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Behaviour of composite conical tanks under hydrostatic pressure

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ABSTRACT

Conical vessels are used around the globe for liquid storage in water tanks. These vessels can be made of steel, reinforced concrete, or composite; i.e. concrete and steel. Composite vessels consist of an external steel shell attached to an internal reinforced concrete wall through steel studs. Previous studies available in the literature focused on studying steel or reinforced concrete vessels. To the best of the author's knowledge, this paper presents the first comprehensive study conducted on liquid-filled composite tanks. A Finite Element Model for Composite tanks (CFEM), which accounts for both the geometric and material nonlinearities, is developed. The material nonlinearity is considered by including nonlinear models for both steel and concrete. The developed CFEM also considers nonlinear behaviour of studs by including the nonlinear load-slip and load-peel curves obtained from test results reported in the literature. In the CFEM, both the concrete and steel walls are modelled using 13-node subparametric shell elements, while the connecting studs between the two walls are modelled using 26-node contact elements using a smearing approach. Validation of the CFEM is conducted by modelling two composite slabs from the literature and comparing the results with their counterparts obtained from the conducted experiments. The CFEM is used to evaluate the deflections, stresses, and internal forces in the concrete and steel walls as well as steel studs. An Equivalent Section Method (ESM) for the analysis of composite tanks, which is based on using an equivalent single wall, is introduced. Deflections, stresses, and internal forces in the steel and concrete walls predicted using this simplified approach are compared to those predicted by the detailed finite element model.

1. Introduction

Vessels with truncated conical shapes are commonly used as liquid containments in elevated conical tanks. The main structural components of conical tanks are the supporting system and the vessel, as shown in Fig. 1. The vessels can be made of steel or reinforced concrete, with steel being more common especially in North America. Recently, composite steel-reinforced concrete construction has been used for conical vessels combining the benefits of both materials as explained later. In this type of construction, the vessels consist of an external steel shell made of curved steel panels and an internal reinforced concrete shell that is cast-in-situ. The steel and reinforced concrete shells are connected together using steel studs that are welded to the steel shell and embedded into the reinforced concrete shell, which will be referred to here as "concrete wall". The state of stress in liquid-filled conical vessels was described in detail by El Damatty et al. [5]. The hydrostatic pressure associated with the contained liquid leads to tensile stresses in the hoop (circumferential) direction and compressive in the meridional (axial) direction. While steel conical vessels are efficient in resisting the tensile hoop stresses, they are susceptible to bulking under the meridional compressive stresses. In fact, a number of steel conical tanks collapsed in the past because of buckling, such as in Belgium, in 1972 and in Fredericton, Canada, in 1990, which were reported by Vandepitte [1] and Korol [2], respectively. In contrast, reinforced concrete conical vessels have strong resistance to buckling under compressive meridional stresses, but they are weak in resisting the tensile hoop stresses. Composite conical tanks overcome the disadvantages of reinforced concrete and steel conical tanks by making full use of the capacity of the two materials. As a result, the construction of composite conical tanks has been recently spreading in different locations around the globe. However, no guidelines exist in the current codes of practice regarding the analysis and design of this type of composite structures. The literature review on studies related to structural behaviour of hydrostatically loaded conical tanks indicates that a number of studies were done for steel tanks, a few exists for reinforced concrete tanks, and none is available for composite tanks.

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Fig. 1. Photograph of an elevated conical tank.

Following the collapse of a steel conical tank that happened in Belgium, 1972, which was reported by Vandepitte [1], an extensive experimental program was conducted by Vandepitte et al. [3]. In this experimental program, a large number of small-scale truncated conical shell models, made of mylar, brass, aluminum, and steel, were tested. The models were filled gradually with water and the height of water at which buckling occurred was recorded. The study considered geometric imperfections, which are known to affect significantly the buckling capacity of thin-shell structures. Based on the experimental results, expressions were developed to determine the adequate thickness of conical vessels required to prevent buckling for different magnitudes of geometric imperfections. Following the failure of the steel conical tank that occurred in Fredericton, Canada in 1990, an extensive research program was conducted on the stability of hydrostatically loaded steel conical tanks by El Damatty et al. [4,5]. In this research program, an inhouse numerical model for the analysis of steel conical tanks was developed by El Damatty et al. [5]. This element was developed by Koziey and Mirza [6] and then extended by El Damatty et al. [4] to include the nonlinear behaviour of steel. Results of the aforementioned studies showed that inelastic bucking at the vessel's base is usually the main cause of failure of conical steel vessels subjected to hydrostatic pressure. A study by El Damatty et al. [7] showed that inelastic buckling of steel conical tanks was most sensitive to axisymmetric imperfections. El Damatty et al. [8] found that welding stiffeners to the bottom part of steel conical tanks significantly enhances the buckling capacity of conical tanks.

