International Journal of Pressure Vessels and Piping 85 (2008) 728–738

Contents lists available at ScienceDirect

International Journal of Pressure Vessels and Piping

journal homepage: www.elsevier.com/locate/ijpvp

Stress and deflection analyses of floating roofs based on a load-modifying method

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ARTICLE INFO

Article history:
Received 22 June 2007
Received in revised form
24 March 2008
Accepted 27 March 2008

Keywords:
Floating roof
Rainwater load
Load-modifying method
Deflection
Nonlinear analysis

ABSTRACT

This paper proposes a load-modifying method for the stress and deflection analyses of floating roofs used in cylindrical oil storage tanks. The formulations of loads and deformations are derived according to the equilibrium analysis of floating roofs. Based on these formulations, the load-modifying method is developed to conduct a geometrically nonlinear analysis of floating roofs with the finite element (FE) simulation. In the procedure with the load-modifying method, the analysis is carried out through a series of iterative computations until a convergence is achieved within the error tolerance. Numerical examples are given to demonstrate the validity and reliability of the proposed method, which provides an effective and practical numerical solution to the design and analysis of floating roofs.

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1. Introduction

Floating roofs are widely used in the middle- and large-scale cylindrical tanks for crude oil and other liquid hydrocarbon storages around the world because of their advantages such as reducing product evaporation, improving safety, overall operating economy, etc. After a history of over 80 years with continual development and improvement, modern floating roofs with larger diameters for open-top tanks can be classified usually into two common types: single-deck type and double-deck type [1–5]. The single-deck floating roof consists of characteristically a circular deck plate and a pontoon (i.e. a compartmented buoyant ring) which are both constructed with thin plates and jointed together by a connection component, e.g. an angle-iron ring. To meet the increasing capacity of oil storage tanks and to improve the performance of the traditional single-type and double-type floating roofs, a new-style floating roof with continuous beams was also developed [6]. This floating roof has more complex components, which increases somewhat the difficulty of structural analysis.

In the practical operation, the floating roof is usually subjected to rainwater loading resulting from the accumulated rainfall. The rainwater loading will result in a much larger deformation (or deflection) in the deck compared with the plate thickness. In many codes for the design of floating roofs, the whole structure is required to possess good performances such as strength and stability under a standard rainfall of 250 mm over the tank [7,8], i.e. no failure modes such as fracture, buckling or sinking should occur in this rainwater loading. Accordingly, stress and deformation analyses of floating roofs under rainwater loading are practical problems to be solved.

However, the floating roof is actually subjected to complex loads and deformations during the operation. The loads and deformations of floating roofs are nonlinearly coupled with each other, which results in the difficulty of analysis. Mitchell [9] investigated the problem of floating roofs with pontoon, in which the deck plate was treated as membrane and the membrane large deflection equations were solved numerically by assuming a range of starting values. But the proper selection of these values was usually difficult and, of course, important to the solution. A similar method was also used by Epstein et al. [3,10,11] to analyze deformations and stresses for different types of floating roofs, including pan floating roofs, pontoon floating roofs with accumulated rainwater loading or with punctures in the deck, in which the effects of various parameters such as tank diameter and pontoon geometry were also examined. Umeki and Ishiwata [12] improved Epstein's solution and better computational efficiency was achieved, and they replaced the original Runge–Kutta numerical method by the Milne method. Another analytical method, i.e. the ODE-solver (ordinary differential equation solver) method, was proposed by Yuan et al. [13]. This method was used to solve the large deflection equation of floating roofs based on the bending theory rather than the membrane theory. To simplify the problem, some authors [4,14] also presented calculating formulas

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doi:10.1016/j.ijpvp.2008.03.003

