Structural Strength Assessment of 20-ft LNG ISO Tank: an Investigation of Finite Element Analysis and ASME Design Guidance

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Abstract. Following the high demand for LNG as low emission and eco-friendly energy, ISO tank containers are present as an innovative product to support the mass transportation of LNG in a cheap, effective and efficient manner. The 20-ft ISO tank is a container with a pressure vessel structure that can be intermodal with sea or land transportation like other standard dry box containers. The purpose of this paper is to present a complete procedure for evaluating the scantling size of the 20 ft ISO tank LNG type. The criteria are determined based on the standard ASME section VIII division I code for boilers and pressure vessels. The calculation includes the fulfillment of the thickness and conformity with the internal and external pressure design requirements. In addition, the finite element investigation was conducted under the various design loads and operating conditions. This analysis provides the safety level of the ASME design guidance in comparison with ISO standard FEA judgments.

1. Introduction

Liquefied Natural Gas (LNG) has an increasing demand in the global natural gas market. Natural gas is a relatively clean energy source, which produces much less pollution than coal or oil. The ISO tank is a kind of innovation that have been increasing year-by-year. In 2021, the estimated global tank container reached 686,650 units [1]. At the same time, Indonesia as the LNG producer country for more than 35 years, the number of LNG plants have also been increasing in dozens [2]. To support the existing and forecast future gas transportation, the ISO tank provides such an easy transport in land or sea.

The construction consists of a cylindrical pressure vessel as the main component, with an additional reinforcement system in the form of a container structure. Other ISO tank support systems include man holes, temperature indicators and safety devices such as rupture discs, safety valves or air discharges. As for loading and unloading needs, ISO tank containers are equipped with valves that are installed at the bottom or top of the cylinder.

The main structural component of ISO tank is a pressure vessel with a working pressure that is different from atmospheric pressure. Pressure vessels are designed by following commonly used standards such as ASME (The American Society of Mechanical Engineers). Meanwhile, in the operational load simulation, the stacking, lifting, transverse and longitudinal racking schemes use the rules of the international standard ISO 1496.
In order to meet the requirement when the ISO tank is being statically and dynamically transport for road, rail and sea conditions several research have been performed. The example of numerical simulation of the LNG ISO tank has been presented [3]. Results indicated that the area of high stress concentrates in tank support at the upright frame both end of the cylinder. The assessment on the ASME design guidance was then can be found in Niranjana et al [4].

In the meantime, the others perform the used of finite element method to analyse the influence of the liquid inertial force during the transportation [5]. In other works the assessment which focused on the compliance for ISO 1496 have been presented [6]. Some of them were combined with the stacking test scale and normal and high temperature [7,8]. But none from the paper above, it discusses the comprehensive within the ASME design rules and the numerical analysis which conform the ISO rules. Therefore, this paper aims to provide a thorough investigation which combine all of the design practice according the ASME procedures, and the analysis of the results design to determine the conformity against the ISO 1496 testing.

In this study, pressure vessels were designed using ASME section VIII division I code for boilers and pressure vessels. In the calculation of pressure vessels through a basic theoretical approach, pressure vessels are classified into thin-shell and uses shell element modelling assumptions. The analysis was carried out using ABAQUS Finite Element Method (FEM) which taken into account the ISO 1496 as the basis for the assessment.

2. Structural assessment methodology

This initial thickness calculation procedure is carried out after the parameter design has been assumed. These design parameters are used as inputs in performing hand calculations using standard ASME formulas and other standards. In the ASME classification, pressure vessels above 1 bar and below 40 bar are required to use ASME Section VIII Division 1.

![Figure 1](image_url). Flowchart in calculating the strength of the LNG ISO tank as a whole

In accordance with the explanation of the flow diagram in Figure 1. Broadly speaking, the calculation of the ISO tank structure is divided into two (2) stages, namely the calculation of the pressure vessel and the container structure. The results of the geometry calculation in the first stage then become a reference in making the FEM model for which the buckling analysis will be calculated. After the first stage is completed, then the ultimate load consisting of the weight of the pressure vessel, the load, and the weight of the overall construction is inputted into the FEM analysis for the performance of the frame container strength.

However, at this stage the assessment of buckling analysis has skip due to the scantling size which have not been fixed in the project. The analysis then concern to the operational safety standards uses the ISO 1496 standard which regulates the load and force on the frame container structures. In the end,
from all the calculation stages, the safety value and performance threshold of the ISO tank structure can be assessed safely.

