

Article

Comparative FEM Analysis of Vacuum and Perlite Insulation Techniques on the Structural Integrity of Independent Type C Liquefied Natural Gas Tank

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Abstract: In light of escalating global energy demands and the imperative to reduce greenhouse gas emissions, the efficient transportation of liquefied natural gas (LNG) has become increasingly critical. As the evaporation of LNG from storage tanks represents a significant energy loss, improving tank insulation is crucial to optimize storage efficiency. This paper conducts a structural assessment of a smaller-sized Type C independent tank made of AISI 304L steel and examines the impact of two insulation techniques—vacuum and perlite—on their heat, structural, and fatigue behavior. Utilizing the finite element method (FEM), this study performs a heat transfer analysis followed by a structural analysis under combined loads in accordance with the International Gas Carrier (IGC) code. The subsequent fatigue analysis follows IGC procedures and is performed using third-party software. This article presents a detailed analysis of the heat transfer throughout the entire LNG tank and the stress levels under various combined load scenarios while providing insights into the critical stress points and the areas with the lowest fatigue life. Finally, this study confirms the viability of using both novel materials, perlite as an insulation material and Durolight for the tank support, because they meet the required limits.

Keywords: cylindrical LNG tank Type C; perlite; vacuum; strength assessment; IGC code



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1. Introduction

Liquefied natural gas (LNG) is predominantly made of methane with a small mixture of ethane, cooled to cryogenic conditions of approximately $-162\text{ }^{\circ}\text{C}$, and condensed into liquid, occupying less than 0.1% of its former volume in its gaseous state. This form of energy is increasingly acknowledged as a fuel that can substantially reduce SO_x and NO_x emissions, thus playing a critical role in addressing maritime environmental challenges [1]. Given its low carbon emissions, global energy shortfall, and cost-effectiveness, the international trade in LNG has been prioritized in recent years, with projections indicating its continued growth and importance in the global energy market over the coming decades [2].

LNG tanks can be categorised into integrated tank systems, where the strength assessment relies on the surrounding hull structure, and independent, self-supporting tank systems, where the hull's influence is negligible [3]. This study focuses on the independent tank system, Type C, classified as a high-pressure vessel [4], which offers leakage prevention through its simple and cost-effective cylindrical design, capable of withstanding pressures above 10 bar. Considering that cryogenic temperatures are around $-165\text{ }^{\circ}\text{C}$ at atmospheric pressure, stainless steel remains ductile and resistant to brittle failure. Skoczen [5] states that commonly used stainless steel grades for these conditions include the American Iron and Steel Institute (AISI) 304, 304L, 316, 316L, and 316LN. AISI 304L was selected for this study due to its prevalence in LNG tank applications and the extensive documentation of its mechanical properties under cryogenic conditions.

A comprehensive study that included both numerical and experimental tests on the mechanical integrity of a membrane cargo containment system made from 304L steel under collision scenarios, conducted by Elhers [6], showed good agreement between the experimental and numerical results in the initial bulb indentation of the LNG tank space, indicating an accurate representation of the initial stiffness in the numerical model. Additionally, the assessment of cryogenic steel under sloshing loads using a non-linear FE method conducted by Sohn et al. [7] showed that the numerical approach matched the experimental behavior of the fracture under axial tensile load, further validating the reliability of numerical methods in predicting the behavior of cryogenic steels.

Numerous experimental studies have been conducted on the AISI series to predict their mechanical properties under different environmental and loading conditions. Park et al. [8] conducted experimental testing on the AISI series to produce stress-strain curves across various temperatures. A similar study by Paik et al. [9] aimed to compile a database of mechanical properties for the materials used in marine environments, providing stress-strain diagrams across various temperatures and strain rates essential for predicting material stress during static and dynamic loading. In an assessment of the high-cycle fatigue of 304L at an ambient temperature, examining the effects of cyclic hardening and mean tensile stress, Vincent et al. [10] indicated that cyclic hardening diminished under mean tensile stress, which significantly reduced the fatigue life by 30%. Additionally, Oh et al. [11] analyzed the low-cycle fatigue (LCF) behavior of 304L, using welded specimens at $-163\text{ }^{\circ}\text{C}$ and ambient temperatures, across different strain ratios and pointed out the superior low-cycle resistance of 304L at cryogenic conditions as opposed to ambient ones. Finally, the most extensive study on the thermal properties of different AISI steel grades performed at the CERN Institute [12] provided valuable data for other researchers.

During transportation, the system prioritizes preventing gas evaporation, which leads to energy and money loss, by identifying the critical heat zones and adequately insulating the tank. A standard approach involves using a vacuum between the inner and outer tank shells, reducing both the tank weight and conduction surface, as demonstrated by Bo et al. [13]. The problem with the usage of a vacuum as an insulator is the need for constant monitoring and maintenance of the vacuum levels. Another approach is to use a solid insulator. A comparative study of three different insulation materials—polyurethane foam, polyisocyanurate board, and silica aerogel—by Ye and Pei [14] adopted the finite element method (FEM) for verification with an experimental test case. It demonstrated that all three types of insulation materials behave well in terms of thermal resistance and concluded that they are adequate for LNG tanks. In recent years, a novel material suitable for LNG insulation called perlite has been used, and its usage was studied by Li et al. [15]. The perlite was subjected to a series of experimental tests to determine how the thermal conductivity of the expanded perlite behaves in low temperatures regarding its different compacted densities. Comparing four different compacted densities, from 43 up to 63 kg/m³, the thermal conductivity varied by less than 5%, with the lowest conductivity being the one with the lowest compact density. Uluer et al. [16] investigated two different mixtures of mortar and binders for preparing the final binder mixed with expanded perlite. Furthermore, five different theoretical models (the Series, Parallel, Geometrical, Maxwell, and Chang models) for predicting thermal conductivity were compared with an experiment. While the Parallel model gave results closest to the experiment for both mixtures, the Series and Geometrical models underpredicted the thermal conductivity by less than 4%. Finally, Hoang and Joonmo [17] focused on developing a new procedure for assessing the temperature distribution in a multi-layered tank. For this purpose, the researchers developed an in-house code capable of predicting the heat transfer coefficients and, consequently, the temperature distributions in the entire system. The study assumed a one-dimensional steady-state case, where the heat flux flows from the ambient to the cargo in a fully loaded tank with voids, maintaining a uniform temperature distribution. The code is verified by comparing it with other study results, and the differences in heat transfer coefficients between the standard procedure

and the newly developed code are shown, which can lead to significantly different thermal stress results.

As many studies have shown, predicting the structural integrity of the entire system is a very complex issue as novel materials and methods are used to increase the efficiency of the tank while maintaining structural integrity. The article is organized as follows:

- A detailed explanation of the LNG tank structural integrity assessment methodology is presented in Section 2;
- A case study with detailed information on tank components, dimensions, and material properties is presented in Section 3.1;
- The FEM setup with information about the mesh, convergence, and boundary conditions for both heat transfer and structural analysis performed with Abaqus 6.13 and an 8-core CPU is presented in Section 3.2;
- Section 4 presents the results according to the IGC procedure, including heat transfer, structural, and fatigue analysis using Fe-Safe 2019. Both diagrams and graphs are used, and a summary of results for each load case is provided in Section 4.4.
- Finally, Section 5, Conclusions, deals with the results of the article, especially the use of novel perlite and Durolight materials for LNG purposes.

In this paper, two thermal insulation methods—traditional vacuum insulation and state-of-the-art perlite insulation are examined in detail, and in both cases, a novel glass fiber-reinforced polymer called Durolight is introduced to support the tank. Both insulation strategies are directly compared by analyzing their thermal and structural behavior, providing details about the temperature distribution, highest stress, and fatigue life for multiple combined load scenarios.

