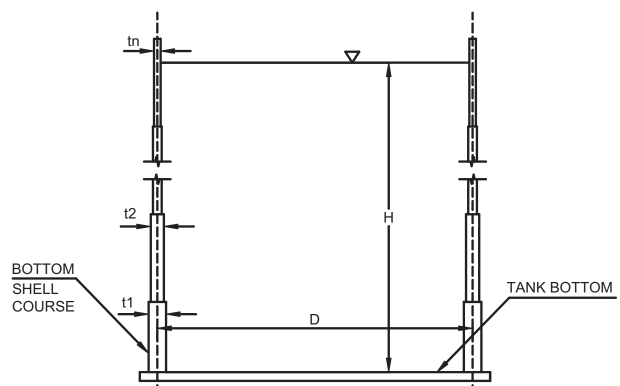

Fig. 1. Typical tank shell cross-section.

We shall first summarize the three design methods for the storage tanks. Then we shall compare the shell designs based on the classic 1FM with those based on VDM. Furthermore, we shall focus on comparison of the VDM results with the theoretical solutions obtained from thin shell theory. Finally, we shall discuss the results and give conclusions.

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