3. Design requirements

In this section the detailed information on the procedure for calculating (sizing) the thickness is provided. The formula code used is sourced from ASME BPVC. VIII.1-2019 (American Society of Mechanical Engineers Boiler and pressure Vessel Code Division [9]).

The result of the hand calculation is the initial input data in carrying out the operational aspect using the ISO 1496 using the Finite Element Analysis program carried out with commercial software.

3.1. ASME section VIII division I code for boilers and pressure vessels

In this chapter some general concepts and criteria pertaining to Section VIII are discussed. These include the material allowable stress and the detail procedures to obtained the thickness of the pressure vessels. These rules have been substantiated by experience and used by industry over a long period of time.

The type of material used in this calculation is SUS 304L alloy steel which has an ASME specification conversion, namely SA 240 Gr 304L-S 30403. In the regulation of ASME Section II, the material properties have been regulated with the following types of nominal material composition, as shown in Table 1.

| Nominal Composition/Spec No/Grade/Alloy Design | Min Tensile Strength (MPa) | Min Yield Strength | Applicable and Max temperature limits | External Pressure Chart No. |
|-----------------------------------------------|----------------------------|--------------------|--------------------------------------|-----------------------------|
| 18Cr-8Ni/SA-240/304L/S30403                   | 485                        | 170                | 427                                  | HA-3                        |

![Figure 2. Input thickness sizing calculation using ASME Section VIII](image)

Paragraph UG-27 of VIII-1 ASME provide the procedure to determine the minimum thickness. The input parameters are described in Figure 2. The code required the thickness is larger than the value calculated by equation (1), as follows:

\[ t = \frac{PR}{SE - 0.6P} \]  

(1)
Here, $P$ is the internal design pressure (MPa), $R$ is the inner radius (mm), $S$ is the allowable stress according to Table 1 (MPa) and $E$ is the butt joint efficiency refer to Table UW-12 ASME. Subsequently, the calculation of the concave side of torispherical shell for the both end of cylinder refers to paragraph UG-32 as shown by Eq. (2) and (3).

\[ t = \frac{PLM}{2SE + P(M - 0.2)} \]  
\[ M = 0.25 \left( 3 + \frac{L}{r} \right) \]  

Where $L$ is the inside crown radius (mm), and $r$ is the inside knuckle radius (mm). The notation of the torisphere is describe in Figure 3.

\[ t_{min} \]

\[ r \]

\[ L \]

\[ L_0 \]

\[ D \]

\[ D_0 \]

**Figure 3.** Cylindrical-end notations

Meanwhile to determine the maximum allowable external pressure (MAEP) for the designed cylindrical shell, the paragraph UG-28 Section VIII [9] is referred. In the first stage, the geometry $D_0/t \geq 10$ have to be confirmed so that the next formula can be used. After being verified, it is continued by using the external load graph reference of Figure G in the Subpart 3 Section II, Part D ASME [10] with the basis values of $L/D_0$ and $D_0/t$ to get the value of factor $A$. After getting the value of factor $A$, then this value is used to calculate the value of factor $B$ in Figure HA-3 [10] which suits the 304L material specification. Finally, the values of factor $B$ are then used to calculate the maximum allowable external working pressure (MAEP) according to Eq. (4). The step is similar to determined maximum pressure of convex side of the cylindrical-end. In this case the referring code is UG-33 [9]. For the last step the factor $B$ is used in the Eq (5).

\[ P_a = \frac{4B}{3 \left( \frac{D}{t} \right)} \]  
\[ P_a = \frac{B}{(R/t)} \]  

To calculate the compressive pressure of the ring-stiffener on the pressure vessel, the calculation refers to paragraph UG-29 Section VIII. For this step the methods required to assume an initial size and shape of the ring stiffener.
\[ B = 0.75 \left( \frac{PD}{t + \frac{A_s}{L_s}} \right) \]  \hspace{1cm} (6)

Where \( A_s \) is the assumed cross-sectional area of the ring stiffener, \( L_s \) is the distance between the stiffener, \( t \) is the calculated shell thickness in the previous stage. After that using Eq. (6) to determine the \( B \) value. From the resulting \( B \) value, then use the external pressure chart in Section II, Part D ASME to find Factor \( A \) that corresponds to the calculated \( B \) value.

\[ I_s' = \left[ D_o^2 L_s \left( t + \frac{A_s}{L_s} \right) A \right] / 14 \]  \hspace{1cm} (7)

\[ I = \frac{t_w h_w^3}{12} \]  \hspace{1cm} (8)

Then calculate the Eq. (7) to determine the required moment of inertia of the stiffening ring only \( I_s \). Next, define the actual moment of inertia of the ring stiffener based on the initial assumptions that have been made according to Eq. (8). Furthermore, comparing the results of the actual inertia must be equal or greater than the required moment of inertia.