2. Methods

The Korean Register [18] emphasizes the importance of conducting a heat transfer analysis as a fundamental step in evaluating the structural integrity of LNG tanks. There are various methods for assessing heat transfer in these tanks. The ABS Guidance Notes on Thermal Analysis [19] recommend using either analytical models or finite element (FE) models that assume steady-state conditions. Alternatively, Cambaz et al. [20] performed a transient heat transfer FE analysis, demonstrating that temperature variations at the same point over two days are less than 1%.

The structural analysis follows heat transfer analysis, which is used not only to calculate stress due to thermal expansion but also to superimpose different loading cases: maximum acceleration due to maneuvering, 30° heeling condition, and collision condition. In a similar analysis performed by Lee et al. [21], the tank was subjected to a superimposed load of pressure, acceleration, and weight. Wang and Quian [22] presented a structural analysis without thermal loads to evaluate how inertial forces and internal pressure deform parts of the LNG tank.

High-cycle fatigue is usually studied under standard operating conditions, while low-cycle fatigue is studied under more severe circumstances, such as during bunkering. Park et al. [23] performed a full structural assessment of an LNG tank considering both low and high-cycle fatigue included. While they used FEM for the structural assessment, fatigue analysis was performed using an analytical approach to calculate damage accumulation, and the Von Mises stress was used as a criterion for determining the number of cycles until crack initiation. The procedure used in this study is shown in Figure 1. Accidental load cases (flooding and collision) and sloshing are out of the scope of this article.

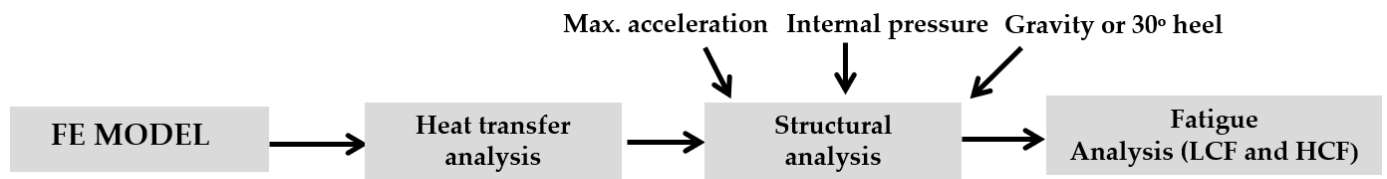


Figure 1. The procedure of structural integrity assessment.

For structural analysis, the maximum acceleration due to the ship maneuver is taken into account, ABS Guide [4]. The maximum acceleration depends on the configuration of the target ship and the position of the LNG tank in relation to the ship's center of gravity (COG). Equations (1)–(3) are used to determine the acceleration in all three directions.

$$a_z = \pm \sqrt{1 + \left(5.3 - \frac{45}{L_0}\right)^2 \left(0.05 + \frac{x}{L_0}\right)^2 \left(\frac{0.6}{C_B}\right)^{1.5} + \left(\frac{0.6K^{1.5}}{B}\right)^2} \quad (1)$$

$$a_y = \pm \sqrt{0.6 + 2.5 \left(0.05 + \frac{x}{L_0}\right)^2 + K \left(1 + 0.6K \frac{z}{B}\right)^2} \quad (2)$$

$$a_x = \pm a_0 \sqrt{0.6 + A^2 - 0.25A} \quad (3)$$

where a_x , a_y , and a_z are accelerations in all three directions, B ship breadth, L_0 ship length, K coefficient dependent on metacentric height and breadth, C_B block coefficient, and x , y , and z distance from ship COG in all three directions. Additional Equations (4) and (5) are used for calculating coefficients A and a_0 :

$$A = \left(0 - 7 - \frac{L_0}{1200} + 5 \frac{z}{L_0}\right) \left(\frac{0.6}{C_B}\right) \quad (4)$$

$$a_0 = k_p \left(0.2 \frac{v}{\sqrt{L_0}} + \frac{34 - \frac{600}{L_0}}{L_0}\right) \quad (5)$$

where k_p is a loading factor, and V is a vessel service speed.

3. Case Study

3.1. LNG Tank

A schematic representation of the case study of an LNG tank is shown in Figure 2. The design solution was developed in cooperation with the Faculty of Mechanical Engineering and Naval Architecture, Zagreb, and Croatian shipyard DIV Brodosplit to open up the global LNG market with a modern solution. This work is supported by the project—“Competence Center for Advanced Mobility” funded by the European Regional Development Fund: [Grant Number KK.01.2.2.03]. The tank structure consists of an inner and an outer tank, saddle supports, and inner supports made from a glass-reinforced polymer called Durolight. Both the inner and outer tanks are reinforced with stiffening rings that have a T-profile shape. The outer tank is reinforced with seven stiffening rings, while the inner tank is reinforced with three rings.

The thickness of the inner tank, the outer tank, and the tank heads is 3.1 cm. The geometry of the inner and outer tanks has a cylindrical center section and torispherical heads. The aim of the study is to evaluate the LNG strength of two different insulation techniques for the tank, namely a vacuum and the perlite used as an insulation material. Detailed specifications and dimensions of the LNG tank and its components are provided in Table 1.

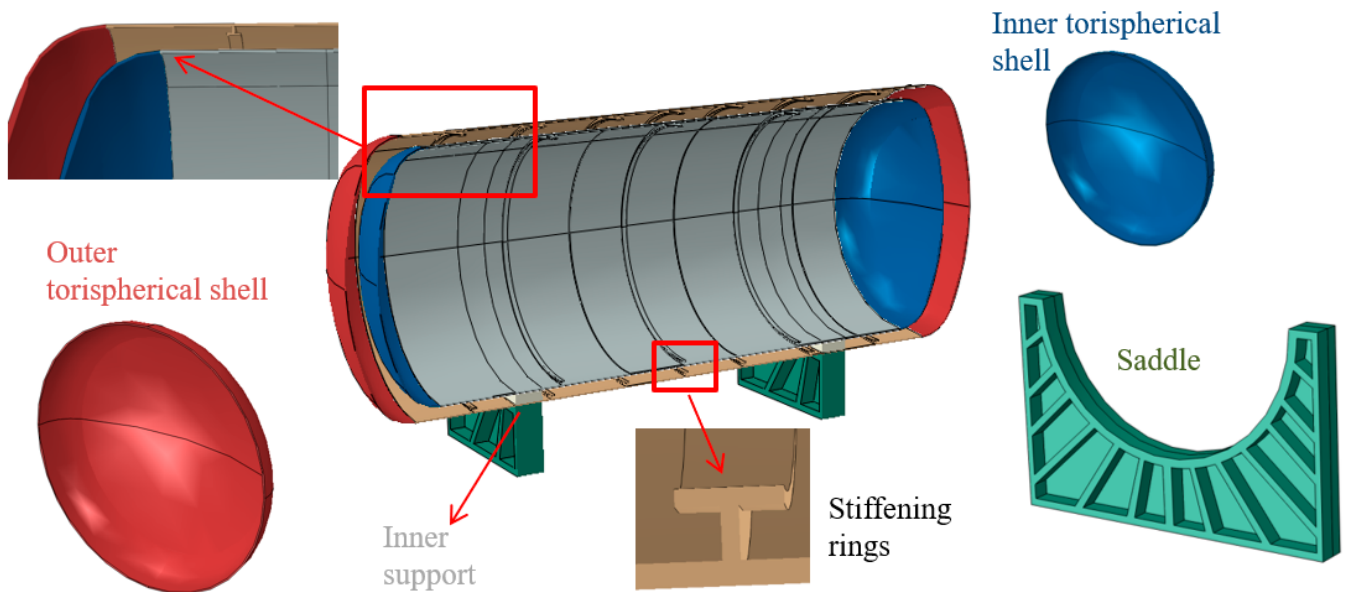


Figure 2. LNG tank structure.

