Thermal Buckling Behavior of Open Cylindrical Oil Storage Tanks under Fire

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Abstract: This paper reports the computational results of an investigation of oil storage tanks with the shape of an open cylindrical shell under thermal loads induced by fire. Interest in this problem has arisen as a consequence of a catastrophic fire that affected an oil storage facility in Puerto Rico in 2009 that caused the failure of 21 large tanks. To identify patterns of deformations that could be expected under various fire conditions, computer modeling has been carried out for one tank geometry. It is assumed that fire occurs outside the tank and induces an increasing temperature field affecting part of the external surface in the circumferential direction. The nonlinear shell response is modeled using finite elements under thermal loads and self-weight. The nonlinear behavior is computed to identify thermal buckling of the shell as a limit point. The response is initially computed for empty tanks, and the influence of various factors is investigated, including the liquid stored, a temperature gradient across the thickness, the circumferential zone affected by fire, and the shell thickness. The results for open tanks show that the location of large out-of-plane displacements attributable to thermal buckling coincides with the heated zone. The importance of thermal gradients in the thickness to the buckling load and mode are shown. **DOI: 10.1061/(ASCE)CF.1943-5509.0000309.** © *2013 American Society of Civil Engineers.*

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Introduction

Explosions and fires in oil refineries and storage facilities have been responsible for damage and failure of storage tanks in recent years, causing significant human, environmental, and financial losses. An investigation on the causes of 242 accidents of hydrocarbon storage tanks that occurred between 1960 and 2003 (Chang and Lin 2006) concluded that fire constitutes the most frequent accident type and (excluding explosions as primary causes) comprise 60% of the cases. North America hosted 47.1% of the cases (of which 43.4% of the cases occurred in the United States), Asia and Australia have 29.8, Europe 15.7, Africa 3.7, and South America 3.7%.

A review of 480 accidents that involve fire in oil storage tanks between 1951 and 2003 shows that the number of accidents increases by at least 20% each decade, with an average of 16 accidents per year in the decade of 1990 (Persson and Lönnermark 2004). Notably, half of the cases registered occurred in the United States. Persson and Lönnermark mentioned that the number of tanks involved in the fire events is considerably larger than the number of accidents, meaning that numerous containers participated actively in each accident. For cases in which the number of tanks under fire is known, the average of those tanks per incident is six, but the largest incident involved 200 tanks. The tank diameters vary between 8 and 90 m, and most of the tanks considered were categorized as floating roof tanks. The majority of those tanks had an external floating roof. Fixed roof tanks, including cone and dome roof tanks, are also listed but in a smaller proportion.

One of the best-known cases of fire in an oil storage facility occurred in Buncefield, United Kingdom, in December 2005, affecting 20 tanks (Buncefield Major Incident Investigation Board 2008). A more recent accident of similar proportions occurred in Bayamon, Puerto Rico, in October 2009, causing the destruction of 21 tanks (Batista-Abreu and Godoy 2011). A common feature in the investigation of most accidents of this type is that there are significant difficulties in reconstructing the sequence of events leading to fire propagation in a tank farm, because the fire tends to destroy most evidence. In a fire investigation, the tanks affected by fire have such a level of destruction at the end of the process that it might be extremely difficult to use that final information as indicative of the source of the accident. On the other hand, there may be photographic records (as in the case of the Puerto Rico accident of 2009) of tanks with various levels of deformation attributable to fire and at various times, and such evidence may be useful for the reconstruction of events. However, the links between distorted shapes and their cause is not self-evident, and it necessitates a careful study of the deformed shapes of shells in tanks under various fire scenarios to be able to understand the deformed patterns observed in real situations.

In essence, fire affects material properties (i.e., stiffness and strength parameters) and induces severe shape changes. Geometric changes become significant whenever there are displacement constraints associated with boundary conditions at the top and bottom of a shell. At an initial stage, fire acts as a thermal loading on the structure, and it may be the case that before strong changes in material

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properties take place, the shape becomes distorted because of thermal buckling.

Efforts to understand the effects of fire in structural systems made by the scientific community in the past three decades have concentrated on the behavior of individual members and frame structures [see, for example, Buchanan (2002) and Wang (2002)]. However, studies of thin-walled oil storage steel tanks under fire that account for the specific behavior of shells are not commonly found in the literature (Liu et al. 2008). A number of questions remain open at present, such as the following: What temperature levels and distributions are required to induce shell buckling? Is this behavior initially dominated by elastic response or is it accompanied by significant plasticity? Does a temperature gradient across the thickness modify the critical temperatures?

This paper reports numerical results obtained from finite-element models of individual open tanks that were affected by fire in the accident at Bayamon, Puerto Rico, to estimate the temperature levels required to trigger buckling of the tank. In all cases, the research emphasizes the onset of the failure process by considering geometric changes that occur in the shell attributable to thermal buckling. The total destruction of the tank is not modeled because of computational difficulties and because it may not be entirely useful in an initial fire investigation and before material tests are carried out. Deformed shapes, on the other hand, become elements of rapid analysis that may provide an overview of how fire propagated in a tank farm.