3.2. ISO 1496 Freight containers—specification and testing

The calculation of the FEM analysis is carried out using the scenarios specified in ISO 1496 [11]. All new or modified designs must be tested according to ISO standards before designs can be certified and permitted for use. The following is a detailed scenario of loading the ISO tank structure.

From the ISO 1496 standard data in Table 2. It is stated that ISO tank 20ft refers to class C which receives a stacking load of 942 at each shoe/corner fitting location. For instance, assume the gross weight of a 20ft ISO tank container (~25 tons) divided at each corner which is at least 6.25 tons or 62 kN. Thus, the value of the strength requirements of ISO 1496 is an extreme standard value with an estimate of up to 9 Tier (exclude the dynamic safety factor of 1.8). However, the ISO tanks are planned to be transported using mini-LNG fleet. The carrying capacity of this fleet is 36 TEUs. During its voyage, each ISO tank will be arranged in maximum 2 tiers. The fleet details are described in Figure 4. The amount of load is summarized in Table 3.
Figure 4. Mini LNG ISO Tank Container 36 TEUs

Table 2. Stacking force of ISO tank structure according to ISO 1496.

| Freight Container Designation | Total Allowable stacking weight force of all each four corners /end fitting | Dynamic force superimposes by a factor of 1.8g |
|-------------------------------|--------------------------------------------------------------------------------|-----------------------------------------------|
|                               | kN                                      | kN                                      | kN                                      |
|-------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|
| 1EEE, 1EE                    | 523                                    | 942                                    | 1883                                   |
| 1AAA, 1A, 1A, 1AX             | 523                                    | 942                                    | 1883                                   |
| 1BBB, 1BB, 1B, 1BX            | 523                                    | 942                                    | 1883                                   |
| 1CC, 1C, 1CX                  | 523                                    | 942                                    | 1883                                   |
| 1D, 1DX                      | 125                                    | 224                                    | 448                                    |
Table 3. Load parameter according to ISO 1496.

| Load scheme | Test          | Description                                                                 | Test layout |
|-------------|---------------|-----------------------------------------------------------------------------|-------------|
|             | Stacking      | $F = 942 \text{kN}$; $\frac{T_g + W_g}{4} = 77.91 \text{kN}$; $W = 107.8 \text{kN}$ |             |
| 1.          | strength      |                                                                             |             |
|             | Lifting       | $R_g = 149.45 \text{kN}$; $\frac{T_g}{4} = 12.74 \text{kN}$               |             |
| 2.          | strength 01   |                                                                             |             |
|             | Lifting       | $R_g = 149.45 \text{kN}$; $2R = 61 \text{ ton}$; $T = 5.2 \text{ ton}$      |             |
| 3.          | strength 02   |                                                                             |             |
|             | Racking       | $F = 150 \text{kN}$                                                        |             |
| 4.          | strength 01   |                                                                             |             |
|             | (Transverse)  |                                                                             |             |
|             | Racking       | $F = -150 \text{kN}$                                                       |             |
| 5.          | strength 02   |                                                                             |             |
|             | (Transverse)  |                                                                             |             |
|             | Racking       | $F = 75 \text{kN}$                                                          |             |
| 6.          | strength 03   |                                                                             |             |
|             | (Longitudinal)|                                                                             |             |
|             | Racking       | $F = -75 \text{kN}$                                                         |             |
| 7.          | strength 04   |                                                                             |             |
|             | (Longitudinal)|                                                                             |             |

3.2.1. **Stacking strength test**

The stacking test involves the total weight of a 20 ft container. In this case, ISO requires a weight equivalent to 942 kN on four corner fittings or approximately equivalent to a total weight of 384 tons. In addition, the weight of the tank capacity is also included approximately 107.8 kN, which is approximately equivalent to 25000 liters of LNG.
The load is applied in a concentric position or exactly at the midpoint of each corner fitting. The purpose of this test is to prove the ability of the ISO tank supporting structure to support the mass of containers in a tiered arrangement taking into account in the sea condition. Details of this loading can be seen in load scheme no. 1

3.2.2. Lifting strength test

Lifting load consists of two tests. First by taking into account the weight of the load. Second neglecting the weight. The load required for this test is the R (gross weight) and T (tare weight) components.

