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Failure modes of API 12D tanks with a semicircular-topped rectangular cleanout and stepped shell design

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ABSTRACT

The American Petroleum Institute Specification 12D (API 12D) provides the oil and gas industry with ten tank designs with nominal capacities ranging from 500 bbl (79.5 m^3) to 10,000 bbl (1590 m^3). These tanks serve as a temporary product storage medium at the upstream segment of the industry, and are mass-produced to accommodate the demand. The structural performance of these ten 12D tanks is assessed in this study to verify that safe operation is maintained under various loading conditions. This study investigates the behavior and performance of the API 12D tank designs with a new rectangular cleanout with a semicircular top that is surrounded by a reinforcement pad. Various loading patterns were modeled in a finite element analysis approach including internal pressure, vacuum, hydrostatic pressure, and wind load. An elastic stress analysis, an elastic-plastic stress analysis, and an elastic buckling analysis were used in this work to compare the behavior of the tank designs against the failure criteria specified for each type of analyses. The stress level, plastic strain, buckling load, and tank uplift are reported for each of the ten API 12D tank designs and possible shell thickness variations are provided as insight into the performance expected with the new cleanout detail.

1. Introduction

The oil and gas industry is in constant need for product storage in parallel and in support of all other production processes. The liquid product is usually stored in aboveground vertical axis cylindrical steel tanks, with varying sizes depending on the needs of the facility. The American Petroleum Institute (API) provides a variety of standards and recommendations to address the design, fabrication, maintenance, repair and testing, and fitness-for-service criteria. One such standard is the API Standard 650 "Welded Tanks for Oil Storage" [1], where the general design calculations for cylindrical storage tanks are provided; for example, the minimum permissible shell thickness and stiffener design requirements. Many aspects of the tank design are left to the discretion of the designer in API 650, which allows the user the freedom to implement various design approaches for each tank structure. However, some oil and gas facilities need a specific size storage tank for a majority of their operations, which eliminates the need to design the same tank multiple times. API 12 F "Specification for Shop Welded Tanks for Storage of Production Liquids" [2] is a specification that includes tanks of specific sizes, for which rigorous engineering calculations have been undertaken to optimize their design to become safer more economical. Another specification is API 12D "Specification for Field Welded Tanks for Storage of Production Liquids" [3], which includes tanks with larger capacities than API 12 F; API 12D tanks nominal capacities range from 500 bbl (79.5 m^3) to 10,000 bbl (1590 m^3), while API 12 F tanks nominal capacities range from 90 bbl (14.3 m^3) to 750 bbl (119.2 m^3).

The need for pre-designed tanks that are produced in large numbers requires careful calculations of the various modes of failure a tank may go through. The performance deficiencies the API 12D tanks may experience are of interest to improve the current design specifications. This investigation focuses on studying the failure modes of the ten API 12D tank designs and their ability to withstand their designated design pressures. The API 12D tanks are analyzed with a new cleanout design that is rectangular with a semicircular top, which is being considered for the next edition of API 12D. Recently, similar work has been done on API 12 F tanks by Rondon and Guzey [4–6].

The need for an economical design for API 12D tanks stems from the large number of tanks usually used in the upstream segment, also known as exploration and production segment, of oil and gas industry to store extracted product. For this reason, the need to have a safe and durable design for each tank is a necessity. The failure, or uncontrolled failure, of one tank may lead to the failure of adjacent tanks resulting in economical loss, environmental tragedies, and/or possible loss of life. To prevent such failures, the reliability of tanks and pressure vessels is to be ensured by meeting the criteria of the industry Standards and

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Codes [7–9]. It is important to investigate the behavior of tanks thoroughly under the possible design loads for different failure modes. In a recent study, Chang and Lin [10] discuss a number of tank failure cases and their causes.

The work presented here studies vertical, cylindrical, closed-top, flat bottom, aboveground field-welded API 12D tanks with the addition of a rectangular with semicircular top cleanout surrounded by a reinforcing pad (repad). This new cleanout design is meant to reduce the stresses at the corners of the shell-to-cleanout junction resulting in increasingly durable tanks with longer operational service lives. This study neglects the effect of nozzles and seam welds connecting the shell plates, the reader can refer to references [11–15] for more information about the influence of these components.

Many tank failures may have resulted due to different failure mechanisms like ratcheting as discussed by Zeman [16], fatigue as studied by Cunha et al. [17], Xing et al. [18], and Lee et al. [19], fracture as discussed by Lee et al. [19], or buckling as discussed by Takla [20], Burgos et al. [21] and Magnucki et al. [22]. This work focuses on the excessive stresses and buckling occurring due to internal pressure and vacuum and uplift due to wind pressure in API 12D tanks, fatigue and brittle fracture failure in these tanks will be investigated in future work.

Explosions in the tank due to the ignition of the fumes of the stored product may present an increase in internal pressure; excessive internal pressure can lead to failure due to bursting of the tank [23–25] or buckling of the roof-to-shell junction [26]. Additionally, failure can be caused by axial stress due to roof load and self-weight [27,28] or a combination of axial and internal hydrostatic pressure [29]. In oil storage facilities, the failure of one tank can be amplified to adjacent tanks with catastrophic consequences, thus, a thorough study of commonly used tanks is presented here to assess the performance of API 12D tanks. This work focuses on the effects of the stored product, internal pressure, and wind loading on the failure behavior of API 12D tanks.

