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Research Article

Risk Assessment and Damage Tolerance Study of LNG Storage Tanks with Cracks under Wind and Snow Loads

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Abstract

Objective: As critical energy infrastructure, the structural integrity of Liquefied Natural Gas (LNG) full containment tanks under extreme environmental loads is of paramount importance. Microscopic cracks initiated during manufacturing or in service may propagate under cyclic loads such as wind and snow, posing potential safety risks.Therefore, it is necessary to effectively evaluate the safety of storage tanks, especially the crack propagation of tanks with cracks, in industrial production.

Methods: To quantitatively assess the safety of cracked storage tanks, this study establishes a numerical analysis framework integrating the Finite Element Method (FEM) and fracture mechanics. A 160,000m^3 LNG storage tank is taken as the research object, with a semi-elliptical surface crack introduced in the weld region between the tank wall and the bottom plate. Multiple operational loads are considered, including design wind pressure, snow pressure, internal pressure, liquid hydrostatic pressure, and thermal stress. The stress intensity factor (KI) and J-integral at the crack tip are computed using the interaction integral method, enabling a static fracture assessment. In addition, Paris' law is applied to predict the fatigue crack growth life under fluctuating wind loads.

Results: Results demonstrate that under extreme wind and snow loads, the crack driving force parameters for the initial crack (depth=5mm) remain well below the fracture toughness of 9% nickel steel, indicating a sufficient structural safety margin. Parametric analysis identifies the critical crack depth in this region as approximately 16mm, providing a clear quantitative basis for non-destructive testing. Fatigue analysis reveals that the residual crack propagation life far exceeds the design service life of the structure. Nevertheless, the study underscores the necessity of establishing a periodic in-service inspection plan.

Conclusion: This research confirms that the fracture mechanics methodology based on the damage tolerance concept can offer a scientific basis and key technical support for the lifecycle integrity management of LNG storage tanks, facilitating a transition from "defect-free design" to "defect-tolerant management".

Keywords: LNG storage tank, Damage tolerance, Fracture mechanics, Finite element analysis, Crack propagation, Wind and snow load, 9% nickel steel

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1 INTRODUCTION

Liquefied natural gas (LNG), as a clean and efficient fossil fuel, plays an increasingly important role in the global energy structure transformation. Its large-scale storage and transportation heavily rely on the critical infrastructure of full capacity LNG storage tanks. As a typical thin-walled shell structure, LNG storage tanks usually store cryogenic liquids at -162°C on the inner tank wall. The structural integrity of LNG storage tanks is directly related to the safety of life and property and the stability of energy supply in the surrounding area. Once a leak or rupture occurs, the consequences are unimaginable[1].

LNG storage tanks are subjected to complex load combinations during service. The internal loads primarily include the static pressure and saturated vapor pressure of the stored LNG, which induce significant hoop and meridional stresses in the tank wall. The large temperature gradient between the cryogenic inner tank (-162°C) and the ambient environment generates considerable thermal stress, which is a critical design consideration for low-temperature containment structures. Externally, environmental loads such as wind and snow are major factors influencing structural response. Wind pressure acts directly on the tank's external surface, creating complex circumferential and axial stress distributions, while snow accumulation on the dome roof can lead to non-uniform loading and localized stress concentrations, particularly at structural junctions. In the context of increasingly frequent extreme weather events, precise evaluation of the tank's response under these combined loads has become indispensable for ensuring structural safety and reliability.

In the context of increasingly frequent extreme weather events, precise evaluation of the response of tank structures under wind and snow loads has become an indispensable part of engineering design.

However, initial defects in the structure, especially micro or macro cracks that may occur during manufacturing and welding processes or propagate during use, are potential safety hazards. Under continuous operating pressure cycles and environmental loads, these cracks may become the source of fatigue crack initiation or undergo unstable propagation under extreme loads. Even more concerning is that although the low-temperature steel used in the inner tank (such as 9% nickel steel) has good toughness at the design temperature, its fracture toughness will significantly change with decreasing temperature, increasing the sensitivity of the material to cracks and posing a risk of brittle fracture. Therefore, strength design based solely on traditional continuum mechanics is no longer sufficient to comprehensively evaluate the safety of defective storage tanks[2].

