THERMAL BUCKLING ANALYSIS OF THIN-WALLED STEEL OIL TANKS EXPOSED TO AN ADJACENT FIRE

C. Maraveas
School of Mechanical, Aerospace and Civil Engineering, University of Manchester,
Manchester, M13 9PL, UK and
C. Maraveas Partnership – Consulting Engineers, 11 Metsovou street,
Athens, 10682, Greece. c.maraveas@maraveas.gr

ABSTRACT

This paper presents a finite element study of a steel oil storage tank with cylindrical shell shape and conical roof subjected to an adjacent fire. Fire is one of the main hazards associated with tanks containing combustible materials. Several catastrophic accidents have taken place during the last decades revealing the consequences and losses arising from such events and highlighting the importance for proper design against thermal buckling. Oil storage tanks are usually placed in large groups and closed distances. Therefore, it is assumed herein that the fire occurs outside the tank. Critical buckling temperatures are calculated considering that the temperature profile along the circumference of the tank is defined according to a cosine square distribution. The influence of the roof stiffness, of the circumferential area exposed to fire and of the filling level is examined. Apart from the thermal loads, the self-weight of the tank and the hydrostatic pressure exerted by the liquid are taken into account in the static analyses. The mechanical properties of steel are taken according to Eurocode 3.

KEYWORDS

Finite elements, fire, steel tanks, thermal buckling.

INTRODUCTION

Fire is one of the main hazards associated with oil storage tanks (a review of recent accidents has been presented by Chang and Lin 2006 and Liu 2011). They are commonly placed in closed distances and as a result in case of a fire event high temperatures also develop to the adjacent tanks, which are susceptible to thermal buckling due to their small wall thickness to diameter ratio.

The structural behaviour and the overall stability of steel tanks subjected to thermal loads can be assessed by means of finite element numerical analyses. Specifically, assuming a temperature distribution pattern, the critical thermal buckling load can be calculated. The influence of the various parameters involved into the problem (e.g. the liquid level, the heating range in the vertical and in the circumferential direction, the stiffness and the inclination of the roof, the wall thickness to tank radius ratio, etc.) can be investigated through the performance of numerous calculations. Liu (2011) and Godoy and Batista-Abreu (2012, 2013) have extensively examined the behaviour of oil storage tanks exposed to fire. This paper aims to present the results derived from the finite element modelling of a steel tank, following the above works.

FINITE ELENENT MODELLING

A cylindrical tank of diameter equal to 15m with conical roof is considered, satisfying the requirements of EC3-1.6 (2007). The height of the cylindrical shell is taken equal to the diameter and the inclination of the roof equal to 10°. The thickness of the wall is considered to be 10mm, in contrast to the thickness of the roof which varies (in order to examine the influence of its stiffness on the structural behaviour of the tank). Its weight is appropriately decreased (corresponding to a thickness equal to that of the wall) in order to avoid overloading of the tank. Figure 1 shows the finite element model for an empty (left) and a half filled tank (right), respectively. The half tank is analysed due to the symmetry in the horizontal direction by applying appropriate boundary conditions in the symmetry plane. Moreover, all the translational degrees of freedom are restrained at the bottom nodes of the structure. A finer mesh is applied to the base of the shell, to its intersection with the roof and to the level of the liquid.

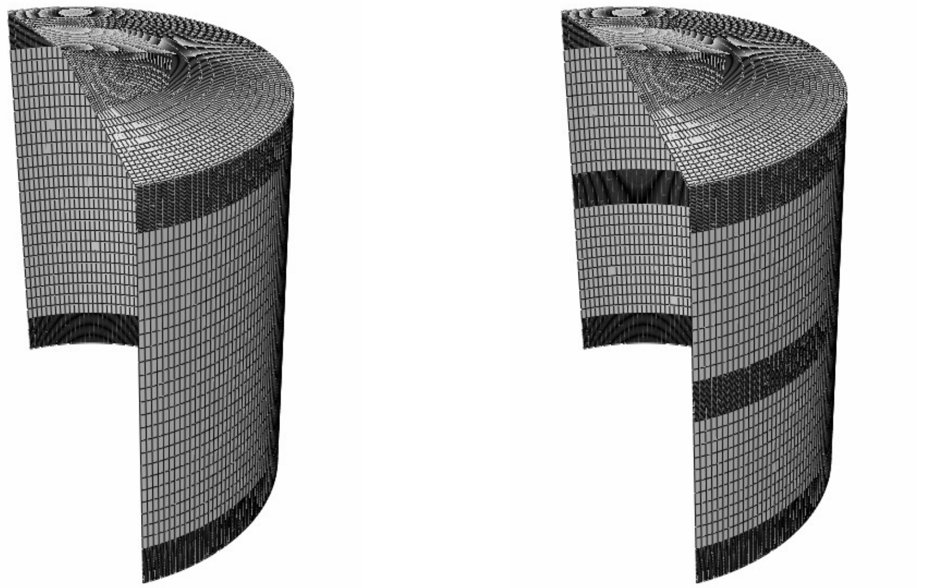


Figure 1. Finite element model for an empty (left) and a half filled tank (right)