Table 1. LNG tank particulars.

Part	Radius [m]	Length [m]	Thickness [m]
Outer torispherical shell	6.55	1.36	0.031
Inner torispherical shell	5.93	1.36	0.031
Stiffening rings	5.93	0.15	0.025
Saddle	3.285	0.7	0.7
Inner tank	5.93	12.9	0.031
Outer tank	6.55	12.9	0.031
Inner supports	3.285	0.7	0.268

All parts are made from AISI 304L steel except the inner supports made from Durolight. The material properties are listed in Table 2.

Table 2. AISI 304L and Durolight properties.

Material Property	AISI 304L	Durolight
Density [kg/m ³]	7800	45–50
Specific heat capacity [J/kg·K]	480	1100
Thermal conductivity [W/m·K]	20	0.21
Emissivity [-]	0.1–0.7	0.1–0.7
Young modulus [GPa]	200	0.3
Linear expansion coeff. [-]	1.2×10^{-6}	2.4×10^{-5}

The inner support made of Durolight is a crucial part of the tank assembly. Its main purpose is to support the weight of the inner tank. Therefore, it is designed as a 120° cut-off section with a height equal to the distance between the inner and outer tank. During assembly, these supports are initially attached to the inside of the outer tank. The inner tank is then positioned and rests on these supports, as shown in Figure 3c.

During tank assembly, perlite is poured down into the space between the inner and outer tank and additionally compacted. In the present analysis, perlite is modeled as an isotropic, homogenous material, Figure 4.

Most conservative properties regarding thermal resistance, specific heat capacity, and mechanical properties used by Uluer et al. [16] are listed in Table 3.

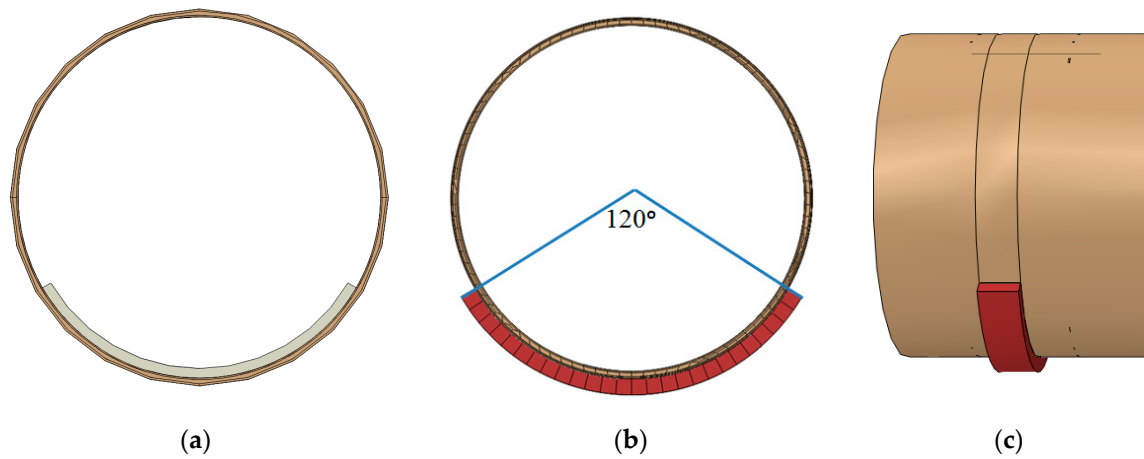


Figure 3. Durolight: (a) with Inner tank; (b) section view; (c) with Outer tank.

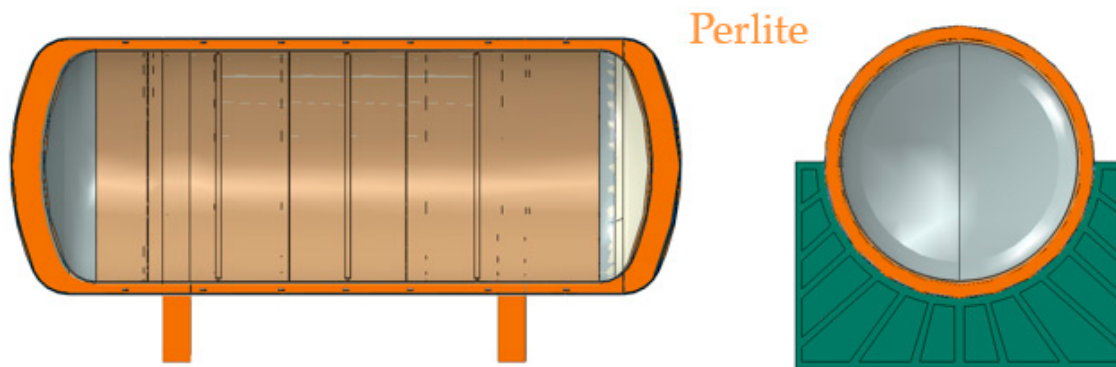


Figure 4. 3D geometry of perlite.

Table 3. Perlite properties.

Material Property	Perlite
Density [kg/m^3]	40
Specific heat capacity [$\text{J}/\text{kg}\cdot\text{K}$]	837
Thermal conductivity [$\text{W}/\text{m}\cdot\text{K}$]	0.039
Emissivity [-]	-
Young modulus [GPa]	9
Linear expansion coeff. [-]	1.2×10^{-6}

3.2. Model Setup

Initially, a convergence analysis is conducted to determine the minimal number of elements required for accurate numerical analysis, aiming to optimize mesh size and computational efficiency (see Section 3.2.1). A complete numerical model of the Type C tank is then created for both cases of insulation, vacuum insulation, and perlite insulation and tested with superimposed loads. ABAQUS software 6.13 is used for the preprocessor, postprocessor, and solver.

3.2.1. Convergence Analysis

To adequately model the heat transfer analysis, a 3D FE model mesh with solid finite elements is generated. To reduce the number of elements and increase convergence, second-order hexahedral elements C3D20R are used. In contrast to the conventional linear hexahedral elements, which have eight integration points, the second-order parabolic elements consist of 20 integration points and offer the capability of describing parabolic displacements, which ensures faster convergence. A convergence analysis is performed

for the first model with vacuum insulation, where pressure is applied to the inner tank to compare the resulting displacement, Figure 5a, with different finite element sizes and mesh sizes. As shown in the diagram in Figure 5b, four different meshes with an average finite element size of 0.3 m to 0.1 m were tested. As can be seen from the diagram, the displacement calculated with 70,000 elements at an average size of 0.15 m differs by less than 0.1% from the displacement calculated using 130,000 elements at an average size of 0.1 m. This indicates convergence of the mesh so that an average size of 0.15 m is used in further analysis, as it is more efficient in terms of computing resources.

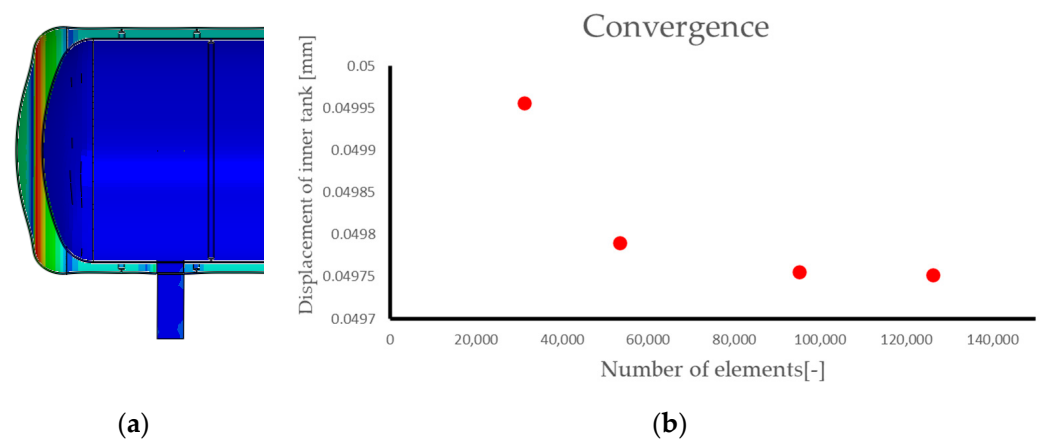


Figure 5. Convergence analysis—vacuum-insulation case: (a) Deformed tank; (b) Convergence diagram.

