Engineering Structures 126 (2016) 27–39

Contents lists available at ScienceDirect

Engineering Structures

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

Assessment of equivalent cylinder method and development of charts for analysis of concrete conical tanks

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ARTICLE INFO

Article history:
Received 15 February 2016
Revised 29 June 2016
Accepted 30 June 2016

Keywords:
Conical tanks
Cylindrical tanks
Nonlinear
Finite element
Reinforced concrete
Hydrostatic pressure

ABSTRACT

Elevated conical tanks are widely used as water reservoirs in various locations around the globe. The vessel of a conical tank can consist of a truncated cone solely or a truncated cone with a top cylindrical part. Current codes of practice do not provide any provisions or guidelines for designing reinforced concrete conical tanks under hydrostatic loading. Available provisions are limited only to cylindrical and rectangular tanks. In this paper, a nonlinear Finite Element Model (FEM), based on shell element discretization, is used to analyze hydrostatically loaded reinforced concrete conical tanks. A common simplified approach used in the design of conical tanks involves replacing the conical vessels with equivalent cylinders. The adequacy of this simplified method is assessed in this study through comparison with the detailed finite element results. The FEM is then used to develop a set of charts which can be used to determine the adequate thickness as well as straining actions that develop in a liquid filled reinforced concrete conical tank. The use of this set of charts in designing reinforced concrete conical tanks is illustrated through worked examples.

1. Introduction

Elevated conical tanks usually consist of a conical vessel supported on a shaft, as shown in Fig. 1. Often the vessel has a superimposed cylindrical part and in this case the tank is referred to as "combined conical tank", whereas a conical vessel without a top cylindrical part is referred to as "pure conical tank". The shaft is usually made of reinforced concrete, while the vessel is made of either steel or reinforced concrete.

Conical steel tanks were modelled and studied by El Damatty et al. [4] using a 3-D consistent sub-parametric shell element that was developed by Koziey and Mirza [5]. This element has the advantage of avoiding the spurious shear stress variations which were found in isoparametric shell elements. El Damatty et al. [6] extended this element to account for the geometric nonlinear effect and included as well a nonlinear strain-hardening material plasticity model for steel. Their numerical model accounted for the effects of geometric imperfections and residual stresses, which are quite important for thin-walled shell structures. This numerical model was then used by El Damatty et al. [7] to develop a simplified design procedure for liquid-filled steel conical tanks. This simplified approach was extended by Sweedan and El Damatty [8] to cover the design of combined conical tanks.

Sabir and Mousa [9] analyzed combined conical steel tanks with girder stiffeners under hydrostatic pressure using a linear elastic Finite Element Model (FEM). Cylindrical and conical elements were implemented in the formulation of this model. Results from their investigation showed that large stresses develop at the connection between the upper cylindrical and lower conical parts of the tanks. These stresses were found to be significantly reduced by incorporating a circular girder near this connection. Zielnica [10] performed an analytical study on the buckling capacity of conical tanks under twisting shear loads using inelastic analysis. It was concluded that the critical moment of twist that triggers buckling for conical tanks is significantly affected by the vessel's thickness and layout dimensions. El Damatty et al. [11] found that a significant enhancement of the buckling capacity of steel pure conical tanks can be provided by welding longitudinal stiffeners to the bottom part of the tanks. Their analysis was performed on both existing and newly designed conical tanks. The buckling behaviour of combined conical steel tanks was studied by Niloufari et al. [12]. They conducted an experimental investigation on a set of steel tanks under hydrostatic pressure. Their investigation revealed that buckling capacities for the studied tanks with ($t/R = 0.003$) reduce significantly due to geometric imperfections, where t and R are the wall's thickness and bottom radius, respectively.

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http://dx.doi.org/10.1016/j.engstruct.2016.06.053
0141-0296/

Fig. 1. Reinforced concrete elevated conical tank in Saudi Arabia in Alriyadh News Paper [3].