This test is carried out to prove the ability of the ISO tank structure to withstand lifting from the top corner joint and should also be considered as proof of the ability of the tank housing to withstand forces arising from accelerating loads in lifting operations. Details of this loading can be seen in load scheme no. 2 and 3

3.2.3. Racking strength test

This test is carried out to prove the structure of the container against racking forces as a result of transportation handling from transport ships, trains, and other transportation intermodal routes. According to the procedure established by ISO, there are two racking forces, namely transverse and longitudinal directions. In this condition the container tank is assumed to be empty. Furthermore, for transversal, one side of the container, a load of 150 kN is directed into or away from the side of the container. Under these conditions the bottom area is ensured using boundary conditions that prevent vertical and lateral movement. Details of this loading can be seen in load scheme no. 4 and 5.

For longitudinal racking, a load of 75 kN is required in the longitudinal direction facing the square cross-section of the container with the direction away from and approaching the side of the container. While the boundary conditions are set at the bottom area where vertical and lateral motion are locked. Details of this loading can be seen in load scheme no. 6 and 7. In the actual structure, the integrity assessment of the container structure in this test must be proved that there are no signs of leakage, abnormal conditions that cause operational disturbances for the ISO tank.

4. Numerical set-up

4.1. Meshing and material

In processing the FE model, the geometry is first modelled using CATIA software and for analysis purposes, the model is imported into ABAQUS CAE. In the preparation of the FE model, the mesh density is the main factor that needs to be considered in obtaining accurate results from an FEM model.

A fine mesh can produce a precise actual response but requires a long computation time. Thus, before starting the main analysis, it is necessary to perform mesh convergencies analysis to determine the appropriate mesh size both in terms of accuracy and computation time. The alternatives have been taken by using a coarse mesh in global and fine mesh in the local area which predict with a high concentrated stress. Table 4 contains detail of the meshing parameters analyzed in the convergence analysis. From these data, it is determined that the selected model is a mesh size of 50 x 50 mm.

Material and section properties.

All materials from the main component (LNG Tank) and other supporting structural components use steel material with an elastic modulus of 210000 MPa. Material details are shown in Table 5. In carrying out material modelling input in the analysis, the assumption of a linear elastic perfectly plastic material is used. So that the input material yield strength is used as a reference as the ultimate strength where the material switches to the plasticity regime. Figure 5 shows detail of sectional properties of the 20ft ISO tank model. Simplified corner fitting model is used conservatively with shell elements to save computational time.
| FE Model | Variable |
|----------|----------|
|          | Type of Element : S4R Shell element |
|          | Number of elements : 354067 |
|          | Mesh size : 10 x 10 mm |
|          | Computed time : 6 hr |
|          | Displacement magnitude : 1.69 mm |
|          | Type of Element : S4R Shell element |
|          | Number of elements : 78574 |
|          | Mesh size : 20 x 20 mm |
|          | Computed time : 4 hr |
|          | Displacement magnitude : 1.73 mm |
|          | Type of Element : S4R Shell element |
|          | Number of elements : 16321 |
|          | Mesh size : 50 x 50 mm |
|          | Computed time : 1.5 hr |
|          | Displacement magnitude : 2.03 mm |
|          | Type of Element : S4R Shell element |
|          | Number of elements : 7786 |
|          | Mesh size : 70 x 70 mm |
|          | Computed time : 1 hr |
|          | Displacement magnitude : 2.54 mm |
Table 5. FE material on the ISO tank structure.

| Material name           | Properties | Density (tonne/mm³) | Young’s Modulus N/mm² | Poisson’s Ratio | Yield Strength N/mm² | Plastic strain |
|-------------------------|------------|---------------------|-----------------------|-----------------|----------------------|---------------|
| Steel frame [12]        |            | 7.85E-009           | 210000                | 0.3             | 340                  | 0             |
| LNG Tank SA240Gr304L-PV [10] |            | 7.85E-009           | 193000                | 0.3             | 115                  | 0             |
| ISO Corner casting [13] |            | 7.85E-009           | 210000                | 0.3             | 275                  | 0             |

4.2. Loading and boundary conditions  
Section properties of the ISO tank FE model structure.

To reduce computational time, movement locking using kinematic coupling is used in the top and bottom areas. The kinematic coupling constraints will actively lock a group of nodes that are constrained to the rigid body motion of a single reference point. In load application the kinematic coupling constraint can be used to provide coupling between continuum and structural elements. Details of the settings can be seen in Figure 6. A fixed assumption is used in the boundary condition.

Figure 5. Section properties of ISO tank FE model.