Nomenclature

$\boldsymbol{a}$	displacement vector in the FE equation
c_1,c_2	deformation coefficient of the outer rim and inner rim of the pontoon, respectively
C	ratio of increments of water and liquid heads
E	Young's modulus of the floating roof
$f(r)$	deflection of the deck plate
$f_{\max}$	maximum deflection of the deck plate
$\boldsymbol{F}$	restoring load vector in the FE equation
g	9.8 N/kg, gravitational acceleration
G_s	weight of the floating roof excluding the deck plate
h_0	typical rainfall
h_c	equivalent deflection of the deck plate
h_s	liquid head in the tank
h_w	water head on the deck plate
h_α	sinking depth of the floating roof due to slope of the pontoon's bottom plate
H_0	installing height of the deck plate
H_1, H_2	heights of the outer rim and inner rim of the pontoon, respectively
H_g	sinking depth of the floating roof due to its weight
i	number of iteration in the load modification
$\boldsymbol{K}_L$, $\boldsymbol{K}_{NL}$	linear and nonlinear stiffness matrices in the FE equation, respectively
M	total mass of the floating roof
M_c	mass of the deck plate
N_r	number of radial continuous beams
N_a	number of annular continuous beams
N_v	number of vertical ribs
$p_b(r)$	net pressure on the bottom plate of the pontoon
$q(r)$	net pressure on the deck plate
q_c	weight of deck plate per unit area
q_s	liquid pressure applied on the deck plate in the tank
q_w	rainwater loads on the deck plate
$\boldsymbol{Q}$	applied load vector in the FE equation
r	radial coordinates of the floating roof
R_0	radius of the tank
R_1,$\bar{R}_1$	radius of the outer rim of the pontoon before and after deformation, respectively
R_2,$\bar{R}_2$	radius of the deck plate or the inner rim of the pontoon before and after deformation, respectively
R_m	mean radius of the pontoon
R_w	radius of the area of rainwater filling the deck plate
t	thickness of the deck plate
t_1, t_2	thicknesses of the outer rim and inner rim of the pontoon, respectively
t_3, t_4	thicknesses of the top and bottom plates of the pontoon, respectively
V_1, V_2	two parts of water volume on the deck plate due to redistribution
V_e	water volume on the deck plate
w_A, w_B	vertical displacements of the bottom of the outer rim and inner rim, respectively
z	vertical coordinates of the floating roof
α	tilt angle of the pontoon's bottom plate
δ_1, δ_2	radial displacements of the outer rim and inner rim of the pontoon, respectively
Δh_0	rainfall increment
Δh_w	water head increment
Δh_s	liquid head increment
ΔH	difference between installing height of the deck plate and sinking depth of the floating roof
ε	error tolerance
λ_0	coefficient of determining the water distribution status on the deck plate
λ_w	ratio of equivalent water volumes on the deck plate
v	Poisson's ratio of the floating roof
θ	time of deformation progression
ρ_0	water density, 1.0×10^{-6} kg/mm^3
ρ_1	liquid (oil) density in the tank
τ, $\bar{\tau}$	ratio of the inner rim's and outer rim's radii of the pontoon before and after deformation, respectively
τ_w	ratio of water distribution's and deck plate's radii
ϕ	rotation angle of the pontoon

for the large deflection of the deck in floating roofs. These formulas, however, were based on a water test condition in which the loads on the deck plate distribute uniformly. In addition, with the development of computer modeling and corresponding numerical methods in modern engineering and sciences, the finite element method (FEM) was also employed in the structural analysis of floating roofs. Uchiyama et al. [15] and Yoshida [16] analyzed floating roofs under rainwater load by a nonlinear axisymmetric FEM, and special program codes for analysis of floating roofs, THANKS V-III and KOSTRAN, were, respectively, used in these two studies to compute the deformation and stress.

The above methods for analysis of floating roofs were usually based on the axial symmetry theory, and the floating roof is simplified to a plane structure with this theory and the components such as bulkheads (necessary to divide the pontoon into several compartments) in the pontoon were neglected. These methods would be no more applicable when floating roofs with nonaxial symmetry or with 3-D complex structures such as the newly developed floating roof with continuous beams mentioned above, are used. Moreover, the rainwater was usually assumed to fill the whole deck plate in these methods. The rainwater, however, would fill only part of the deck plate if the floating roof has a large enough diameter. On the other hand, although some FEM solutions were used to conduct the analysis of floating roofs, these solutions were based on a simple axisymmetric method and only simple plane problem was dealt with. Accordingly, it is necessary to develop a general numerical method for practical analysis of floating roofs with 3-D structures in order to ease and aid implementations of structure design, analysis and optimization of floating roofs.

This paper proposes a general and practical finite element (FE)-based numerical method, i.e. the load-modifying method (LMM), for the 3-D structural analysis of floating roofs under rainwater load. A relationship between loads and deformations is developed firstly according to the equilibrium of the floating roof, in which two cases of rainwater distribution on the deck plate are considered, one case in which the rainwater fills only part of the deck plate and the other case in which the rainwater fills the whole deck plate. Then the FE analysis of the floating roof with this relationship is conducted based on the LMM. In the analysis procedure with the LMM, an initial condition (e.g. the condition with no deformation) is assumed to begin the nonlinear FE analysis with iterative computations, and then the load magnitudes in the current iteration are modified with computational results in the previous iteration and are ready for a new iterative analysis if necessary. Before each iterative analysis, the case of rainwater distribution on the deck plate is determined by results of the previous iteration. This analysis process is carried out

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