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Stability of combined imperfect conical tanks under hydrostatic loading

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ABSTRACT

Steel conical vessels with upper cylindrical caps are widely used as liquid containments in elevated water tanks. This type of structure for containing water is referred to as "combined conical tank". A number of catastrophic failures of combined conical tanks occurred during the past decades in various locations around the globe. Previous studies available in the literature focused on pure conical tanks, where the vessels have no upper cylindrical caps. The current study focuses on characterizing the buckling behaviour of combined conical tanks under the effect of hydrostatic pressure. The study is conducted numerically using a three-dimensional finite element model developed in-house. The effects of geometric imperfection and residual stresses as well as the variation of the geometric and material parameters on the buckling capacity of combined conical tanks are investigated. Finally, a comparison between the buckling capacities of combined and equivalent pure conical tanks is conducted.

1. Introduction

Conical steel vessels are widely used as containments in elevated water tanks. The photos of two elevated conical tanks are shown in Figs. 1a and 1b. In the first figure, the vessel has a truncated conical shape and the tank is referred to as "pure conical tank". The vessel of tank shown in Fig. 1b has a truncated conical shell with a superimposed cylindrical part. Such a type of structure is referred to as "combined conical tank". For those two configurations, the steel vessel consists of a number of curved panels, which are welded together along both the circumferential and longitudinal directions. The steel vessel is typically welded at its bottom edge to a circular steel plate, which is in turn anchored to a heavy reinforced concrete circular slab supported by a reinforced concrete tower. A number of catastrophic failures of conical tanks happened during the past few decades in various locations around the globe. One of those failures occurred in Belgium in the seventies while another failure happened in Fredericton, New Brunswick, Canada, in the early nineties. A number of similarities exist between those two failure incidents. Both failures occurred while the structures were subjected to vertical loads resulting mainly from the weight of the contained fluid. Also, both failures were initiated by the buckling of the steel vessel as stated by Korol [1] and Dawe et al. [2]. The buckling, which occurred at the bottom region of the steel vessels, was attributed to the use of an inadequate thickness for the steel shell in this region. Following the collapse of the conical tank in Belgium, a research program was initiated at Ghent University led by Professor Vandepitte [3]. The research was mainly conducted experimentally. A large number of small-scale conical vessel models were constructed. The models had different dimensions and were made of different materials, with majority of them made of Mylar. The experiments were conducted by gradually increasing the height of water inside the models. The water height at which each model buckled was detected. The experimental results were employed to develop a set of equations that can be used to assess the stability of conical tanks [3]. An expression for the wavelength of the buckling mode of conical tanks was also recommended. Based on the outcomes of these experimental studies, the European recommendations related to shell buckling, published by the convention for Constructional Steel work [4], have adopted a more rational approach for the design of steel conical tanks with an angle in the range of 15° to 65°. It should be noted that Vandepitte's experimental program was conducted strictly on pure conical vessel models. The method of construction of small-scale models is different from that of full-scale vessels. The latter involves both circumferential and longitudinal welding, which do not exist for small-scale models. As a result, the type of geometric imperfection which could exist in full-scale structures might be different from those existing in the small-scale models. In the late nineties another European research project was conducted by Guggenberger [5], which aimed at the enhancement of ECCS design recommendations for axially loaded cylindrical steel shells on local column supports. This project consisted of two parts, a testing part carried out at the laboratory for Model Testing at the University of Ghent and a numerical–theoretical part carried out at the Technical University Graz. The main outcome of this project was the derivation of

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Fig. 1a. Photo of a pure conical tank.

Fig. 1b. Photo of a combined conical tank.

design rules for axially loaded steel cylinders on local supports. Following the collapse of the Fredericton conical tank in the early nineties, an extensive research program focusing on the stability of such structures was initiated in Canada. The buckling behaviour of conical tanks, including the effect of geometric imperfections and residual stresses, was studied by El Damatty et al. [6,7]. A simplified design procedure was then developed by El Damatty et al. [8], followed by another investigation that was conducted by El Damatty and Marroquin [9], where a design approach was developed to ensure safety of hydrostatically loaded combined steel conical tanks against buckling. In this design approach, the finite element results together with a nonlinear regression analysis are used to develop magnification factors that relate the overall shell stress to the membrane stress which can be evaluated analytically. This design procedure is considered in the current study as the basis for the design of tanks. The current study focuses on the stability analysis of combined conical tanks with the specific objectives:

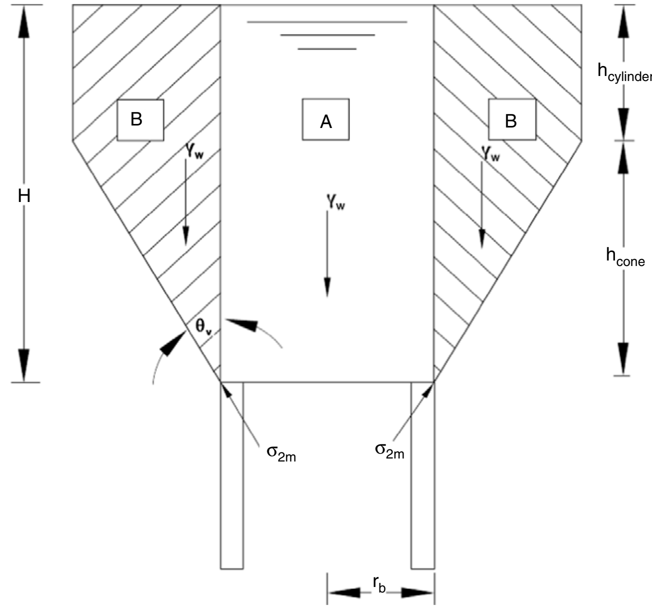

Fig. 2. Cause of failure of conical tanks.

(1) Determine the wavelengths of the buckling mode.
(2) Assess the effect of residual stress on the buckling capacity.
(3) Assess the variation of buckling capacity with the following parameters: tanks' geometry, imperfection wavelength, and imperfection amplitude.
(4) Compare between the buckling capacities of combined and equivalent pure conical tanks.

The study is conducted numerically using the finite element method. The study starts by describing the cause of failure of conical tanks. This is followed by a description of the numerical model, the method of analysis and the assumed geometric imperfection shapes. The results of the analysis related to the four above mentioned objectives are then provided. Finally the main conclusions obtained from the study are stated.

2. Causes of failure of conical tanks

Fig. 2 shows the vertical projection of a combined conical vessel filled with water. In this figure, volume "A" is bound by an imaginary cylinder having a radius equivalent to the bottom radius r_b of the vessel. Volume "B" is bound by the surface of the vessel and the surface of this imaginary cylinder. The weight of water inside volume "A" is directly resisted by the vertical support underneath the vessel. The weight of water inside volume "B" is supported by the inclined walls of the vessel. This leads to meridional compressive stresses acting along the longitudinal direction of the shell and hoop tensile stresses acting in the circumferential direction. The bottom region of the vessel is the most critical in terms of stress concentration since it supports the total weight of volume "B" and has the smallest cross section. In addition, the boundary conditions at the bottom of the vessel restrain the displacements, leading to bending deformations and bending stresses in this region. As such, conical tanks can fail by instability due to a localized buckling effect near the base of the vessel. The buckling capacity of the vessel can be reduced due to the presence of geometric imperfections and welding residual stresses at this bottom region.

3. Finite element model

Three-dimensional numerical models are developed for combined conical tanks using the finite element method. The numerical