Apart from the self-weight of the tank, the hydrostatic pressure exerted from the liquid to the tank wall is considered. A fluid-structure interaction would be relevant in the case of dynamic loading, e.g. in the presence of seismic excitation (Batista-Abreu and Godoy, 2013). The specific weight of steel is taken as 78.5 kN/m^3 and that of the fuel as 8 kN/m^3.
The temperature pattern around the circumference of the tank is based on the following square cosine function (Liu 2011):

$$T(\theta)=\begin{cases}\left(T_{0m}-T_{0a}\right)\cos^2\left(\dfrac{\theta}{\theta_0}\dfrac{\pi}{2}\right) & , \quad |\theta|\leq\theta_0 \\ 0 & , \quad |\theta|>\theta_0\end{cases} \tag{1}$$

where θ is the circumferential coordinate, originating from the meridian facing the fire, θ_0 is the critical angle, which defines the extent of the heating zone, T_{0a} is the ambient temperature (considered equal to zero throughout this study) and T_{0m} is the maximum temperature reached in the tank wall on the most heated meridian (i.e. θ = 0). Figure 2 plots this function for five different values of the critical angle.

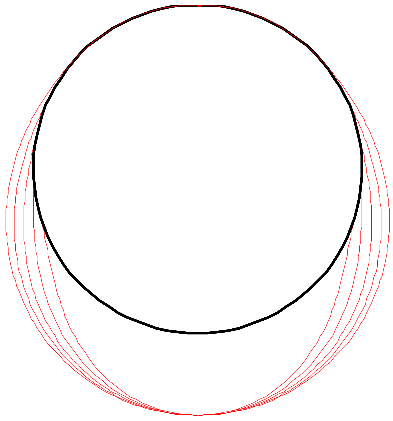


Figure 2. Temperature distribution along the circumference of the tank for 5 different values of the heating zone (θ_0 = 75°, 90°, 105°, 120°, 135°) with the same maximum temperature

The temperature distribution is considered unaltered along the height of the tank, while the roof is always considered cold. In the presence of liquid, the wall below its level is considered also cold and the aforementioned distribution is applied to the remaining shell above it. No transition zone is taken into account either to the fluid level or to the eaves. The temperature gradient along the shell thickness is disregarded, i.e. a uniform temperature is considered.

The temperature dependent mechanical properties of steel (i.e. the elastic modulus, the Poisson's ratio and the coefficient of thermal expansion) are taken according to the EC3-1.2 (2004). The yield stress was not considered since Liu (2011) and Godoy and Batista-Abreu (2012) have shown that in the problem under examination the developed stresses are low before buckling and thus the incorporation of geometric nonlinearity is sufficient.

All the analyses have been performed with the Abaqus finite element software (Dassault Systèmes 2010) using 4-node reduced integration shell elements (S4R). Moreover, the Lanczos eigensolver was used for the linear buckling analyses and the Riks (1979) method for the static analyses.