In the case of perlite insulation, the convergence analysis is carried out by comparing different mesh sizes during heat transfer, as perlite is primarily used for thermal insulation and not for structural support. Three different meshes are tested: 2, 3, and 4 elements per perlite thickness, and the temperature gradient across the tank is compared. A cross-section of perlite mesh with 3 elements per thickness is shown in Figure 6a. Since the heat conduction through the perlite determines both the internal and external temperature of the tank and, consequently, the stress due to expansion, an accurate calculation is crucial. Therefore, convergence is conducted by comparing the temperature distribution across the perlite thickness (Figure 6b). It can be seen that the mesh already converges at 3 elements per thickness, Figure 6c, with the difference between 3 and 4 elements per thickness being less than 1%.

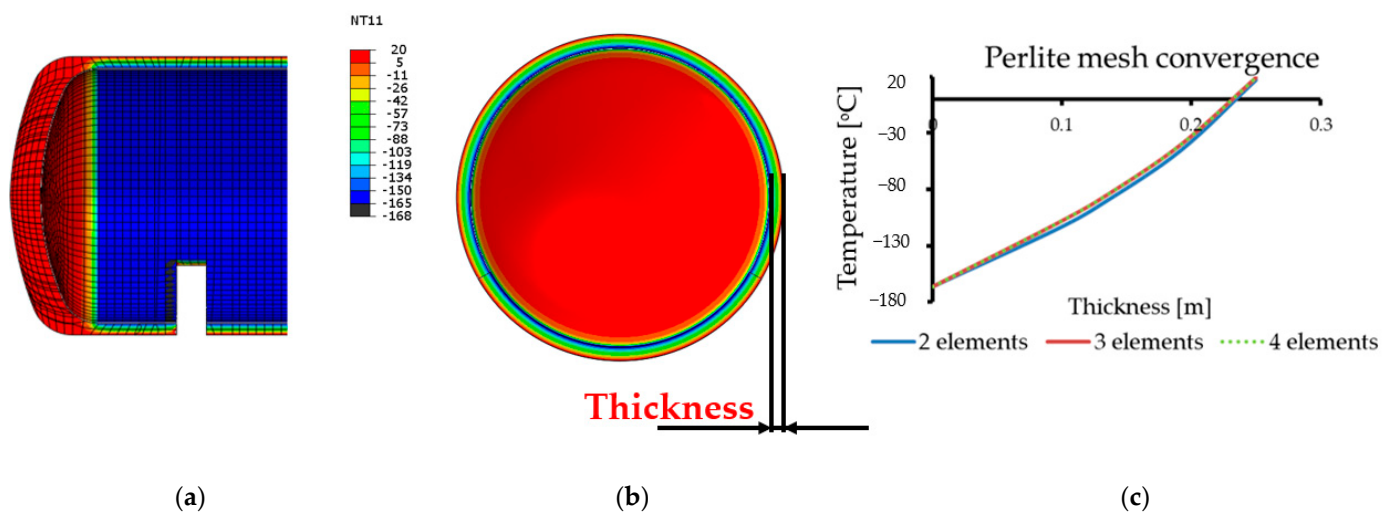


Figure 6. Perlite insulation case: (a) Perlite mesh, (b) Perlite temperature distribution (NT11 in °C), (c) Convergence diagram.

3.2.2. Numerical Model

The numerical model for both cases is identical with one difference: in the case of perlite insulation, perlite is added as a 3D body. Since the thickness of both the inner and outer tank is small compared to the average element size, the mesh could not ensure more than one element per thickness. This problem is solved by splitting the entire tank with multiple planes perpendicular to the X and Y axis, while two elements per thickness are prescribed on local radial curves. The final model consists of 90,740 elements and 452,608 nodes for the vacuum-insulation case model, Figure 7a, and 105,623 elements and 512,429 nodes for the perlite case model. Perlite is modeled as a 3D body, Figure 7b, which is numerically connected to the surface of the outer and inner tank using the Tie option. This option imposes translational and rotational constraints between nodes on two surfaces, effectively bonding them together.

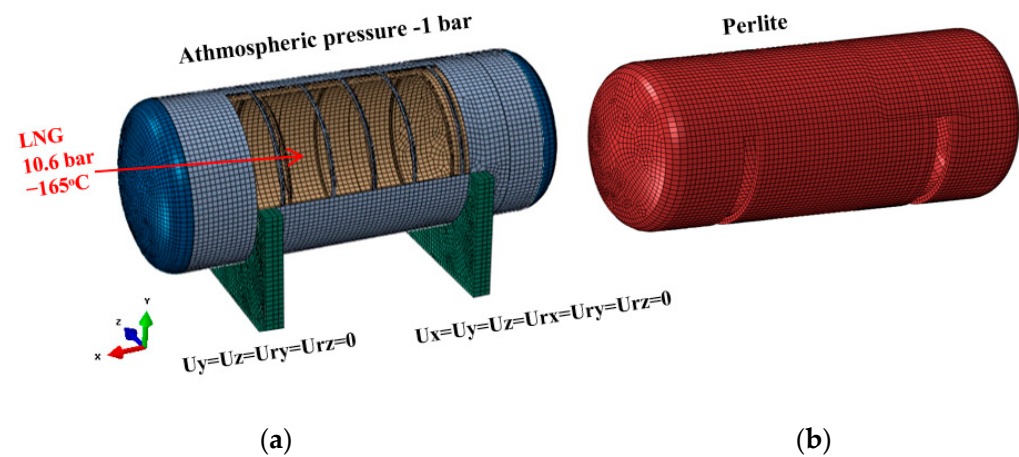


Figure 7. Final numerical model: (a) tank support insulation; (b) perlite mesh.

4. Results

The results are presented using the structural integrity assessment flow chart shown in Figure 1. Both thermal insulation strategies will be described jointly, and the final comparison of structural and fatigue analysis between the two models will be shown in Table 4.

4.1. Heat Transfer Analysis

A proper temperature distribution is essential for an accurate assessment of the strength of the LNG; therefore, a steady-state heat transfer analysis is performed. The internal temperature of the tank is set at $-165\text{ }^{\circ}\text{C}$, while the external temperature is maintained at $20\text{ }^{\circ}\text{C}$. The air convection coefficient on the outer surface of the tank is set to $15\text{ W/m}^2\text{ K}$. The mesh used in this analysis is identical to the one depicted in Figure 7, except for the DC3D20 element type, where second-order hexahedral elements are used for the heat transfer analysis. This ensures the compatibility of the mesh between heat transfer and structural analyses and enables a seamless transfer of temperature data from the heat transfer model to the structural model. It is assumed that all interfaces between the parts are perfectly bonded, with the components being connected using the Tie option in ABAQUS. The initial thermal conditions are illustrated in Figure 8. The surface film conditions define convection on the outer tank surface, while radiation is considered on both the inner and outer tank surfaces.

The temperature distribution of the inner tank and the inner support is shown in Figure 9. It can be observed that when perlite insulation is used, temperature distribution on the inner tank is more uniform with a smaller gradient across the outer surface and Durolight support, Figure 9b, while with the vacuum insulation, the maximum temperature can be seen in the form of red zones, Figure 9a.