Summary of the 2009 Accident in Bayamon

On October 23, 2009, a catastrophic accident happened at the facilities of Caribbean Petroleum Corporation (CAPECO), a large oil storage plant located in Bayamon, Puerto Rico (west of the city of San Juan). The plant was located in an area of approximately 500,000 m^2 and included the following four main areas: the administrative office building, a farm of oil storage tanks, a wastewater-treatment plant, and a refinery that has not operated since 2000. The CAPECO facility also had a water lagoon in the northeastern zone, with a surface area of about 12,000 m^2, and a private harbor in the San Juan Bay for loading and unloading products, equipped to receive multiple ships simultaneously and located 3 km from the plant.

The plant hosted 76 containers of which 40 were used to store gasoline, diesel, gasoil, aviation fuel, liquefied petroleum gas, oil fuel, and crude oil. Those were cylindrical tanks, fabricated with steel or aluminum, with conical or spherical external fixed roofs and with internal floating roofs. According to Godoy et al. (2002), a single U.S. company built most of these containers in the 1970s. The largest tank had a diameter of 74 m, and typical tanks had diameters of approximately 30 m and a height of 12 m. The foundations were of the following two types: some tanks were supported on reinforced-concrete rings, whereas others were directly placed on consolidated soil. No tanks in this facility were supported on piles. Tanks with a fixed roof had welded connections between the cylindrical body and the conical roof. A tank without a fixed roof is shown in Fig. 1 before the accident. Several of those tanks had been analyzed in the past by one of the authors and coworkers to investigate their response under wind (Sosa and Godoy 2005), earthquakes (Virella et al. 2006), and support settlement (Godoy and Sosa 2003).

On the morning of Friday, October 23, 2009, a series of explosions and fires occurred at the CAPECO facilities. The first and most powerful of multiple blasts was registered at 12:23 a.m. The final explosion registered by the firefighter team occurred at 8:16 a.m. the same day. The weather conditions on the day of the explosions showed maximum and minimum temperatures of 34 and 26 °C, respectively. The reported peak wind velocity was 29 km/h. No rain fell during the day of the explosions. The Puerto Rico Seismic Network (2009) recorded waves generated by the first blasts in 13 of the 25 monitoring stations installed in the region, with a magnitude which is equivalent to that of an explosion in a gas plant. As described by Batista-Abreu and Godoy (2011), the accident involved more than half of the tanks at the farm, caused significant damage to the environment and to the population in the disaster zone, and generated a huge economic loss.

Agents of the Federal Bureau of Investigation (FBI) stated that this was the biggest fire in the history of Puerto Rico. The flames propagated quickly, reaching 30 m high. According to FEMA, 21 tanks ended up involved in the fire. Flames covered approximately 50% of the storage farm area, including most of the tanks located in the northern area and half of the tanks of the central part of the farm. A column of black toxic smoke almost 6 km high shrouded the CAPECO plant, hindering the visibility of the area.

The U.S. Chemical Safety and Hazard Investigation Board and the FBI were in charge of investigating the oil plant accident. It is believed that the initial source of the fire was associated with the failure of the liquid level gauges in one of the steel containers identified as number 105 (shown in Fig. 2), which was overfilled with gasoline pumped from a ship docked in the San Juan Bay.

Fig. 1. Tank without external fixed roof located in the CAPECO Bayamon tank farm before the 2009 accident

Fig. 2. Tank 105 in the CAPECO Bayamon tank farm before the 2009 accident; it is believed that the accident started in this tank

This was a cylindrical tank with fixed external roof located in the southeastern region of the storage farm; it had a diameter of 45 m and a height of 18 m. It is believed that a failure in the security system devices of Tank 105 unleashed a chain of events that resulted in the catastrophe. Notice that an almost identical triggering effect was also present in the Buncefield accident in the United Kingdom (Buncefield Major Incident Investigation Board 2008; Batista-Abreu and Godoy 2009).

The excess liquid in the tank eventually escaped, thus forming a volatile mixture in a gaseous state. The volatile mist was dispersed in the area of the oil plant until it reached a source of ignition. Fuel could infiltrate throughout the drainage system and reach the wastewater-treatment plant in the northeastern zone of the plant. Various possible sources of ignition of electrical origin became objects of investigation; among them, one possibility is that a fluorescent lamp in the refinery might have generated an electric spark, which would have been enough to ignite the fuel vapor. The fire would quickly spread from the ignition source through the fuel cloud toward the closer and most susceptible containers, generating an explosion. The fire continued spreading as it simultaneously generated new fires involving other tanks. Finally, the explosions and fires affected 32 tanks, of which 21 suffered significant damage or destruction.

To understand the mechanics leading to the distorted geometry of steel storage tanks under fire, it is important to have information on their conditions before and during the accident, such as the volume of fuel contained, the tank area directly affected by fire, and the location of fire sources, among others.

