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ScienceDirect

Natural Gas Industry B 5 (2018) 276–281

www.elsevier.com/locate/ngib

Research Article

A design algorithm used for the roof frame and liner system of extra-large LNG storage tanks☆

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Received 11 September 2017; accepted 25 November 2017
Available online 11 June 2018

Abstract

The design of roof frame is one of the most important parts of LNG tank design. In China, however, the calculation of roof frame system of extra-large LNG tanks is currently faced with a series of problems. For example, there is no united yardstick on buckling characteristic value, the calculation is based on many assumptions, and the calculation is inconsistent with domestic specifications and stipulations. In view of these problems, the material non-linearity and structural non-linearity were introduced and the initial defect was taken into consideration. Then, the large non-linear finite element calculation software ABAQUS was adopted to carry out modeling on the roof frame and liner system of extra-large LNG tanks and calculate and analyze the force applied on them and their stability. Finally, a complete set of design algorithm for the roof frame and liner system of extra-large LNG tanks was established and applied to the design of a certain LNG tank (20×10^4 m^3) in China. It is indicated that this design algorithm can simulate the actual situations accurately. This design algorithm is structurally composed of shell units and beam units, and it is connected in the pattern of common node. Besides, force calculation is conducted in 10 operational modes and the buckling calculation in 7 operational modes, including all operational modes in the construction process of roof frame and liner system of LNG tanks. It is also revealed that the maximum stress on the roof frame is 125.7 MPa, that on the liner is 101.4 MPa and the minimum safety coefficient used for buckling calculation is 2.57. Under this system, the force and stability of the roof frame of LNG tanks are satisfactory. The research results can be used as reference for relevant design and calculation.

Keywords: Extra-large LNG storage tank; Roof frame; Liner structure system; Design algorithm; Stress; Buckling; Non-linear; Initial defect; Finite element; ABAQUS software

1. Introduction

The structure of a full-containment LNG storage tank consists of the piled foundation, piled cap, skin, dome roof, inner tank, aluminum ceiling, dome roof steel structure and other parts [1,2]. The dome roof steel structure consists of roof frame and liner, which are the load carrier of the dome roof during concrete pouring; the air-lifting process of the dome roof steel structure is considered to be one of the most critical links during storage tank construction [3] and the roof frame design is also one of the most important parts in the storage tank design [4,5]. There are many more and complicated factors to be considered besides the load, stability and other aspects of the roof frame and liner structure system, so fundamental assumptions applicable for small storage tanks may not be applicable for extra-large storage tanks.

Mechanical analyses of the roof frame and liner system should include both the stress analysis and stability analysis [6,7]. Basically the same stress analysis methods are adopted around the world, and they usually cover load determination and combination, modeling, calculation by operational mode

☆ Project supported by the Special and Significant Project of China National Offshore Oil Corporation "Study on the design of full-containment large LNG storage tank and engineering applications" (No.: CNOOC-KJ125ZDXM14QD-04QD11).
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Peer review under responsibility of Sichuan Petroleum Administration.

https://doi.org/10.1016/j.ngib.2017.11.012

and stress check and other processes. As for the stability analysis, common practice of international companies for dome roof calculation of LNG storage tanks is linear perturbation analysis, without considering the initial structural defect, material plasticity and structural geometric non-linearity and using the buckling characteristic value of the structure as the safety coefficient.

Currently, main problems facing the roof frame system analysis and calculation are:

1) No united yardstick on buckling characteristic values

Criterion I [8,9]: Roof frame system computation covers only stress analysis but not stability analysis. This is not incomplete at this point. According to the drawing designed based on Reference [8], stability of the dome roof steel structure is relatively weak, angle steel ring beams are used, while the longitudinal beams are welded inside the roof liner through sequence welding, which has a poor continuity performance, stability of the whole system is open to question. According to the drawing designed based on Reference [9], stability of the dome roof steel structure is relatively strong, there is significant difference.