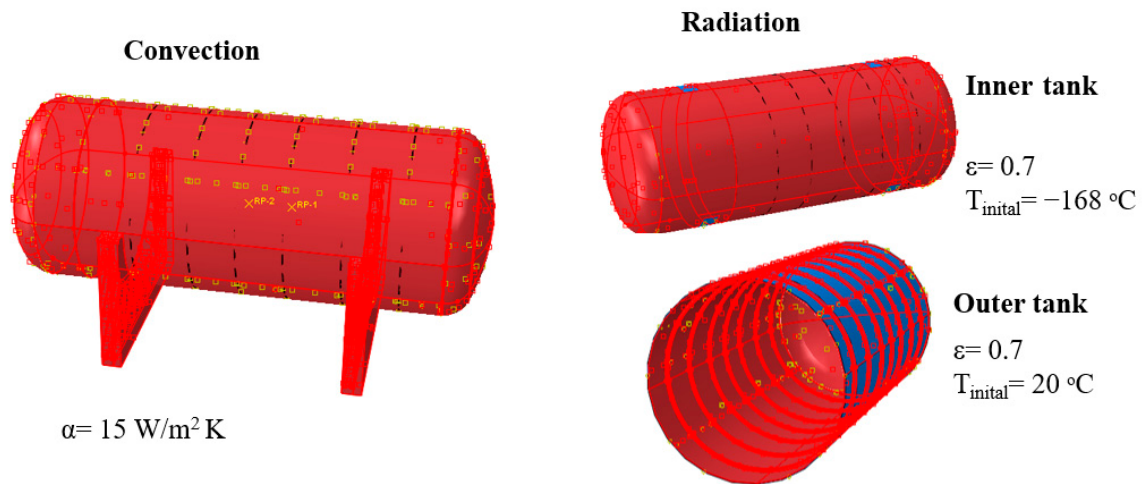
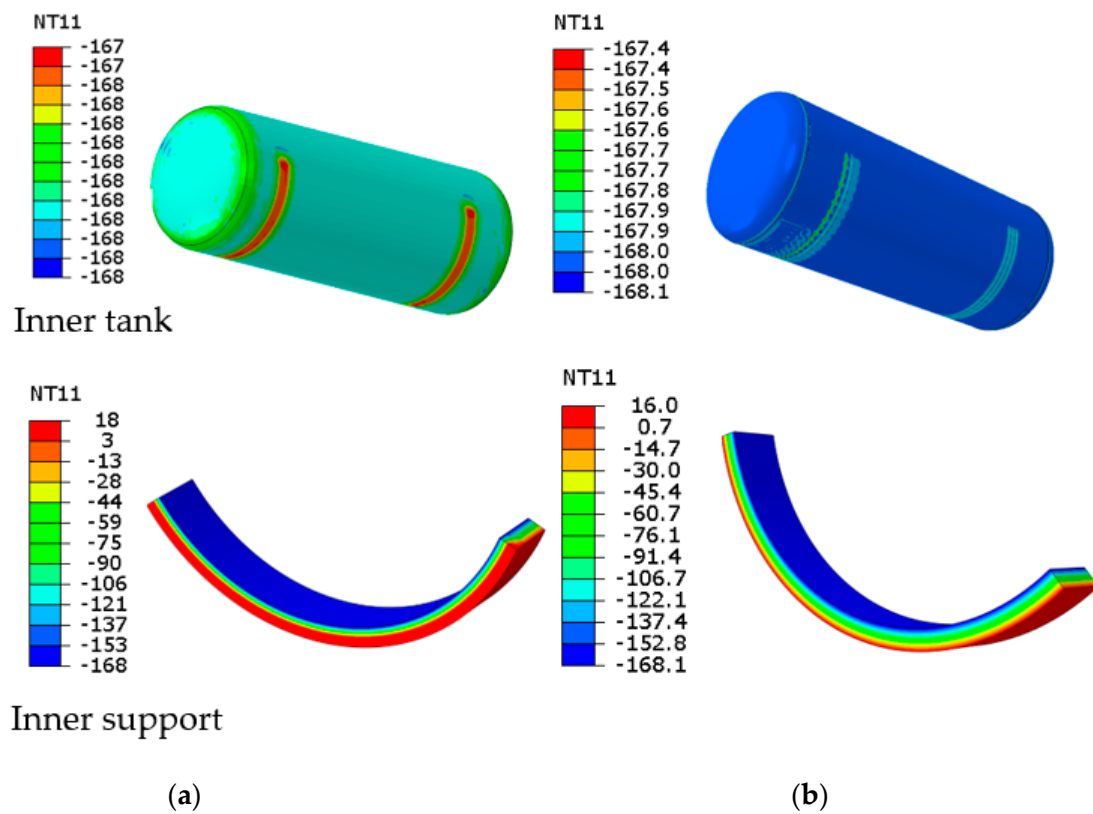


Figure 8. Initial steady-state thermal conditions.

Figure 9. Temperature distribution (NT11 in $^\circ\text{C}$): (a) Vacuum insulation; (b) Perlite insulation.

Two path directions are chosen, as shown in Figure 10a, to assess heat transfer across the system. If Path 1 is considered, Figure 10b, the heat across perlite distribution is linear, while for perlite, the middle vacuum part is non-existent. If heat across the inner support is analyzed, Figure 10c, perlite insulation has a less steep gradient in contrast to the gradient in the case of vacuum, which is shown in Figure 10b. This means that in the case of vacuum insulation, most of the heat sink is concentrated on the inner support, while perlite insulation results in a more uniform distribution.