Regarding reinforced concrete tanks, Chau and Lee [13] developed a computer-aided package, RCTANK, to analyze and design rectangular and circular reinforced concrete tanks. In this computer code, the base, wall, and roof of a tank were analyzed using analytical equations under hydrostatic water pressure. Based on the analysis results, this computer package can be utilized to predict rectangular and circular tanks' wall thickness and required reinforcement. However, this numerical tool is limited to certain tank dimensions of $6 \times 6 \times 6$ m for rectangular tanks and 6 m diameter $\times$ 6 m depth for circular tanks. Ramanjaneyulu et al. [14] developed another computer package, based on analytical equations, to evaluate the load carrying capacities of reinforced concrete cylindrical tanks. This package can estimate the collapse loads for short, medium, and long cylindrical tanks without any limitations on tank dimensions. In their program, they considered the effect of variation in reinforcement along the tank's height. El Mezaini [15] analyzed reinforced concrete cylindrical tanks with a conical base using SAP 2000 software that was developed by Wilson and Habibullah [16]. The tanks were modelled using a 3-D shell element available in SAP 2000 software. El Mezaini [15] compared the internal forces obtained from the numerical model to their counterparts from the Portland Cement Association, PCA design aids [2]. Bruder [17] extended the work of El Mezaini [15] by considering a larger number of concrete tanks with practical dimensions. He concluded that the PCA design aids [2] provides inadequate design for cylindrical tanks with conical base. El Mezaini [15] and Bruder [17] reached the same conclusion that significant discrepancies were noticed between the internal forces from the numerical model and the PCA design aids [2]. Therefore, they recommended that designers should utilize finite element analysis to properly design concrete conical tanks. Recently, Ghali [18] analyzed circular storage tanks by developing a numerical model based on a conical shell element. The developed numerical model was validated by comparing the results obtained from the analysis of a set of concrete tanks to those based on closed form analytical solutions. This validated numerical model was then utilized to develop a set of tables to determine the straining actions of circular tanks. The aforementioned numerical and analytical investigations were conducted on rectangular or circular tanks and were not validated for conical tanks under hydrostatic loads. Azabi [19] analyzed a set of reinforced concrete conical tanks using a FEM that is based on the 3-D consistent element developed by Koziey and Mirza [5]. He assessed the accuracy of a simplified approach for the analysis and design of reinforced concrete conical tanks. This approach is based on the PCA design aids [2] combined with the equivalent cylindrical approach proposed by the American Water Works Association, AWWA [1]. His study concluded that the simplified design approach, which is based on the PCA design aids [2] combined with the AWWA [1], provides an inadequate design if applied to conical tanks. It is worth mentioning that Azabi [19] did not take into account the nonlinear behaviour and cracking of concrete.

The investigation conducted by Azabi [19] was extended by Elansary et al. [20] by accounting for shrinkage and the nonlinear behaviour of concrete. Shrinkage is considered by adding initial tensile stresses in the finite element model based on the PCA design aids [2]. The nonlinearity of concrete was considered by including a concrete constitutive model previously developed by Pietruszczak et al. [21] and Jaing [22]. A set of twelve reinforced concrete conical tanks covering a wide range of practical dimensions were analyzed by Elansary and El Damatty [23] and Elansary et al. [20]. The analysis was conducted under both working and ultimate loads using the extended finite element program that considers shrinkage and nonlinear behaviour of concrete. Results of the analysis showed that the maximum deflection for the tank's wall occurs at the middle one-third of the tank's height and the maximum hoop stresses occur at 1/5–1/6 of the tank's height. Elansary et al. [20] found that the ratio between the maximum displacements from the linear to nonlinear analyses is 0.9. Furthermore, results from their analysis revealed that the maximum meridional stresses in the concrete wall and reinforcing bars occur within the bottom 10% region of the tank's vessel. This was noted for the studied tanks under either working or ultimate loads.

Elansary et al. [20] selected the material concrete model by Pietruszczak et al. [21] and Jaing [22] for two reasons. First, Koziey [24] showed that this material model was compatible with the 3-D consistent element, which was adopted by Elansary et al. [20], without showing numerical instabilities. Second, this model was able to capture the ductile behaviour of concrete, enhancement in strength due to confining pressure, and the nonlinear behaviour of the stress-strain relation. It is worth mentioning that the nonlinear behaviour of concrete was studied in many other investigations, same as Selby and Vecchio [25], Wang et al. [26], and Chen [27]. However, the compatibility of these models with the 3-D consistent element was not validated in their investigations. These investigations revealed that the nonlinear behaviour of concrete should be considered in the analysis of concrete structures in order to model them accurately. They reported that the nonlinearity in concrete occurs due to the formation of cracks, hardening/softening, aggregate interlock, reinforcement slippage, and dowel action.

The current paper has three main objectives. The first objective is to assess the effect of shrinkage and effect of change in concrete strength on the design of reinforced concrete conical tanks. The effect of shrinkage is assessed by evaluating the required concrete wall thickness while considering/ignoring shrinkage. Meanwhile, the effect of change in concrete strength is assessed by evaluating the required concrete wall thickness using two different practical concrete strengths. The second objective is to check the adequacy of analyzing and designing reinforced concrete conical tanks using a simplified method based on the AWWA design code [1] and the PCA design aids [2]. In this method, the AWWA design code [1] is used to obtain the dimensions of an equivalent cylinder and then the PCA design aids [2] are used to analyze and design the equiva-