According to the conditions in which the tanks were found in Bayamon after the fire, the following three groups could be distinguished (Batista-Abreu and Godoy 2011): (1) tanks without fixed roof that remained standing after the fire; (2) tanks with a fixed roof that remained standing after the fire (such tanks had large deformations in the roof and in the top region of the cylindrical shell after fire exposure); (3) tanks without fixed roof that collapsed, as if the material had melted because of the high temperatures.

This paper addresses modeling of the first group mentioned above, i.e., tanks without a fixed roof, and some examples of tanks damaged in this way during the Bayamon fire are shown in Figs. 3–6. Those tanks show a significant curvature in the vertical direction. There is a wavy pattern of deformations in the upper zone of the cylindrical shell, but the lower zone is almost undisturbed.

Computational Models

The tank geometries analyzed in this study correspond to tanks affected by the Bayamon accident in 2009. The plant owner did not allow the authors to have direct access to the tanks, because the case was under litigation and the owner was not interested in helping an academic investigation like the present one. The tank dimensions were thus estimated using information available from a previous reconnaissance mission (Godoy et al. 2002), and the design code API 650 (API 2007) was used to verify the shell thickness of each tank.

Because interest in this research was mainly concerned with shell buckling under thermal loads induced by fire, a structural (rather than a thermomechanical) model was adopted. Because of the lack of empirical evidence on the thermal behavior under fire, several scenarios were investigated regarding the temperature distribution across the thickness and around the circumference. However, the authors acknowledge that there is a need to obtain detailed empirical information on the thermal behavior of shells, including the temperature distribution in time.

The structures were modeled with simply supported conditions at the base and with free boundary conditions at the top. Poisson's ratio was assumed to be 0.30, and values of the elastic module, yielding stress, and thermal expansion coefficient were assumed to change with temperature as shown in Fig. 7 [European Committee for Standardization (CEN) 2005]. In cases where the liquid pressure inside the tank is included, the density of the petroleum is taken as 900 kg/m^3. The assumed yield stress is 250 MPa at ambient temperature, and the von Mises yield criterion was adopted in all cases to identify the occurrence of plasticity.

To carry out the structural analysis including geometric and material nonlinearities caused by the thermal action, a general-purpose finite-element package was used (*ABAQUS*). Wang (2002) identified that this is an adequate package for evaluating the performance of structures under thermal action from fire. The cylindrical shell was discretized by means of four-node doubly curved quadrilateral shell elements identified as S4R in *ABAQUS*, which account for finite membrane strains. Based on convergence studies, the models for

Fig. 3. Deformed configuration of a tank without external fixed roof after the Bayamon accident occurred in 2009 (with permission from GFR Media, LLC)

Fig. 4. Deformed configuration of a tank without external fixed roof after the Bayamon accident occurred in 2009

Fig. 5. Deformed configuration of a tank without external fixed roof after the Bayamon accident occurred in 2009

Fig. 6. Deformed configuration of a tank without external fixed roof after the Bayamon accident occurred in 2009

tanks opened at the top included 31,560 elements. The nonlinear solution was achieved by means of the Riks method (Riks 1979). Temperature was increased until a limit point was reached in the equilibrium path.

The analysis considers self-weight and fire on the structure in terms of a mean temperature and a thermal gradient across the thickness. To investigate the influence of the circumferential zone