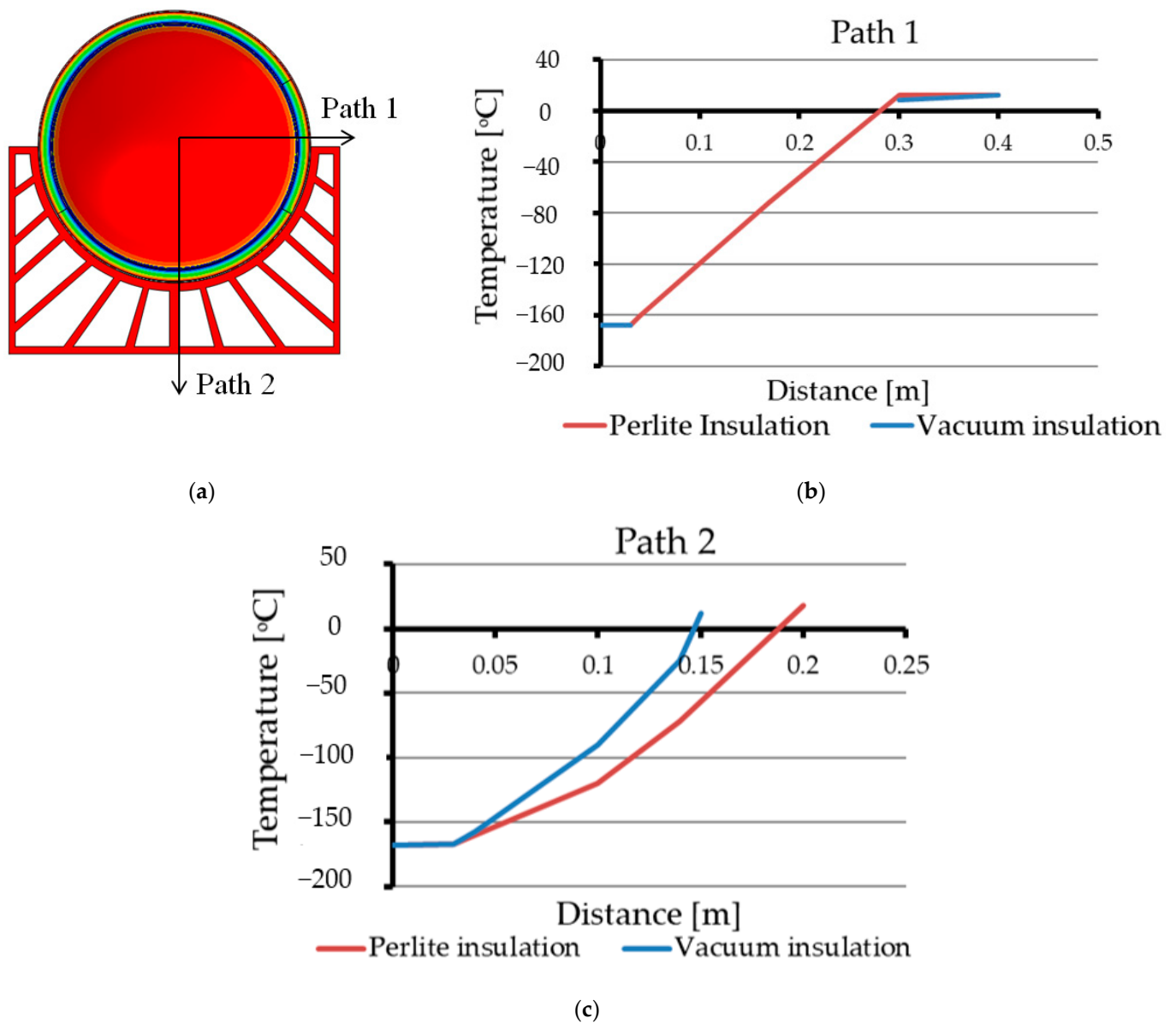


Figure 10. Temperature distribution over a section: (a) model section; (b) Path 1 diagram; (c) Path 2 diagram.

4.2. Structural Analysis

As already presented in the flowchart, Figure 1, several loads are superimposed and applied to the entire LNG tank. The temperature distribution calculated in the previous step is applied to the compatible mesh. Gravity is applied in the vertical direction of the tank to account for the load caused by the weight of the tank and the LNG cargo of 76 tons. The accelerations due to maneuvering are also taken into account. They are calculated using Equations (1)–(5) and their values are:

$$a_x = 1.079 \text{ m/s}^2$$

$$a_y = 4.12 \text{ m/s}^2$$

$$a_z = 3.772 \text{ m/s}^2$$

The cross-section for the vacuum insulation is shown in Figure 11. The maximum stress occurs at the connection between the inner tank and the inner torispherical part (marked in red).

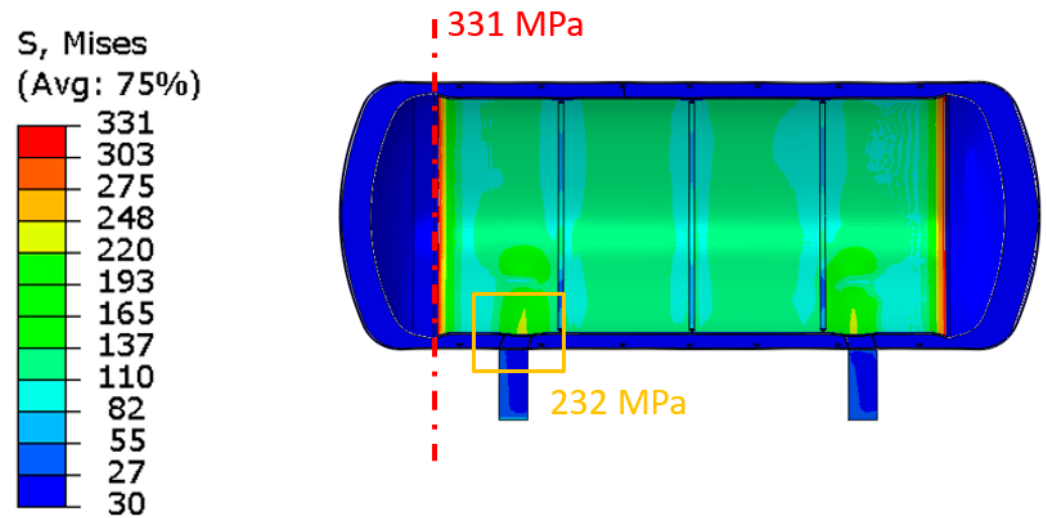


Figure 11. Stress distribution for vacuum insulation (in MPa).

For the independent tank C, the IGC code prescribes an allowable stress limit that shall not be exceeded:

$$\begin{aligned}
 \sigma_m &\leq f \\
 \sigma_L &\leq 1.5 f \\
 \sigma_b &\leq 1.5 f \\
 \sigma_L + \sigma_b &\leq 1.5 f \\
 \sigma_m + \sigma_b &\leq 1.5 f \\
 \sigma_m + \sigma_b + \sigma_g &\leq 3f
 \end{aligned} \tag{6}$$

where f is the reference allowable stress expressed as an $f = \min (R_m/A, R_e/B)$, A and B are coefficients determined by the steel grade and are equal to $A = 3.5$ and $B = 1.5$ for the selected 304L steel. As can be seen from Equation (6), the sum of local bending, membrane, and secondary stress ($\sigma_m + \sigma_b + \sigma_g \leq 3f$) is the most critical condition since stress is generated due to complex load cases, thus consisting of all the combined loads, Park et al. [23].

The summarized results are shown in Table 4 for both insulation strategies, with the location of maximum stress indicated. A more detailed presentation of the results can be found in Table A1 in Appendix A, where the results of the individual loads and the type of load are given. As can be seen from Table 4, all AISI 304L parts satisfied the most critical condition for the allowable stress limit. Stress concentrations are observed in several areas, particularly in the saddle and inner tank, where components are joined. Even if these stress concentrations appear due to over-constraining the models and result in conservatively high-stress levels, they are still well below the limit, so there is no need to investigate them in more detail. Two parts are not assessed according to these criteria: perlite, whose allowable limit is not decisive due to its granular properties, and the inner support made of Durolight. The stress limit for Durolight is not well-established due to limited experience with its use. However, the stress results for Durolight in both cases are well below its tensile strength ($R_m = 75$ MPa), indicating that it satisfies the stress limit.

Table 4. The maximum stress in the LNG tank assembly.

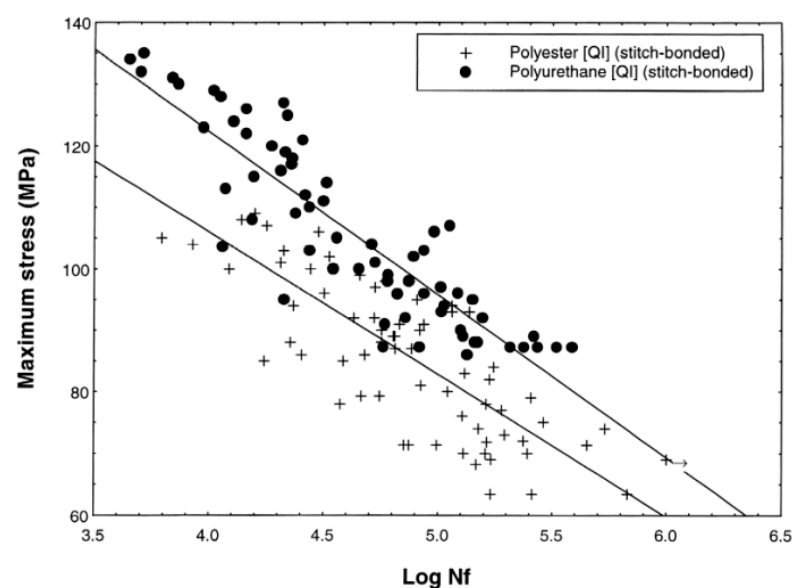
Part Name	Vacuum Insulation	Perlite Insulation	$3f = 350$ MPa
Inner support	9 MPa (SC * on the fixed surface)	9.4 MPa (SC on fixed surface)	OK
Saddle	223 MPa (SC around BC **)	226 MPa (SC around BC)	OK
Inner tank	232 MPa (SC around Inner support)	242 MPa (around Inner support)	OK
Outer tank	80 MPa (SC around Saddle connection)	105 MPa (Stiffening ring)	OK
Inner torispherical shell	331 MPa (Inner radius)	333 MPa (Inner radius)	OK
Outer torispherical shell	30 MPa (Inner radius)	31 MPa (Inner radius)	OK

* SC-stress concentration, ** BC-boundary condition.