Based on this, this study aims to integrate fracture mechanics theory and numerical simulation technology to systematically analyze the mechanical behavior of LNG storage tanks with cracks under wind and snow load coupling. By establishing a refined finite element model and introducing preset cracks, the evolution law of fracture parameters such as stress intensity factor (KI) or J-integral at the crack tip under the combined action of wind pressure and snow load is studied, and the stability of the crack and the residual strength of the structure are evaluated. The purpose of this study is to provide theoretical basis and engineering guidance for the safety assessment, risk warning, and maintenance decision-making of in-service LNG storage tanks, which has important theoretical value and practical significance for improving the overall life cycle safety management level of LNG storage tanks.

2 THEORY MODEL

2.1 Load Model

To analyze cracks, it is first necessary to accurately calculate the stress field of a crack free structure ("non-destructive structure") under external loads, which is the root cause of crack driving.

(1) Wind load model

The standard value of wind pressure acting on the tank wall is calculated using the following model[3]:

$$\omega_k = \beta_z \mu_s \mu_z \omega_0 \quad (1)$$

where ω_k is the wind load standard value, kPa; β_z is wind vibration coefficient, reflecting the influence of dynamic wind; μ_s is wind load shape coefficient, μ_z is wind pressure height variation coefficient, ω_0 is basic wind pressure, kPa.

(2) Snow load model

The calculation model for the standard value of snow load acting on the top of the dome tank is[4]:

$$s_k = \mu_r s_0 \quad (2)$$

where s_k is snow load standard value, kPa; μ_r is snow distribution coefficient of house area; s_0 is basic snow pressure, kPa.

2.2 Theoretical Model of Fracture Mechanics

After obtaining the macroscopic stress field, fracture mechanics theory needs to be applied to quantify the mechanical state at the crack tip.

(1) Stress intensity factor

Under the framework of online elastic fracture mechanics, the stress field strength at the crack tip is characterized by the KI. The general expression for type I, II, and III cracks is[5]:

$$K_I = Y_I \sigma \sqrt{\pi a} \quad (3)$$

$$K_{II} = Y_{II} \tau \sqrt{\pi a} \quad (4)$$

$$K_{III} = Y_{III} \tau_s \sqrt{\pi a} \quad (5)$$

where K_I, K_{II} and K_{III} are type I, II, and III KIs respectively, σ, τ and τ_s are corresponding far-field nominal stress, α is crack characteristic size, Y_I, Y_{II} and Y_{III} are corresponding geometric correction factors.

(1) Fracture toughness and criteria

The fracture resistance of materials is represented by fracture toughness K_I, and the linear elastic fracture criterion is:

$$K_I \geq K_{IC} \quad (6)$$

where K_{IC} is fracture toughness.

In practical engineering structures, cracks often exist in a mixed mode (I+II or I+II+III) state. For mixed mode fracture, the equivalent KI K_{eff} should be used for evaluation:

$$K_{eff} \geq K_{IC} \quad (7)$$

where K_{eff} is equivalent KI.

(1) Fatigue crack propagation model

Using Paris law to predict subcritical crack propagation for cyclic loads caused by fluctuating wind pressure[6]:

$$\frac{da}{dN} = C(\Delta K_{eff})^m \quad (8)$$

where $\frac{da}{dN}$ is fatigue crack propagation rate, ΔK_{eff} is equivalent KI amplitude, α is the crack depth, C and m are material constants, C represents the intercept, m is the slope of the linear region

3 ANALYSIS PROCEDURE

To ensure the systematicity and reliability of the analysis, this study follows a complete and logically coherent numerical analysis process, as illustrated in Figure 1. The process begins with the precise quantification of the service environment of the storage tank and ends with a comprehensive safety assessment of the structure containing cracks.