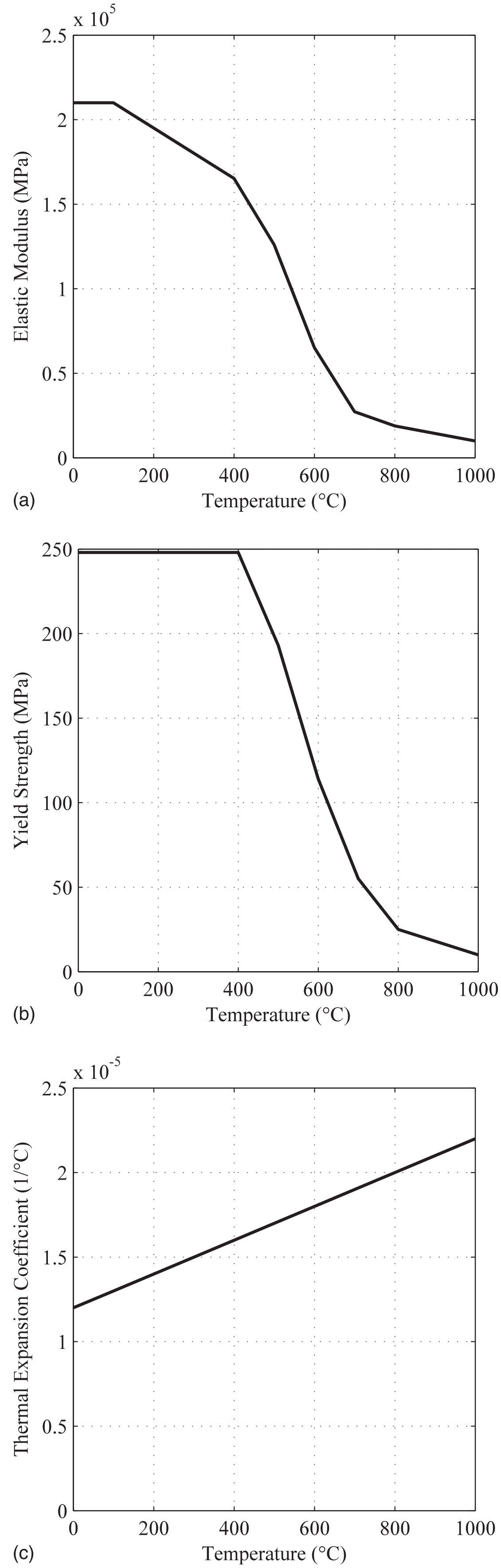

Fig. 7. Assumed dependence of steel parameters on temperature; (a) elastic modulus; (b) yield strength; (c) coefficient of thermal expansion

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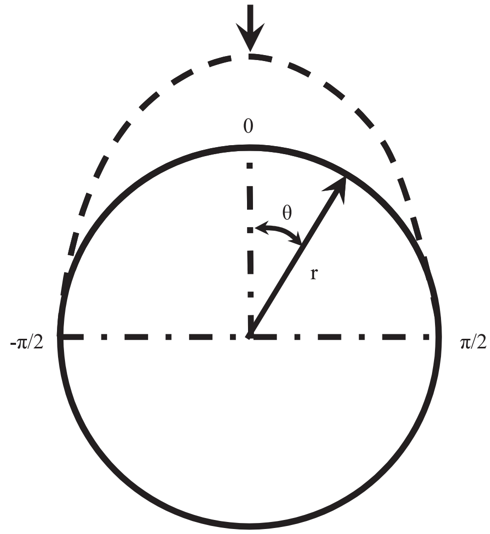

Fig. 8. Temperature distribution on the tank circumference when fire acts on half of the cylindrical body

affected by fire, the temperature was assumed to act on a zone of the tank in the circumferential direction following a cosine square distribution, as illustrated in Fig. 8. The assumption regarding the temperature distribution was adopted in the absence of empirical data on this issue and attempts to model a fire that approaches the tank from a specific direction, in which case it is expected that the meridian located in that direction would have the highest temperature, with temperatures decreasing in a gradual way around the circumference. Other models of temperature distribution could be used, but this one seemed to be a reasonable starting point to investigate the shell buckling response. This cosine square distribution was previously employed by Liu et al. (2008). The temperature distribution obtained by using the cosine-squared pattern is consistent with the results of temperature simulations performed by Landucci et al. (2009) on cylindrical storage tanks in domino events triggered by fire.

Behavior of Open Cylindrical Tanks

Several tanks that were destroyed during the Bayamon fire did not have a fixed roof to restrain the top deformations, such as the tank illustrated in Fig. 1. The specific tank geometry considered in the analysis has a diameter of 33.57 m, a height of 12.77 m, and a thickness of 11 mm; the dimensions were obtained during a visit to the plant in 2002 (Godoy et al. 2002). Thermal buckling is investigated for this tank, followed by studies on the influence of a thermal gradient across the thickness, and the level of fluid stored in the tank.

Critical Buckling Temperature of Open Cylindrical Tanks

The basic model taken as a reference considers a tank that is empty, with a uniform temperature distribution in the vertical direction and through the thickness and a cosine square distribution in the circumferential direction affecting half of the perimeter of the cylinder.

The tank was first subjected to a uniform thermal distribution through the shell thickness (case A-1 in Fig. 9). The computed response shows large radial and vertical displacements in the heated zone when buckling takes place at 500°C in the meridian of maximum temperature. The structure can hold a relatively high temperature, because it is free to deform at the top and is only restricted by boundary conditions at the base. The heated zone undergoes an expansion until stresses and deformations in the transition zone (between the heated region and the region that is not affected by temperature) induce thermal buckling. Notice that large deformations occur in this case at about 90° from the meridian of maximum temperature.