Figure 6. Boundary conditions and concentrated load scheme.
In FEM analysis, tie constraint is used to define non-linear contact interaction between cylindrical tank and ISO tank frame structure. According to Figure 7, there are two areas, among others, (1) the front and rear spherical tanks with the support plate aft and the forward structure. Then in the second area, the tie constraint connects the bottom cylindrical tank with the bottom girder.

![Master and slave tie constraints between support plate and spherical of the cylindrical tank](image1)

![Master and slave tie constraints between bottom girder and bottom foundation of cylindrical tank](image2)

**Figure 7.** Contact interaction for container dan cylindrical tank.

5. Results and discussion

The following is a summary result of the thickness calculation using the rules of ASME Section VIII Division I Boiler and Pressure Vessel Codes.

| Calculated Parameter                              | ASME  |
|---------------------------------------------------|--------|
| Inner cylindrical shell thickness [mm]            | UG-27  | 7.75   |
| Inner cylindrical end thickness [mm]              | UG-32  | 9.62   |
| Outer cylindrical shell thickness [mm]            | UG-47  | 6.09   |
| Outer cylindrical end thickness [mm]              | UG-32  | 7.31   |
| $P_{external}$ [MPa]                              | UG-28  | 0.21   |
| Moment of Inertia (ring stiffener) [mm$^4$]       | UG-29  | 1999691.47 |
| Moment of Inertia (ring stiffener and flange) [mm$^4$] | UG-29  | 2792222.24 |

The following results are a response to stacking strength with a total load of 1019.91 kN on each corner fitting which is equivalent to approximately 13-tier stacks of 30 tons-ISO tank size 20 ft. The maximum stress response reaches 221 MPa from the yield limit of ISO tank frame structure material around 340 MPa. Figure 8 shows the displacement response in the z-deflection direction (vertical shortening) of 2 mm. In general, the results of stacking strength are still within the safety limits in accordance with ISO regulations.
The other critical scenario was the racking test. The results of the racking simulation are carried out using a load with a frontways direction of 75 kN at two concentration points on the top of the fitting corner. The analysis shows a displacement of about 33 mm with a maximum stress of 275 MPa at the front tank support. The results of longitudinal racking are shown in Figures 9 which exaggerated for 10 times.

### Table 7. Summary of FEM results

| Load test           | Ratio of Stress Maximum to yield limit of each part components |
|---------------------|---------------------------------------------------------------|
|                     | Structural frame Yield limit: 340 MPa | Pressure vessels Yield limit: 115 MPa | Corner fitting Yield limit: 275 MPa |
| Stacking strength   | 0.88 | 0.02 | 0.84 |
| Lifting strength 01 | 0.28 | 0.01 | 0.24 |
| Lifting strength 02 | 0.29 | 0.12 | 0.12 |
| Transverse Racking 01 | 0.56 | 0.16 | 0.23 |
| Transverse Racking 02 | 0.55 | 0.18 | 0.24 |
| Longitudinal Racking 03 | 0.81 | 0.24 | 0.40 |
| Longitudinal Racking 04 | 0.81 | 0.23 | 0.39 |

The summary of numerical analysis is presented in Table 7. From the strength criteria the allowable stress of the structural frame, pressure vessels, and the corner fitting are 340, 115, and 275 MPa, respectively. As shown in the table, the results of stacking strength and longitudinal racking strength seems higher. Therefore, it is recommended to strengthen the vertical and horizontal frame with additional bracket.
6. Conclusions
In this paper, the design procedures have been carried out on the LNG ISO tank through the guidance of ASME Section VIII division I. The Finite Element Analysis was then performed on the sample tank parameters presented and the typical container structure specified in the ISO 1496 Standard. From this presented paper, the following conclusions were drawn:

1. The analysis of the ISO tank structure container defined the procedures in several scenarios such as stacking, lifting and racking. The FE results so far have shown that the yield requirements are verified for the tank and its supporting structures.
2. The stacking load from the ISO 1496 seem to be over-required for the LNG ISO Tank. It is mainly because under operating conditions the ISO tanks are treated differently from conventional solid goods containers and for this case specifically are only stacked up to the maximum of 2 tiers. For axial/vertical loads applied on the top corner fittings, vertical frames were generally the strongest load resisting components which is close to the yield stress in the frame material.
3. In the racking cases, the max stress is likely occurring at the connection between the cylindrical shell and the container structure. The maximum stress is close to the yield stress in the frame material. For this reason, it is necessary to improve the design to increase the safety allowance in the form of adding brackets or supports both at the horizontal and vertical levels.
4. In the ASME design guidelines, the calculations are mainly for pressure vessel designs only. Therefore, further research is needed to consider non-linear buckling analysis with FEM method.

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