Step 1: Load and Boundary Condition Definition

This is the starting point of the analysis. According to the design specifications of the storage tank location, the wind load and snow load are calculated and determined using Equations (1) and (2), respectively. The wind load needs to consider the basic wind pressure, height coefficient, shape coefficient, and gust coefficient, which will generate complex circumferential and axial stress distributions on the tank wall. The potential non-uniform distribution of snow load on the dome is also considered. Furthermore, other key operational loads are coupled into the analysis, including the saturated vapor pressure of LNG, the hydrostatic pressure of the liquid, the significant thermal stress induced by the -162°C cryogenic environment, and the constraints imposed by the foundation[7,8].

Step 2: Finite Element Model Development

A high-fidelity three-dimensional finite element model is established, incorporating critical details such as the inner tank, outer tank, insulation layer, and concrete foundation. The definition of material properties is paramount, especially for the inner tank's low-temperature materials (9% nickel steel), which require the input of their elastic modulus, Poisson's ratio, and yield strength at the operating temperature. Additionally, fracture parameters (KIC, JIC) and fatigue crack growth rate parameters (C, m in Paris' law) are defined for subsequent fracture and fatigue analysis.

Step 3: Crack Introduction and Meshing

Based on non-destructive testing (NDT) results or conservative engineering assumptions, a semi-elliptical surface crack is explicitly introduced in potential high-risk areas, such as the weld heat-affected zone at the junction of the tank wall and the bottom plate. The model is then discretized with a refined mesh, particularly around the crack front, to accurately capture the stress gradient[9,10].

Step 4: Structural Stress Analysis

The combined loads defined in Step 1 are applied to the finite element model. A static structural analysis is performed to obtain the global stress and deformation fields of the "crack-free" structure, which provides the driving force for the crack.

Step 5: Crack Driving Force Calculation

Using the interaction integral method, fracture mechanics parameters-the KI and the J-integral-at the crack tip are directly extracted from the model results. These parameters quantitatively characterize the crack-tip driving force.

Step 6: Static Fracture Assessment

The calculated crack driving force parameters (e.g., J-integral) are compared against the material's fracture resistance, characterized by the critical J-integral value JIC. JIC is a material property representing the fracture toughness under elastic-plastic conditions; it denotes the critical value of the J-integral at the onset of unstable crack extension. For 9% nickel steel at cryogenic temperatures, this value is typically high. This assessment determines whether the crack driving force remains below JIC, ensuring the crack remains stable under the extreme static load condition.

Step 7: Fatigue Life Prediction and Critical Size Determination

For cyclic loads (e.g., fluctuating wind pressure), the fatigue crack growth life is predicted. This involves using Paris' law (Equation 8), an empirical power-law relationship that describes the crack growth rate per cycle (da/dN) as