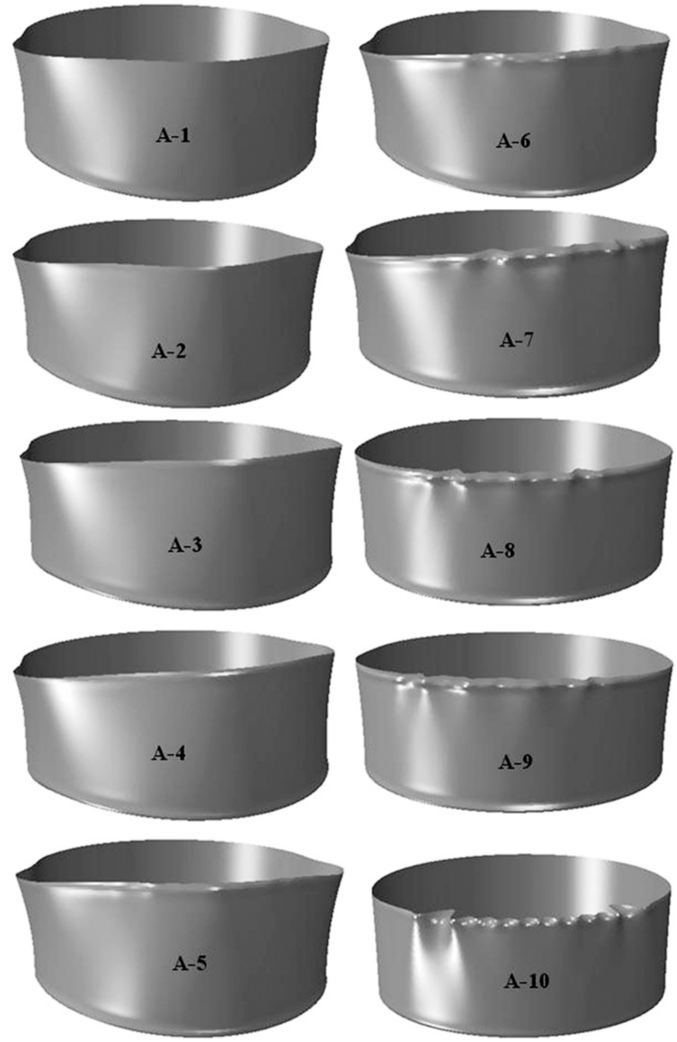

Fig. 9. Deformed configurations of empty open tanks under temperature and thermal gradient through the shell thickness (Case A scenario); thermal parameters for each case are given in Fig. 10

Even though buckling occurs for a temperature level at which material degradation would be active, the structure develops low stresses in the cylindrical body; high stresses are concentrated at the base because of the restriction imposed by the boundary conditions. Therefore, geometric nonlinearity dominates thermal buckling.

Influence of a Thermal Gradient on the Critical Buckling Temperature

Different cases were analyzed to investigate the influence of a thermal gradient across the thickness, ranging from constant temperature through the thickness to combinations of mean temperature and a gradient. The possibilities for imposing thermal loads using *ABAQUS 6.6* include establishing a mean temperature value at the center of the shell thickness and a thermal gradient between the external and internal surfaces. For the nonlinear analysis, *ABAQUS*

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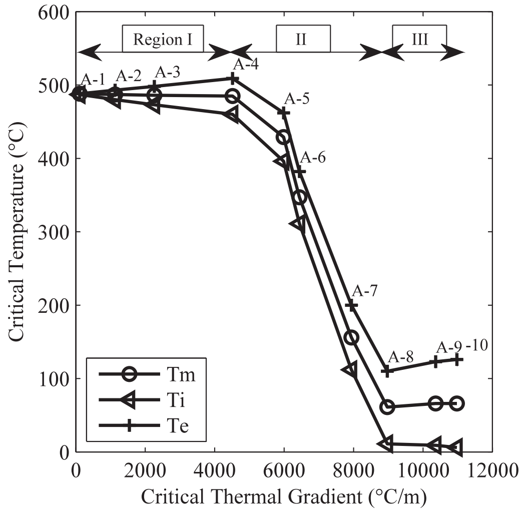

Fig. 10. Failure combinations of temperature and thermal gradient in terms of internal, mean, and external surface temperatures for Case A

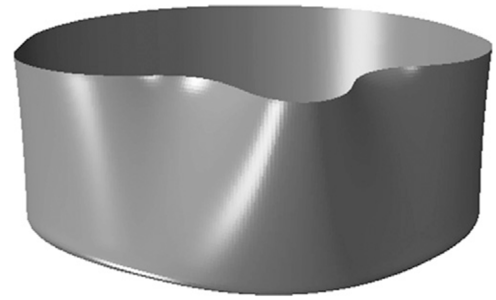

Fig. 11. Advanced postbuckling deformed configuration of the open tank, Case A-1

allows one to establish a lineal relationship between the mean temperature and the thermal gradient.

Results are shown in Fig. 10, in which each point corresponds to a combination of temperature and temperature gradient leading to thermal buckling. The results are shown in terms of the temperatures at the inner and outer surfaces of the shell and their mean values.

Tanks with high thermal gradients through the thickness (see cases A-8–A-10 in Fig. 9) show local buckling in the free boundary along the heated zone, developing waves at the top of the cylinder. In the case of the tanks with low thermal gradient (cases A-1–A-4 in Fig. 9), buckling takes place in the transition zone between the region with high temperatures, which is in expansion, and the region that is not directly affected by temperature. The zone with lower temperatures acts as a constraint to the zone of high temperatures, with the consequence that the structure adopts a new geometric configuration to satisfy the equilibrium conditions.

Finally, for some failure scenarios, as in cases A-5–A-7 in Fig. 9, the deformed configurations have the simultaneous influence of both temperature and gradient effects.

From the results of computational models, it can be said that thermal loads are expected to trigger buckling in steel tanks at temperatures below 500°C. However, lower values of critical temperature should be expected if a temperature gradient is present in the shell thickness.