LINEAR BUCKLING ANALYSES

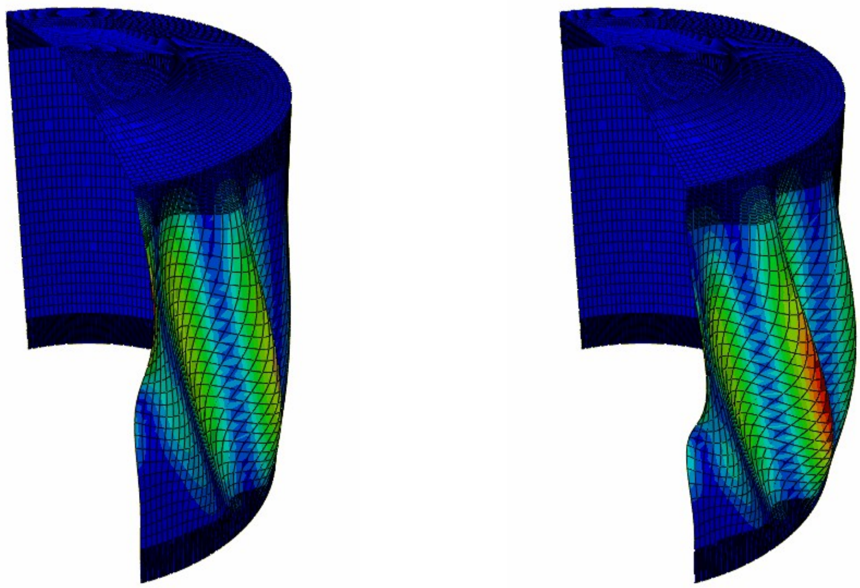
Initially, linear buckling analyses were performed in order to have a first estimation of the magnitude of the buckling temperatures and of the shape of the buckling modes. The self-weight of the tank and the hydrostatic pressure of the liquid were considered for the forming of the base state of the structure. Table 1 summarizes the first five eigenvalues for an empty and a half filled tank, respectively (the fire affects a zone of 90° along the circumference), considering two different values for the roof thickness t, which are explained below. The negative eigenvalues have been removed from the Table since they indicate that the tank would buckle in case of temperature decrease according to the considered distribution of Equation 1 (Liu 2011). Figure 3 presents the corresponding buckling modes for t = 3 mm. It should be noted that the existence of fluid leads to higher buckling temperatures, provided that a lower part of the tank is heated and the exerted pressure on the wall has a stabilizing effect (Godoy and Batista-Abreu 2012). Moreover, the model with the stiffer roof gives slightly lower buckling temperatures.

NONLINEAR STATIC ANALYSES

The results of geometrically nonlinear static analyses are presented in the following, accounting for the temperature dependent mechanical properties of steel, in contrast to the previous eigenvalues analyses, which are generally based on the elastic material properties at the ambient temperature. Furthermore, herein, the deformed state of the structure after the application of the dead loads is taken into consideration. It should be reminded that material nonlinearities (i.e. elastoplastic behaviour) have not been considered, given that the developed stresses prior to buckling are low. The influence of the roof stiffness, of the area exposed to fire and of the filling level, on the critical buckling temperature has been examined.

Table 1. Buckling temperatures obtained from linear buckling analyses

	t = 2mm		t = 3mm	
Mode No.	Empty tank	Half filled tank	Empty tank	Half filled tank
1	182.0	239.8	178.2	238.9
2	194.5	470.3	188.3	446.1
3	199.7	528.5	193.3	524.0
4	221.7	545.5	214.8	540.7
5	222.2	601.4	215.4	596.1



2nd mode 3rd mode

Figure 3. Buckling modes obtained from linear buckling analysis (t = 3mm, empty tank)

Influence of the roof stiffness

The stiffness of the roof depends on the internal support structures used to ensure its stability (e.g. trusses, rafters or columns). Herein, the stiffness of the roof is considered by modifying its thickness (as has already been noted, its specific weight is scaled appropriately). Figure 4 shows the calculated buckling temperature as a function of the ratio of the roof to the wall thickness. The extent of the heated zone is equal to 90° and the tank is empty. Obviously, for ratios greater than 3 the buckling load remains unaltered which indicates that the roof is practically rigid. This is the reason why two values for the roof thickness are considered in the current study (i.e. t = 2 and t = 3).