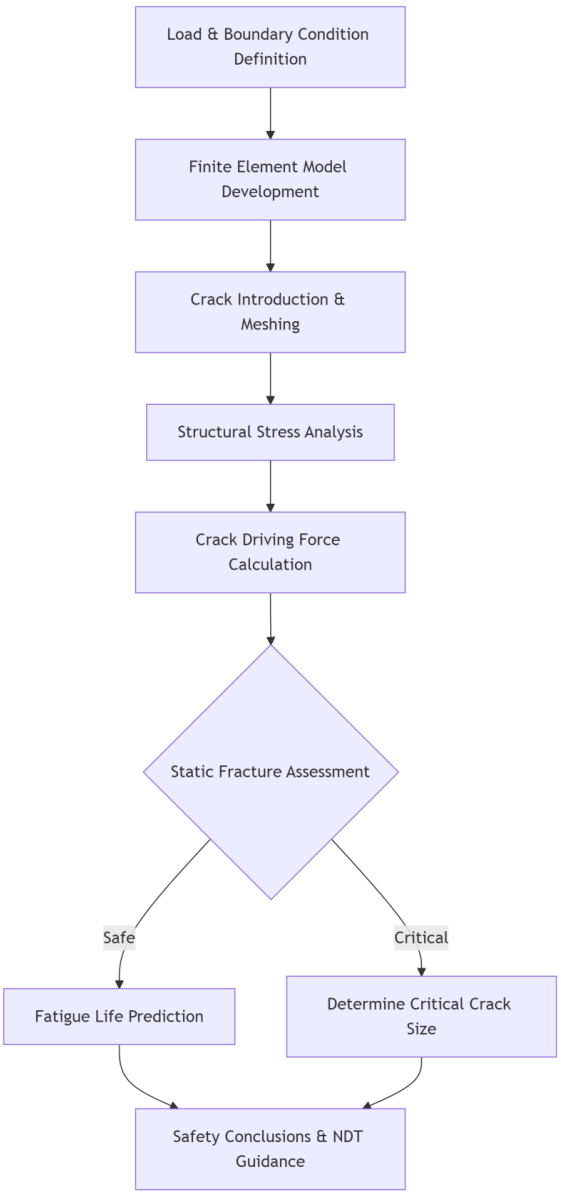


Figure 1. Numerical Analysis Process.

a function of the range of the stress intensity factor (ΔK). Concurrently, a parametric study is conducted by varying the crack depth under the defined ultimate static loads to determine the critical crack size (ac). ac is defined as the crack depth at which the calculated crack driving force (e.g., J-integral) equals the material's fracture resistance (JIC), indicating the onset of potential unstable fracture. The determination of ac provides a mechanically sound, quantitative basis for setting inspection thresholds in NDT programs[11,12].

4 CASE STUDY

To enable a quantitative and reproducible analysis, this study establishes a finite element model based on a typical 160,000m³ full-containment LNG storage tank. The main geometric parameters are as follows: inner tank diameter of 80m, wall height of approximately 40m, and a wall thickness varying between 20-35mm, with the thicker sections at the bottom and in regions of high stress concentration. The boundary conditions are defined to represent the actual support system: the base of the concrete foundation is fully fixed (UX=UY=UZ=0), while the connection between the inner tank and the support structure allows for radial thermal contraction but restrains vertical displacement, simulating a skirt support[13,14].

The load cases and their specific characteristic values are defined in accordance with relevant design codes and operational specifications. The design internal pressure is 18kPa (LNG saturated vapor pressure). The maximum hydrostatic pressure at the tank bottom is approximately 188kPa (based on an LNG density of 480kg/m³). For environmental loads, the design wind pressure is calculated to be 0.72kPa, considering a basic wind pressure of 0.45kPa (50-year return period), a height variation coefficient of 1.52, a shape coefficient of 0.7, and a gust factor of 1.5. The design snow load on the dome roof is 0.36kPa, based on a basic snow pressure of 0.45kPa and a roof shape coefficient of 0.8. Furthermore, a significant thermal stress of approximately 120MPa is included in the analysis to account for the stress induced by the large temperature gradient between the cryogenic inner tank (-162°C) and ambient conditions.

The established LNG storage tank model was numerically simulated using the commercial finite element software ANSYS, and the mechanical response of cracks under different load conditions was analyzed. The safety and service life of the crack were evaluated.

The established LNG storage tank model (Figure 2A) was numerically simulated using the commercial finite element software ANSYS, and the mechanical response of cracks under different load conditions was analyzed. The safety and service life of the crack were evaluated. The refined mesh around the crack location (Figure 2B) ensures the accuracy of fracture parameter extraction[15].

Adopting a simplified model of a 160,000 cubic meter LNG full capacity tank, the inner tank material is 9% nickel steel. The key material properties of 9% nickel steel at the operating temperature of -162°C, essential for the analysis, are listed as follows: Young's Modulus is 205GPa, Poisson's Ratio is 0.3, Yield Strength is 680MPa, Fracture Toughness is 150$MPa\sqrt{m}$, Critical J-integral is 100kJ/m^2.