4.3. Fatigue Analysis

The fatigue analysis for the LNG tank, which is subjected to repeated loads during maneuvering and bunkering, is performed by third-party software, FE-Safe 2019. Using Fe-Safe, it is possible to determine the exact location of the critical zones as well as calculate the number of cycles until failure.

While the assessment of the fatigue of metals is a well-known area with already standardized procedures, the fatigue of glass-reinforced thermosets such as Durolight is still a challenge, as shown by Amjadi and Fatemi [24]. One problem that occurs is the process of arranging glass fibers into the compound and overall control of production. Dyer and Issac [25] subjected two samples made from different matrix resins to tensile loading, the first from the standard polyester and the second one a polyurethane-vinyl-ester, Figure 12. They concluded that during the high-load application, the damage tends to be dominated by fiber properties, while during low-applied load, the damage is dominated by matrix properties. Another test of glass-reinforced thermoset was carried out by Zaludek et al. [26], in which the thermoset was subjected to a bending load corresponding to 80% of its tensile strength. Studies have shown that glass-reinforced plastic can withstand a considerable number of cycles, namely more than 30,000 cycles, even at such a high load. In both insulation strategies, the Durolight beam is loaded to less than 10 MPa, which corresponds to only 15% of its tensile strength, so the fatigue strength evaluation is neglected.

**Figure 12.** SN curve for Polyester (Dyer and Issac [25]).

4.3.1. High-Cycle Fatigue Analysis

The high fatigue is normally focused on the loads under operating conditions. In the case of LNG tanks, these are loads caused by ship maneuvering. Therefore, the accelerations calculated with Equations (1)–(3) are applied to the FE model and further used to calculate the number of cycles until failure. Since the IGC code states that the frequency of acceleration is equal to 1×10^8 , this is used as the desired number of cycles that the LNG tank should withstand. To ensure this, the stress due to acceleration should be less than the stress limit stated for 1×10^8 in the S-N curve, which is 14 MPa [27].

Stress due to acceleration in each direction and fatigue calculation are shown in Table 5. In the longitudinal and transversal directions, the stress range is below the chosen limit, which ensures that no fatigue damage will occur.

Table 5. Summary of high-cycle fatigue results.

	Load Case	Stress Range (MPa)	Fatigue
Vacuum insulation	Longitudinal acceleration	4	$>1 \times 10^8$
	Transversal acceleration	7.3	$>1 \times 10^8$
	Vertical acceleration	20	6.3×10^7
Perlite insulation	Longitudinal acceleration	4.2	$>1 \times 10^8$
	Transversal acceleration	7.6	$>1 \times 10^8$
	Vertical acceleration	21	5×10^7

In the longitudinal and transversal directions, the stress range for both insulation cases is below the chosen limit, which ensures that no damage will occur due to fatigue. The only problem occurs in the vertical direction for both insulation strategies, where only a small stress concentration area appears around the saddle-outer tank connection, Figure 13. As the entire tank is welded to the saddle, the vertical acceleration leads to a higher deformation and, consequently, higher stresses than in the transverse and longitudinal cases, as the stiffness of the tank is lower in the vertical direction. To reduce this stress, the straight edge connection between the saddle and outer tank should be replaced by a radius.

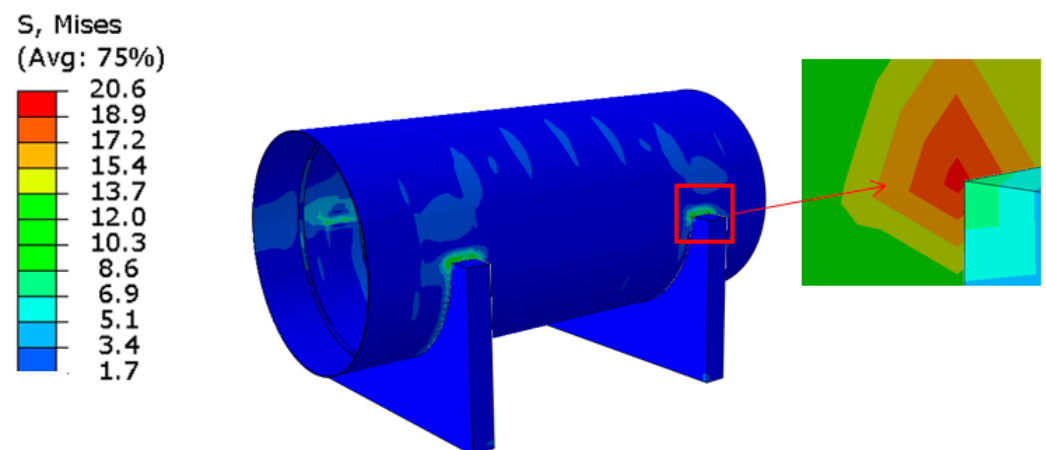


Figure 13. Stress concentration (MPa) for vertical acceleration load (vacuum-insulation case shown).

4.3.2. Low-Cycle Fatigue Analysis

During bunkering, the LNG tanks are exposed to extreme temperature drops, from ambient temperature, which is assumed to be 20 °C, to storage temperature of the fuel of −165 °C. This temperature drop leads to thermal stresses, which, as previous results show, put the most stress on the tank itself. It is assumed that the stress amplitude in this case is between the empty and full tank conditions and that the total number of loading

and unloading cycles is greater than 1000 (according to the IGC code). For the applied fatigue limit of 14 MPa curve and fatigue algorithm using the method for normal stress, the vacuum-insulation case showed that the only local critical region is at the inner radius of the inner torispherical shell (Figure 14, left), with the number of cycles until failure equal to 2818. In the perlite insulation case (Figure 14, right), the minimum number of cycles until failure is 2041 at the contact point between the inner tank and the inner support, again due to numerical reasons.

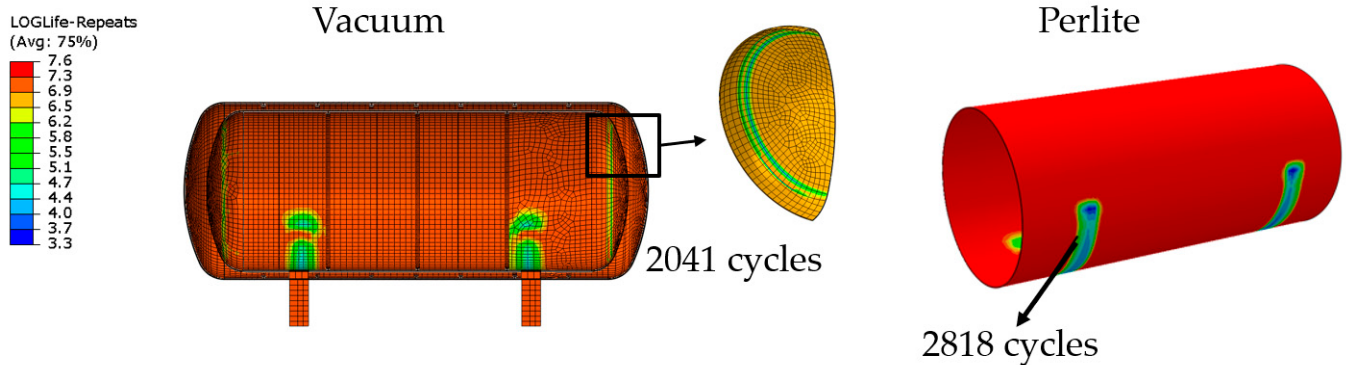


Figure 14. Critical locations for both insulation types (results showed in log scale, 10^X).