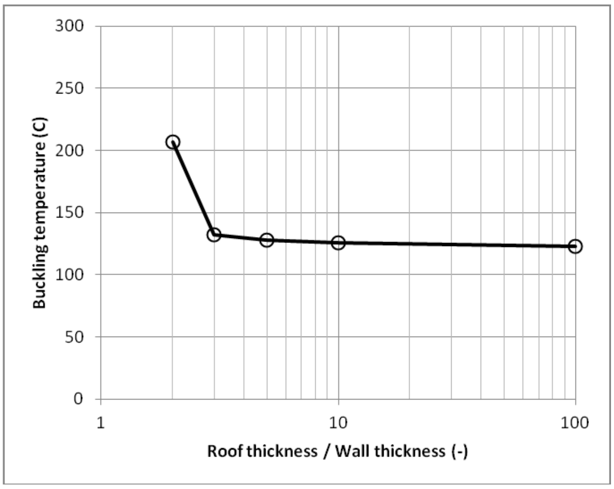


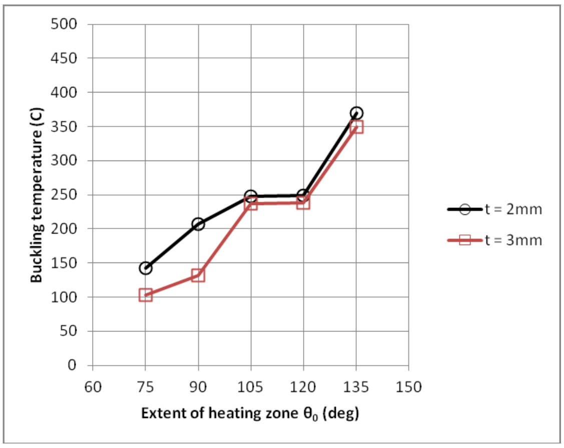
Figure 4. Buckling temperature with respect to the ratio of the roof to the wall thickness

Influence of the extent of the heating zone

Figure 5 (left) shows the buckling temperature with respect to the extent of the heated zone, described by the critical angle θ_0 (see Equation 1), for an empty tank. Obviously, the higher the heating area, the lower is the restriction of thermal expansion of the heated tank wall and thus the higher is the buckling temperature. Note that the stiffer roof leads to slightly lower buckling temperatures similarly to the linear buckling analyses.

Influence of the liquid level

Finally, the influence of the filling level is examined considering a heating zone of $\theta_0 = 90°$. As noted above, an ambient temperature is considered up to this level and thus the heated zone is limited to the upper part of the cylinder. Figure 5 (right) depicts the buckling temperature, which increases with the volume of the fluid stored, which indicates that the exerted hydrostatic pressure on the wall has a stabilizing effect (Godoy and Batista-Abreu 2012).



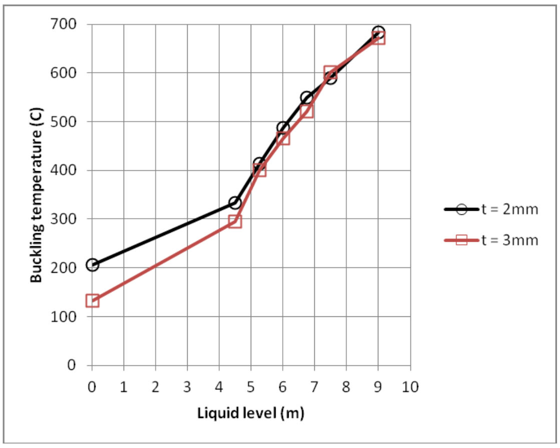


Figure 5. Buckling temperature with respect to the extent of the heating zone (left) and to the liquid level (right) for two different roof thicknesses

CONCLUSIONS

The structural behaviour of a steel oil storage cylindrical tank with conical roof exposed to an adjacent fire was examined in the present paper by means of finite element numerical analyses. Critical buckling temperatures were predicted considering several scenarios for the roof stiffness, the circumferential area of the tank subjected to fire and the level of the stored liquid. A square cosine function was adopted for the temperature distribution along the circumference of the shell. It was shown that the range of temperatures causing thermal buckling is large, depending on several parameters. However, for an empty tank with moderate heated area may not exceed 200°C. The derived results are in agreement with more comprehensive studies of the topic.

REFERENCES

Batista-Abreu, J.C. and Godoy, L.A. (2013) "Thermal buckling behavior of open cylindrical oil storage tanks under fire", *Journal of Performance of Constructed Facilities*, ASCE, Vol. 27, No. 1, pp. 89-97.

Chang, J.I. and Lin, Ch.-C. (2006) "A study of storage tank accidents", *Journal of Loss Prevention in the Process Industries*, Vol. 19, pp. 51-59.

Dassault Systèmes (2010) *Abaqus 6.10 – Analysis User's Manual*.

European Committee for Standardization (CEN) (2004) *Eurocode 3: Design of steel structures – Part 1-2: General rules – Structural fire design*.

European Committee for Standardization (CEN) (2007) *Eurocode 3: Design of steel structures – Part 1-6: Strength and stability of shell structures*.

Godoy, L.A. and Batista-Abreu, J.C. (2012) "Buckling of fixed-roof aboveground oil storage tanks under heat induced by an external fire", *Thin-Walled Structures*, Vol. 52, pp. 90-101.

Liu, Y. (2011) *Thermal buckling of metal oil tanks subject to an adjacent fire*, Doctor of Philosophy Dissertation, The University of Edinburgh, U.K.

Riks, E. (1979) "An incremental approach to the solution of snapping and buckling problems", *International Journal of Solids and Structures*, Vol. 15, pp. 529-551.