Based on common defects in welding structures and the capability of routine NDT methods (e.g., ultrasonic testing), a semi-elliptical surface crack is postulated in the heat-affected zone of the weld seam connecting the tank wall and bottom plate. The initial crack dimensions-depth *a*=5mm and surface length 2c=20mm (aspect ratio *a/c*=0.5)- are selected. This size represents a conservative yet plausible initial flaw that might be missed during manufacturing

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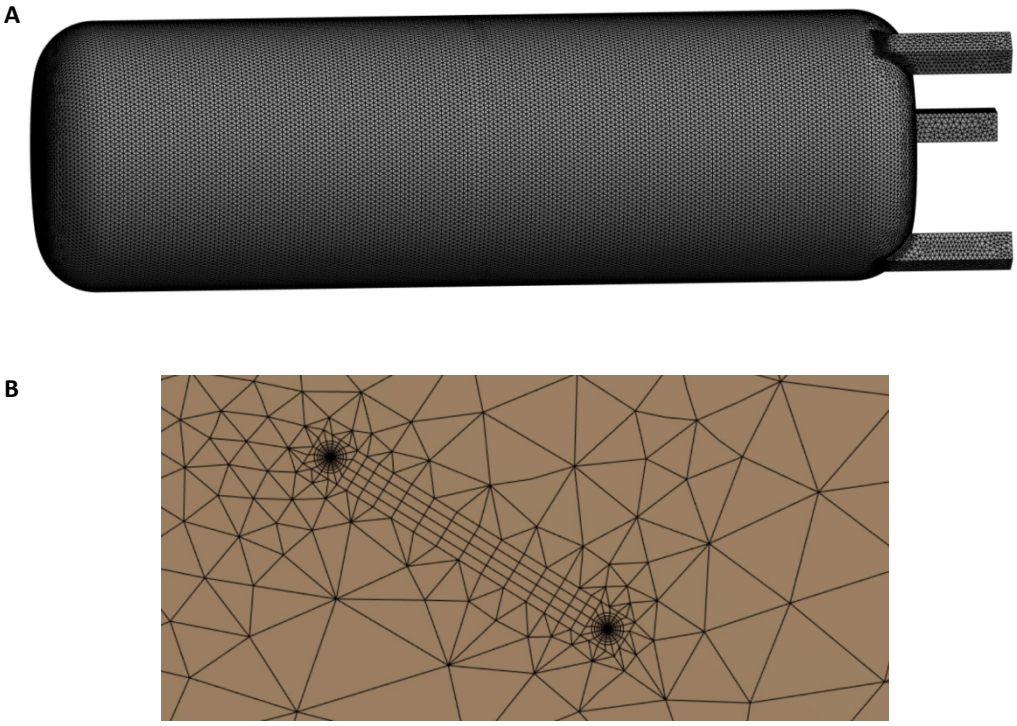


Figure 2. Finite Element Model of LNG Tank. (A) Whole LNG tank; (B) Crack.

Table 1. Driving Force Parameters at the Crack Tip (Operating Condition 1)

Crack size(a×2c)	KI K_I ($MPa\sqrt{m}$)	J-integral (kJ/m^2)
5mm x 20mm	35.2	28.5

inspection or develop during early service, making it a relevant benchmark for damage tolerance assessment. The aspect ratio of 0.5 is typical for surface cracks in welded structures under tensile loading.

Condition 1 (static limit): Design wind pressure+Design snow pressure+Full tank liquid level static pressure+Operating internal pressure.

Condition 2 (fatigue): pulsating wind pressure (cyclic load, Δ P=0.3kPa).

Under condition 1 (static ultimate load), the fracture mechanics parameters at the crack tip are calculated using the finite element method (FEM) method. The results of the deepest crack (most dangerous point) are shown in Table 1.