Many investigations are found in the literature covering the analysis of concrete rectangular or circular tanks under hydrostatic pressure, such as the studies conducted by Green and Perkins [9], Chau and Lee [10], and Ghali [11]. None of these investigations accounted for the nonlinear behaviour of concrete. Green and Perkins [9], and later Anchor [12] presented a simplified procedure for the analysis and design of reinforced concrete rectangular tanks. In their studies, they used the classical beam theory to obtain the internal forces in rectangular tanks subjected to hydrostatic water pressure. Chau and Lee [10] analyzed circular in addition to rectangular tanks using a self-developed computer program, RCTANK. They validated this program by comparing the results for four different reinforced concrete tanks with their counterparts obtained from manual methods. Two years later, Ramanjaneyulu et al. [13] developed another computer program, TANK, to evaluate the load capacity of reinforced concrete tanks by applying the limit analysis approach. The four aforementioned studies are based on analytical solutions that are valid for rectangular or circular tanks and cannot be used for conical tanks. Recently, Ghali [11] analyzed circular storage tanks using a Finite Element Model (FEM) based on a conical shell element. The FEM was validated by comparing the analysis results for a set of tanks with those obtained from closed form analytical solutions. Ghali [11] developed a set of tables that show straining actions of circular tanks with a wide range of practical dimensions. However, the adequacy of using the developed tables to determine the straining actions of conical tanks was not tested by Ghali [11]. El Mezaini [14] and Bruder [15] analyzed a set of reinforced concrete cylindrical tanks with a conical base using SAP 2000 software. Azabi [16] analyzed a set of reinforced concrete pure conical tanks using a FEM that is based on the 3-D consistent element developed by Koziey and Mirza [6]. Azabi [16] assessed the accuracy of a simplified approach for the analysis and design of reinforced concrete conical tanks. This approach is based on the Portland Cement Association, PCA design aids [17] combined with the equivalent cylindrical approach by the American Water Works Association, AWWA [18]. El Mezaini [14], Bruder [15], and Azabi [16] compared between the internal forces obtained from their numerical models with those resulting from the PCA design aids [17]. Significant discrepancies were obtained between the internal forces resulting from the numerical models and the PCA design aids [17]. The FEM by Azabi [16] was extended by Elansary et al. [19] to account for shrinkage and the nonlinear behaviour of concrete. The nonlinearity of concrete was considered by including a concrete constitutive model previously developed by Pietruszczak et al. [20] and Jaing [21]. Elansary et al. [19] used the developed FEM to study the behaviour of twelve reinforced concrete conical tanks with a wide range of practical dimensions. They reported that the maximum deflection of the tank's wall occurs at the middle one-third of the tank's height and the maximum hoop stress occurs at 1/5–1/6 of the tank's height. Their study showed that the maximum meridional stress in the concrete wall and reinforcing bars occur within the bottom 10% region of the tank's vessel.

The aforementioned studies on reinforced concrete tanks revealed the necessity of using significantly large thickness to prevent cracking for large capacity tanks. Meanwhile, the investigations on steel tanks showed that they can suffer from buckling if inadequate thickness is used. The facts that concrete is superior in resisting buckling and steel is superior in resisting tensile stresses led practitioners to combine the two materials in composite structures. As mentioned earlier, no studies are found in the literature regarding the behaviour of composite conical tanks. The behaviour of composite slabs can provide an insight on that of composite tanks. An early study on the behaviour and strength of one-way composite slabs was performed by Daniels and Crisinel [22,23]. They conducted experiments on a set of one way composite slabs and found that the behaviour and strength of the connection between the steel plate and concrete slab may be estimated using the pull-out and push-out tests. Good agreement was noted between the experimental results and those obtained from analytical solutions. Another two studies by Eldib et al. [24] and Shanmugam et al. [25] focused on the finite element modelling of two-way composite slabs using the commercial software, COSMOS