4.4. Result Summary

The comparative analysis of the heat distribution between perlite and vacuum insulation shows that perlite achieves a more uniform temperature profile across the inner tank, inner support, and consequently also in the outer tank, as illustrated in Figure 9. Despite the higher temperature gradients observed in the vacuum-insulation case, the maximum temperature difference between neighboring elements in the inner tank is minimal, about 0.5 °C. In vacuum insulation, most of the heat transfer occurs through the inner support, which leads to greater deformation in the contact area between the inner tank and the inner support. In contrast, with perlite insulation, the maximum stresses occur mainly in the stiffening rings of the inner tank, as shown in Figure 11. Despite these differences, the stress in both cases remains well below the critical stress limit, which is identified at the inner torispherical radius with a stress of around 330 MPa for both insulation strategies. According to the International Gas Carrier Code (IGC), the allowable stress limit is derived from the “3f criteria,” which accounts for the sum of local bending, membrane, and secondary stresses, and it is set at 350 MPa. The comparison of these allowable limits with the calculated stresses (presented in Table 4) confirms that both insulation strategies provide a safe design framework, with the maximum stresses for both scenarios being close to each other at approximately 330 MPa.

As LNG tanks are subjected to stresses during transport and bunkering, both high-cycle and low-cycle fatigue analyses are performed to ensure the integrity of the tank. High-cycle fatigue results showed stresses of 20 and 21 MPa due to ship maneuvers, slightly above the limits but with a service life of over 50 million cycles of life, indicating good durability. Low-cycle fatigue assessed during bunkering was in line with the minimum of 1000 cycles prescribed by the IGC code. The perlite insulation showed critical wear at the contact points between the inner tank and support, while in the vacuum case, wear occurred at the inner radius of the torispherical shell. A summary table (Table 6) compares the performance of the two insulation types under these conditions to enable an optimal choice of insulation for safety and efficiency.

Table 6. Summary of results.

	Analysis	Peak Value	Location
Vacuum insulation	Heat transfer analysis	Temperature gradient of 0.5 °C	Inner tank
	Thermal analysis	303 MPa	Inner torispherical radius
	Structural analysis	331 MPa	Inner torispherical radius
	30° Heel	328 MPa	Saddle
	High-cycle fatigue	6.3×10^7 cycles	Saddle-Outer tank
	Low-cycle fatigue	2818 cycles	Vacuum insulation
Perlite insulation	Heat transfer analysis	Temperature gradient of 0.1 °C	Inner support
	Thermal analysis	304 MPa	Inner torispherical radius
	Structural analysis	333 MPa	Inner torispherical radius
	30° Heel	332 MPa	Saddle
	High-cycle fatigue	5×10^7 cycles	Saddle-Outer tank
	Low-cycle fatigue	2041 cycles	Inner tank

5. Conclusions

The paper investigates the effects of perlite and vacuum insulation on the structural integrity of LNG tanks using international standards for strength and fatigue analysis to evaluate how each insulation strategy affects tank performance. A mesh convergence analysis, which is crucial for predicting the integrity of such complex structures, confirms that even a minimal number of elements in layers—three per layer thickness with second-order elements—provides consistent results, ensuring reliable data for evaluating the structural impact of different insulation methods.

The primary analysis for determining the structural integrity of LNG tanks involves evaluating heat transfer due to thermal expansion. Given the size of the structure, even small localized temperature gradients can result in significant localized expansion and strain. To ensure a conservative approach, maximum values are used for parameters like linear expansion coefficient, heat transfer coefficient, and specific heat density, resulting in higher temperature gradients due to the greater differences between the heat source and sink. Nevertheless, the maximum local temperature gradient in the case of vacuum insulation is only 0.5 °C. If other loads, such as internal pressure, acceleration, and weight, are added to the thermal loads, no plastic deformation is observed. While the weight of the perlite insulation increases the stresses in the outer tank by 30%, the peak stress values in both insulation scenarios are almost the same due to the dominance of thermal expansion and LNG pressure, especially at the critical inner torispherical radius. Even when compared to the strict conditions of the IGC code, the tank fulfills the required limits in both insulation cases.

Finally, the fatigue analysis is conducted for both high-cycle and low-cycle fatigue. For the high-cycle fatigue, the limit corresponds to the expected number of ship acceleration during maneuverability, 1×10^8 . While longitudinal and transversal acceleration satisfies the maximum stress criteria, stress is marginally above the limit in the case of vertical acceleration for both insulation strategies. The area around the saddle and outer tank connection should be investigated further. For the bunkering case, both strategies satisfy the limit.

Studies show that the use of perlite as an insulation material does not compromise the performance of LNG tanks compared to traditional vacuum insulation. Despite the additional mass of perlite, the critical stress areas in the LNG tank are primarily influenced by the LNG pressure and thermal expansion. The maximum stresses consistently occurred in the inner radius of the inner torispherical section under various loading conditions. However, in scenarios involving acceleration loads, the highest stresses are observed in the

saddle and outer tank, marginally exceeding the specified limits. The stress concentrations identified in the saddle area shown in Figure 13 are due to design angles and can be mitigated by minor design modifications. Overall, both insulation strategies—perlite and vacuum—have shown comparable results in maintaining structural integrity, confirming that both approaches are suitable for the construction of LNG tanks.

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Nomenclature

a_0	ship acceleration coefficient	σ_m	equivalent membrane stress
a_x, a_y, a_z	acceleration in ship X, Y, and Z direction	σ_L	equivalent primary membrane stress
B	the breadth of the ship	σ_b	equivalent primary bending stress
C	characteristic tank dimension	σ_g	equivalent secondary stress
C_b	block coefficient	f	allowable stress
COG	ship center of gravity	R_m	tensile stress
k_p	loading factor	R_e	equivalent membrane stress
L_0	vessel length	n_i	number of cycles until failure
P_e	external pressure	σ_i	stress amplitude
V	vessel service speed	$\Delta\sigma_A$	Allowable dynamic membrane stress
x	distance from ship COG in Z direction	P_{ed}	internal design pressure
y	distance from ship COG in Y direction	P_{gd}	total liquid pressure
z	distance from ship COG in Z direction		

Appendix A

Table A1. Summary of structural analysis results.

	Part Name	Vacuum Insulation Stress Range [MPa]	Perlite Insulation Stress Range [MPa]
Acceleration Long.	Inner support	4.1	4.4
	Saddle	4	5.3
	Inner tank	1.2	2
	Outer tank	2.3	4
	Inner torispherical shell	0.17	0.47
	Outer torispherical shell	0.3	1

Table A1. Cont.

	Part Name	Vacuum Insulation Stress Range [MPa]	Perlite Insulation Stress Range [MPa]
Acceleration Transversal.	Inner support	1.9	1.4
	Saddle	3	3.1
	Inner tank	5.7	6
	Outer tank	7.3	8
	Inner torispherical shell	1.7	1.75
	Outer torispherical shell	0.6	1
Acceleration Vertical	Inner support	5.4	5.5
	Saddle	5	5.3
	Inner tank	17	18
	Outer tank	20	21
	Inner torispherical shell	4.9	4.8
	Outer torispherical shell	1.8	1.7
30° Heel	Inner support	8.9	9.2
	Saddle	200	212
	Inner tank	232	217
	Outer tank	82	93
	Inner torispherical shell	328	332
	Outer torispherical shell	29	31

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