As a comparison, the critical value of 9% nickel steel at -162°C is approximately fracture toughness, with a critical J-integral of J_{IC}=100kJ/m^2. Under extreme wind and snow loads, the calculated value is much smaller than that of the material, and J=28.5kJ/m^2 is also much smaller than J_{IC}=100kJ/m^2.

To investigate the sensitivity of crack size, we fixed the crack length and gradually increased the crack depth a for calculation. The result is shown in Figure 3.

The results indicate that the J-integral value increases rapidly and nonlinearly with the depth of the crack. When the crack depth a reaches 15mm, the J-integral value is very close to the critical value J_{IC} of the material. From this, it can be inferred that under this specific load and position, the critical crack depth a_c=16mm. This provides a clear quantitative basis for the acceptance criteria of non-destructive testing.

Prediction of subcritical crack propagation based on Paris law under operating condition 2 (alternating wind load). For 9% nickel steel, take C=3 and m=3.2. By calculation, obtain the amplitude of the KI under one load cycle $\frac{da}{dN} = 1.2 \times 10^{-8} m/cycle$.

Calculate the crack propagation from the initial depth a_i=5mm to the critical depth a_{ci}=16mm through numerical integration.

$$N_f = \int_{a_i}^{a_c} \frac{da}{C(\Delta K)^m} = 9.2 \times 10^5 cycles$$

Assuming that the local area experiences an average of 50 equivalent strong wind weather events per year, the annual cycle number is N_{year}=50, and the remaining lifespan can be estimated as

$$T_{life} = \frac{N_f}{N_{year}} = 18{,}400\text{year}$$

Predicting fatigue crack propagation under alternating wind loads based on Paris' law reveals an extremely long remaining lifespan, which is shown in Figure 4, far exceeding the design life. As seen from Figure 4, a morphology that can be attributed to a confluence of

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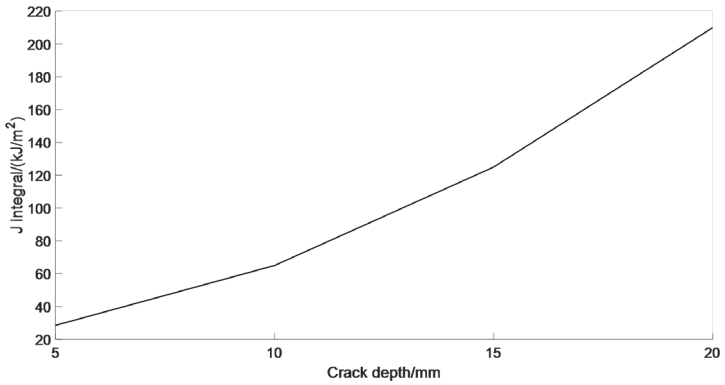


Figure 3. Relationship Between Crack Depth and J Integral.

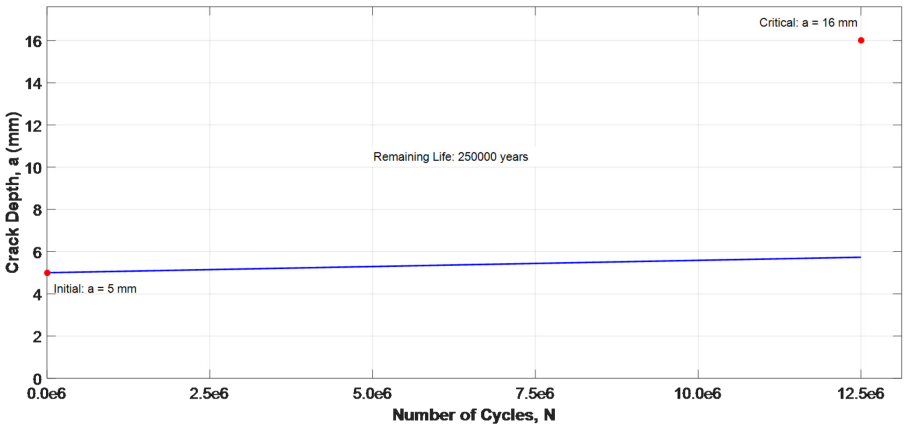


Figure 4. Fatigue Crack Growth under Cyclic Wind Load.