The incidence of a temperature gradient is seen to affect not just the critical temperature but also the mode shape, as illustrated by the cases shown in Fig. 9. The buckling mode is induced by the expansion of a highly heated region, which attempts to deform but is restricted by boundary conditions and by other regions of the same shell that are subjected to lower temperatures.

Three regions can be seen in the curve of failure combinations (see Fig. 10). In Region I, buckling is controlled by the mean temperature of the shell. The thermal gradient in this region has little influence on the critical temperature of the structure. In Region III, buckling is caused by high gradients and low values of mean temperature, which imply significant differences in the temperature between the internal and external faces of the cylindrical shell. Finally, there is a transition in Region II, in which the response is controlled by both the mean temperature and the thermal gradient. The value of the mean temperature that causes buckling is highly sensitive to the thermal gradients.

In summary, the maximum temperature that the structure reaches when it buckles is about 500°C and occurs for low gradient levels (Fig. 10). For gradients higher than 5,000°C/m, buckling is no longer controlled by the mean temperature, but by the interaction of the mean temperature and the thermal gradient, corresponding to a temperature difference between the external and internal faces of about 50°C. Buckling is strongly controlled by the thermal gradient for values on the order of 9,000°C/m.

When buckling occurs, the maximum displacements of the structure range from 2 to 14 times the shell thickness, for cases A-10 and A-1, respectively. Models with high thermal gradients developed large stresses compared to models with a uniform thermal distribution through the thickness. The elasticity modulus of steel was degraded by less than 40% with respect to its value at ambient temperature. In this and in the following cases, thermal buckling of the cylindrical shell occurs with stresses that are below plasticity limits.

Fig. 3 shows a tank affected by the Bayamon fire. Models A-7–A-10 have a configuration similar to the tank for which large deformations are observed along the free boundary at the top. From the modes at buckling shown in Fig. 9, such a displacement shape is more closely associated to scenarios in which there is a thermal gradient across the shell thickness rather than situations in which the temperature remains uniform in the thickness.

Evidently, tanks are not found just at the buckling state after a fire like that at Bayamon. During a fire, the temperature might rise almost continuously, causing the structure to deform beyond the onset of buckling, so that the final configuration may considerably differ with respect to the initial shape at thermal buckling. Thus, it may be illustrative to estimate possible shapes for advanced postbuckling states. Fig. 11 shows the deformed shape corresponding to case A-1 under a maximum temperature of 1,000°C. It can be seen that the geometry changes significantly with respect to the buckling mode initially observed and now has large displacements at the meridian with high temperatures.

Influence of the Liquid Stored in an Open Cylindrical Tank

It was assumed in the previous section that a tank was empty during the occurrence of fire. In a real situation, tanks would have different levels of stored fluid, and it is important to understand how this influences the buckling process. To model the problem, some assumptions are made regarding the effect of liquid on the thermal loads. Following Liu et al. (2008), it is expected that the thermal inertia of the fluid stored in a tank will significantly reduce the temperatures in the shell wall. From the perspective of structural stability, the pressure exerted by the liquid stored in the tank stabilizes the shell. The fluid action is included in the loads, and no fluid-structure interaction is

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taken into account. This interaction is typically included in seismic analysis, but does not seem relevant in thermal analysis.

To investigate possible extreme scenarios, it is assumed that thermal loads attributable to fire will only affect those regions of the shell located above the internal fluid level. As before, the temperature is assumed to act directly on a 180° sector of the circumference.

The results are shown in Fig. 12 for a liquid level that reaches half of the cylinder height. All the cases analyzed show that shell buckling takes place without the occurrence of plasticity. Large deformations are concentrated in the upper region right above the fluid level. Liu et al. (2008) also observed this pattern.

Cases in which the uniform thermal distribution through the shell thickness determines buckling (cases B-1 and B-2 in Fig. 12) show localized damage in the zone with direct heat, above the level of stored liquid. In other cases (B-3–B-12), the thermal gradient influences the results and generates a wavy pattern at the top.

A summary of the critical states, as given by temperature and thermal gradient, is presented in Fig. 13. In approximately half of the range of thermal gradients included in the analysis, i.e., from 0 to 6,000°C/m, thermal buckling is controlled by the mean temperature of the cross section of the order of 500°C, without a significant influence of the thermal gradient. However, there is a large influence of the thermal cross-sectional gradient for gradients larger than 6,000°C/m, in which case the critical temperature associated to buckling reduces to values on the order of 100°C.

Cylindrical open tanks failed at less than 500°C, and horizontal waves right above the zone subjected to liquid pressures characterize their deformed configuration. In addition, waves are observed along the free boundary, where high thermal gradients are developed, or above the liquid level for cases with low thermal gradients. Maximum nodal displacements range between 2 and 13 times the shell thickness. Under such temperature levels, the material properties have degradation, and the modulus of elasticity has decayed by 40% or less, whereas the yield stress is about 80% of the yield stress value at ambient temperature.