Criterion II [10]: In addition to stress analysis, there is buckling analysis. However, the computation uses only the linear analysis and does not cover the initial defect. Besides, Ishikawajima − Harima Heavy Industries (IHI) regards the dead load of the roof frame, load of the ceiling, live load and internal pressure as internal load, which is separated from the load of the concrete and only included a safety coefficient of 3.34 and 5.00 in terms of concrete. It is contradictory to the method used for load breadth calculation under linear perturbation analysis, and the breadth of linear perturbation analysis, multiplying the safety coefficient with the integral load, is a measurement to be considered.

Criterion III [11]: Roof frame system computation covers only the linear analysis and does not cover the initial defect. However, the difference between Criteria II and III is that the load under Criteria III is taken into account on the whole and the criteria satisfying the structural stability requirements is "no structural buckling under 3 times the total load".

Criterion IV [12]: Some Chinese engineering units and consulting companies have made certain computational researches on the roof frame system of LNG storage tanks, which complies with the checking standard EN1993-1-1 [12]. However, the question is that, formula specified in it is only for the computations of simple structures under pressure, while the buckling of any single beam cannot be checked for the dome room due to the liner in the load system consisting of beams and liners. As for the complicated structures that non-linear factors should be considered, EN1993-1-1 would also recommend the use of finite element analysis.

2) Too many fundamental computational assumptions

There are too many assumptions to make in the buckling calculation of the roof frame system of storage tanks, without considering the initial structural defect, material plasticity and structural geometric non-linearity. For LNG storage tanks with such a long span shell structure, too many assumptions would be prone to cause large deviation or even error. As revealed by earlier studies with trial calculation, there is a big difference between the results of the operational modes for calculation when the initial defects are introduced or not; and there is even more noticeable difference between the results of the operational modes for calculation when the geometric non-linearity is considered or not.

3) Inconsistency with domestic specifications and stipulations

Roof frame and liner structure system are typical space frame structures, and both load and stability analysis should comply with the Technical Specification for Space Frame Structures (JGJ7-2010) [13]. Its Clause 4.3.2 stipulates that "finite element method (i.e. full-range load−displacement analysis) may be adopted for shell stability analysis. During the analysis, the materials may be assumed with elasticity and may be considered with elastic plasticity. As for large and intricately shaped shell structures, full-range analysis method taking into account of the elastic-plasticity may be appropriate."

Based on the problems mentioned above and combined with the detailed design of an extra-large 20×10^4 m^3 storage tank in China, load and stability studies on the roof frame system of storage tanks were carried out by introducing material non-linearity and structural non-linearity and taking into account of the initial defect.

2. Structure parameters

The dome roof structure of an extra-large (20×10^4 m^3) storage tank consists of roof frames and liners. The liner thickness is 6 mm. The roof frame consists of ring beams and longitudinal beams that are totally fabricated with joist I-beam. Sectional dimensions and quantities are shown in Table 1.

Table 1
Structure parameters.

Structure	Sectional dim. /mm	Qty. /pcs
Primary longitudinal beam	300 × 150 × 6.5 × 9	24
Secondary longitudinal beam #1	300 × 150 × 6.5 × 9	24
Secondary longitudinal beam #2	300 × 150 × 6.5 × 9	48
Central longitudinal beam	300 × 150 × 6.5 × 9	8
Ring beam #0	346 × 174 × 6.0 × 9	2
Ring beam #1	300 × 150 × 6.5 × 9	4
Ring beam #2	300 × 150 × 6.5 × 9	48
Ring beam #3	300 × 150 × 6.5 × 9	48
Ring beam #4	300 × 150 × 6.5 × 9	96
Ring beam #5	300 × 150 × 6.5 × 9	96
Ring beam #6	300 × 150 × 6.5 × 9	96
Ring beam #7	300 × 150 × 6.5 × 9	96

Note: The total weight of the liners is 264030 kg, the total weight of the beams is 142683 kg, the total weight of the dome roof steel structure is 406713 kg and the section thickness is 6 mm.