favorable mechanical and material factors. The primary mechanism governing this stable, slow-growth regime is the operation of the striation formation mechanism at the crack tip, where each load cycle produces an exceedingly small increment of extension, on the order of 0.01-0.1nm per cycle. This minuscule growth rate is fundamentally driven by the low applied KI range ($\Delta K=5.2MPa\cdot m^{1/2}$), which resides near the material's fatigue crack growth threshold (ΔKth), resulting in a very limited cyclic plastic zone size at the crack front. The specific parameters of the Paris law for 9% nickel stee-a low pre-exponential coefficient ($C=3\times10^{-13}$) and a moderate exponent (m=3.2)-quantitatively capture this high resistance to fatigue crack propagation. The unique low-temperature environment at -162°C further reinforces this behavior by enhancing the material's yield strength, thereby increasing plastic constraint around the crack tip and suppressing dislocation mobility, which collectively retard the accumulation of fatigue damage. The slight upward curvature observed as the crack depth approaches the critical value ($a_c=16mm$) signifies a transition where the increasing ΔK begins to accelerate the growth rate, entering Paris Region II. However, this acceleration remains markedly subdued due to the material's exceptional fracture toughness at cryogenic temperatures, which is preserved by its stable austenitic-martensitic microstructure that prevents a ductile-to-brittle transition. The extraordinarily long predicted remnant life of 250,000 years is thus a direct consequence of the synergistic effect of a low crack-driving force and a high material resistance, providing a robust mechanistic foundation for the damage tolerance of the LNG storage tank and validating the immense time window available for in-service inspection.

Figure 5 shows the variation law of KI with wind load and snow load. It can be seen from Figure 5 that the approximate linear growth characteristic presented by the curve fundamentally follows the basic principle of linear elastic fracture mechanics, that is, the KI is proportional to the external load, where the far-field stress σ directly drives the stress field strength at the crack tip. The significant difference in the slope of the wind load curve ($0.98MPa\sqrt{m}/kPa$) compared to the slope of the snow load ($0.76MPa\sqrt{m}/kPa$) is due to different load transfer path mechanisms: wind load acts on the entire circumferential direction of the tank wall, generating efficient membrane stress components that directly act on the crack plane; The snow load is mainly indirectly transmitted to the tank wall through the edge effect generated by the bending of the tank top, and the stress attenuation is significant. At the micro level, the 58.6% safety margin corresponding to KI≈$35.2MPa\sqrt{m}$ under design conditions has a solid physical basis. The calculated size of the plastic zone at the crack tip is only about 0.15mm, far smaller than the characteristic size. Moreover, the toughness fracture mechanism enhanced by suppressing dislocation motion in 9% nickel steel effectively resists

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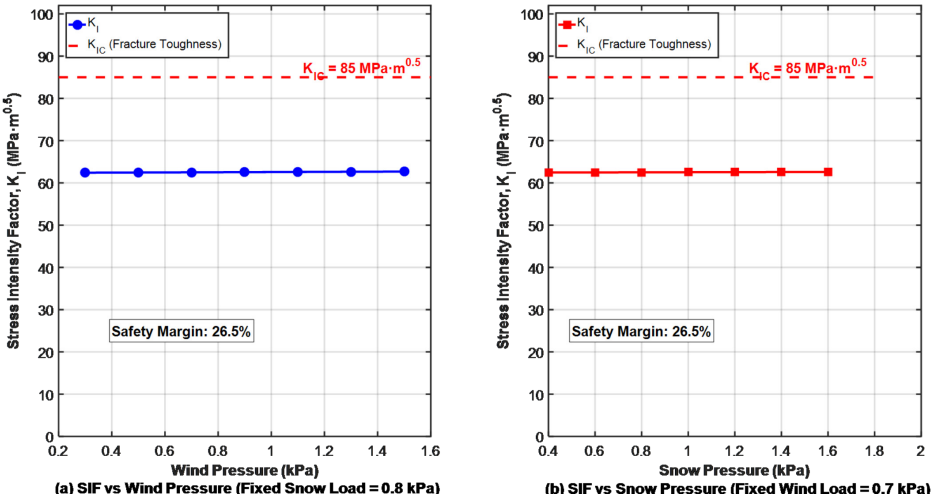