Fig. 12. Buckling configuration of tanks for Cases B-1–B-12

Influence of Shell Thickness on Thermal Buckling of Open Tanks

Next, the influence of the shell thickness is investigated for a tank without an external fixed roof. The temperature is assumed to be uniform throughout the shell thickness in half of the cylindrical body.

According to Table 1, the results show that the critical temperature is not considerably influenced by the shell thickness. By doubling the shell thickness, the buckling temperature is only 1.12 times higher, which implies that an increase in thickness does not significantly modify the temperature required to reach thermal

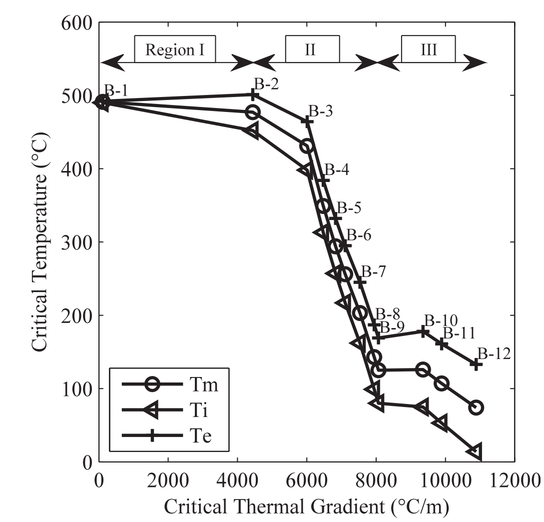

Fig. 13. Combinations of maximum temperature and thermal gradient that induce thermal buckling in terms of internal, mean, and external surface temperatures for Case B

Table 1. Shell Thickness and Critical Buckling Temperature

Case	Shell thickness (m)	Critical temperature (°C)
1	0.0102	487
2	0.0152	521
3	0.0203	547
4	0.0254	563

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buckling. However, this does not mean that changing the thickness does not contribute to increasing the fire resistance of the structure, because the fire resistance time may be considerably changed. The calculation of this time is not possible within the limitations of the present model.

Regarding the material behavior, the stress levels on the structure were considerably below the yield stress of the material, so no plasticity is expected to take place before the sudden change in geometry of the cylindrical body. Tanks with larger thicknesses developed higher stresses when buckled under the action of uniform