Tanks and silos may fail in different modes caused by different loads or their combinations. Failure can occur due to the stored product leading to large shell stresses. Azzuni and Guzey [30] found that some API 650 tank shells may be slightly under-designed due to theoretical approximations in the standard. Yu et al. [31] showed that the stress concentrations near large stress gradients must be assessed with a high degree of accuracy to reflect the behavior of real structures. Stress concentrations may occur due to geometric change at the unction connecting the roof to shell or connecting the shell to the bottom plate. Preiss [32] presented his findings on the stress concentrations in a shell-to-bottom junction due to internal pressure, while Skopinsky [33] studied the stress concentration in a conical to cylindrical shell connection, which may be used to model the roof-to-shell connection of a cylindrical storage tank. Similarly, Davie et al. [34] investigated the plastic collapse of the cone-to-cylinder connection due to internal pressure. These approximations may be useful for idealizing the behavior of the tank junctions at geometry changes, but for the detailed analysis performed in this study these approximations will not be used.

Taniguchi and Katayama [35] showed that a more careful analysis of the rocking liquid is needed to evaluate the overall pressure experienced by the tank shell. The need for a thoughtful seismic design is highlighted by Brunesi et al. [36], Shih and Babcock [37], and many more. To address this safety need, Spritzer and Guzey [38,39] and Zui et al. [40] performed computational and experimental evaluations of tanks under seismic excitation. Similarly, wind loading can lead to catastrophic tank failures as reported by Godoy [41], Flores and Godoy [42], and Santella et al. [43]. Both vacuum and wind can be idealized as external pressure, which may cause buckling in the roof as investigated by Błachut [44,45] if the roof was idealized as a toriconical shell. Azzuni and Guzey [46], Sun et al. [47], Burgos et al. [48,49], and Zhao and Lin [50] addressed wind load considerations that should be taken in future cylindrical tank design.

A computational approach has been used in this study through the use of a general purpose finite element software, ABAQUS/CAE version 2017 [51], to model the tanks and the different loads acting on each tank. The program was used to investigate elastic and plastic failure modes using linear and nonlinear material properties, respectively. Three types of analyses were used in this study to investigate the various possible failure modes: 1) elastic stress analysis, 2) elastic-plastic stress analysis, and 3) elastic buckling analysis. The elastic failure was investigated in buckling due to internal pressure and vacuum, yielding due to internal pressure, and uplift magnitude of the tank bottom due to the wind load. The plastic failure was investigated by increasing the internal pressure until global rupture, where the material was modeled as a nonlinear material.

The sources for tank designs and design verification techniques are discussed in Sec. 2. This paper discusses a variety of design parameters and variations in each tank model in Sec. 3, whereas the methodology used to investigate each failure mode and design variation is presented in Sec. 4. The results are presented and discussed in Sec. 5, and the conclusion summarizing the findings of this work is provided in Sec. 6.

2. Background information

2.1. API 12D specifications for field-welded tanks for storage of Production Liquids

Field-welded tanks specified in API 12D [3] are tanks with typically larger capacities than shop-welded tanks specified in API 12 F [2] but commonly smaller than the API 650 field-welded tanks. The current 11th edition of API 12D tanks provides ten tank designs with various diameters and heights that meet the safety and reliability required for tanks used by the oil and gas industry. Table 1 tabulates the ten API 12D tank sizes and provides the nominal capacities of each tank with their prescribed height and diameter. The design internal and vacuum pressures of each tank is also provided in Table 1, at which the different failure modes were assessed. The numbering scheme of tank cases is not provided by API 12D, but this study numbered the tanks incrementally with the increasing diameters and heights.

Table 1
Dimensions of Studied Tanks and their Approximate Working Capacities.

Tank Case	Nominal Capacity bbl (m^3)	Outside Diameter ft (m)	Shell Height ft (m)	Design Internal Pressure oz/in^2 (kPa)	Design Vacuum oz/in^2 (kPa)
1	High 500 (79.5)	15.5 (4.7)	16 (4.9)	8 (3.4)	0.5 (0.22)
2	750 (119.3)	15.5 (4.7)	24 (7.3)	8 (3.4)	0.5 (0.22)
3	Low 500 (79.5)	21.5 (6.6)	8 (2.4)	6 (2.6)	0.5 (0.22)
4	High 1000 (159)	21.5 (6.6)	16 (4.9)	6 (2.6)	0.5 (0.22)
5	1500 (238.5)	21.5 (6.6)	24 (7.3)	6 (2.6)	0.5 (0.22)
6	Low 1000 (159)	29.75 (9.1)	8 (2.4)	4 (1.7)	0.5 (0.22)
7	2000 (318)	29.75 (9.1)	16 (4.9)	4 (1.7)	0.5 (0.22)
8	3000 (477)	29.75 (9.1)	24 (7.3)	4 (1.7)	0.5 (0.22)
9	5000 (795)	38.67 (11.8)	24 (7.3)	3 (1.3)	0.5 (0.22)
10	10,000 (1590)	55 (16.8)	24 (7.3)	3 (1.3)	0.5 (0.22)