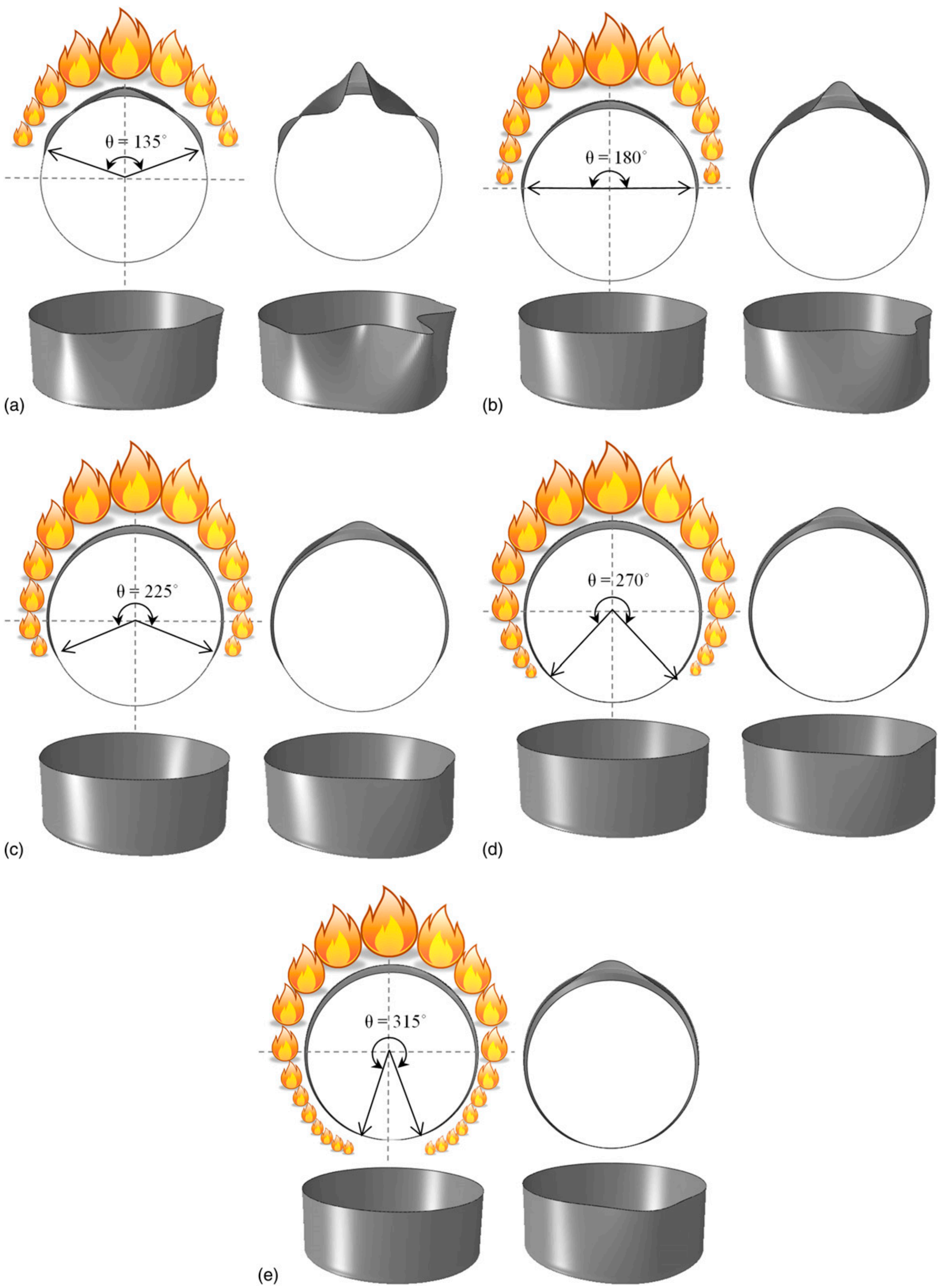

Fig. 14. Buckling (left) and postbuckling (right) deformed configuration of open tanks with different areas exposed to fire, corresponding to (a) 135; (b) 180; (c) 225; (d) 270; (e) 315°

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temperature in the cross section. When buckling occurs, the displacements of the central node in the heated zone of the tank are 0.16 m approximately and vary between 6 and 16 times the shell thickness.

Influence of Circumferential Zone Directly Affected by Fire

This section considers an open tank subjected to various heated zones in the circumferential direction. To carry out the computations, the tank is assumed to be empty, and the temperature is assumed to be uniform throughout the shell thickness.

In all cases, fire acts along the complete height, affecting central angles of 135, 180, 225, 270, and 315° around the circumference. It can be observed that, not considering the size of the surface area on which the fire acts, the temperature needed to produce shell buckling is about 500°C. For this failure scenario, deformed configurations of tanks are shown in Fig. 14 at buckling (left) and postbuckling (right) states. In addition, the cross sections of buckled and postbuckled cylindrical shells attributable to thermal action are shown for each case. Common features in all cases are the formation of bulges on the sides of the heated zone and a pronounced bulge in the zone with higher temperatures. Buckling takes place inside the expanding region.

In all the cases studied for this scenario, the stresses in the structures remained considerably below the material yield stress before buckling, indicating that material degradation is not the main cause of structural failure. The maximum buckling displacements were about 15 times the cylinder shell thickness. After buckling, displacements increased rapidly, being 30–40 times larger than the shell thickness at 700°C. A more localized fire action shows a smaller and more prominent buckling zone. Therefore, the zone affected by temperature in the circumferential direction has a significant effect on the shell response and more specifically on the buckling mode.

Conclusions

The CAPECO accident originated because of a failure in the sensors located in a storage tank that monitors the liquid level, and this initiated a sequence of events that caused the fire. The lack of redundancy in the monitoring system, security system deficiency, and limited control over the processes in this plant led to the catastrophic situation.

Steel oil storage tanks without a fixed roof were analyzed in this paper under thermal action to simulate the effects of fire for different fire scenarios. In all cases, the finite-element models include both geometric and material nonlinearities. However, it is clear that geometric nonlinearities dominate in the response, and buckling occurs within elastic material response.

Temperature increases in tanks exposed to fire action generate thermal expansion, causing nonuniform displacement and stresses in the cylindrical shell. The zone with higher temperatures is constrained by external boundary conditions and by zones of the same shell with lower temperature levels. Eventually, for a certain critical temperature value, deformations on the structure are such that the cylinder suddenly changes its geometric configuration to withstand external actions and satisfy equilibrium. The buckling mode depends on the failure scenario and is influenced by the volume of the fuel stored, the size of the zone directly affected by fire, and the thermal gradient in the cross section. Other factors, such as the cylindrical shell thickness, have a less pronounced influence on the response.

In general, for the cases studied in this paper, the deformed configurations show vertical bulges in almost the entire height of the cylindrical body and large displacements at the level of the stored liquid surface. Cases with high thermal gradients through the shell thickness show waves in the free boundary in open tanks.

The empty structures analyzed show a uniform critical temperature in the cross section of about 500°C for tanks without a fixed roof and a much lower critical temperature of about 130°C for tanks in the case of a high temperature gradient in the shell thickness. The critical buckling temperature of a tank could be higher than the value mentioned if the tank contains a considerable amount of fuel. From the present results, it can be concluded that thermal buckling of oil storage tanks is produced in the early stages of fires.

The current study is limited to tanks that open at the top and does not address the influence of the roof on the thermal behavior. Another limitation concerns the material of the tank, namely, only steel tanks have been investigated, and buckling of aluminum tanks is left as a topic for further research.

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