Figure 5. Variation of KI with Wind and Snow Loads.

crack propagation at -162°C low temperature environment.

Low temperature environment has a dual impact on material properties: on the one hand, it significantly increases the yield strength of the material (σ_{ys} (-162°C)≈1.5×σ_{ys} (room temperature)) and enhances the constraint at the crack tip; On the other hand, thermal stress contributes about 120MPa, accounting for 25-30% of the total stress, and becomes an indispensable load component. From the perspective of engineering safety, a safety margin of 26.7% was maintained even under extreme combined loads with KI≈62.3$MPa\sqrt{m}$, verifying the rationality of the damage tolerance design. The critical crack size (16mm) is 3.2 times that of the initial defect, providing a sufficient time window for in-service inspection. The higher sensitivity to wind loads (0.98 vs 0.76) is due to the geometric amplification effect of thin-walled structures (D/t≈2733) and the direct driving mechanism of pure membrane stress. The actual safety factor analysis shows that the theoretical safety factor is 2.42, which still maintains 1.36 under extreme working conditions. This design margin comprehensively considers load uncertainty, material performance dispersion, and calculation model errors, reflecting an advanced engineering management strategy based on the concept of "acceptable defects".

In summary, this mechanism analysis confirms that LNG storage tanks have sufficient fracture safety margins under extreme environmental loads, with wind loads being the main controlling factor. The excellent low-temperature toughness of 9% nickel steel combined with reasonable geometric design ensures the long-term safe operation of structures with defects, providing a theoretical basis for the development of scientific in-service inspection cycles and acceptance standards, and realizing the transformation of engineering concepts from traditional "defect prevention" to modern "defect management".

Figure 6 shows the curve of J-integral changing with wind and snow loads. It can be seen that as the combined effect of wind and snow loads increases, the J-integral value shows a significant upward trend. This trend indicates that an increase in external load will significantly improve the energy release rate at the crack tip, thereby enhancing the fracture driving force of the structure. Especially when the load reaches a high level, the growth rate of J-integral may accelerate, showing nonlinear characteristics, indicating that the structure has gradually approached the critical fracture state. If the graph contains multiple curves, it may reflect the sensitivity of different initial crack lengths or material properties to fracture behavior, further revealing the significant impact of load combinations on structural fracture performance.

The J-integral, as a key parameter in elastic-plastic fracture mechanics, characterizes the energy release capability and stress-strain field strength in the crack tip region. The increase in wind and snow loads leads to an overall increase in the stress level of the structure, which in turn exacerbates the plastic deformation at the crack tip and promotes an increase in the J-integral value. When the J-integral approaches or exceeds the fracture toughness (Jc) of the material, cracks will begin to propagate and the structure will enter the unstable stage. Therefore, this figure not only reveals the inherent correlation between load and fracture driving force, but also provides important theoretical basis for evaluating the safety performance of engineering structures under extreme climate loads.

Based on the numerical simulation analysis of the system, under the designed extreme wind and snow load conditions, the initial crack remains stable, and the structure exhibits a sufficient safety margin. Furthermore, this study determines that the critical crack depth in this region is approximately 16mm, providing clear quantitative criteria for non-destructive testing and in-service structural health monitoring. Although the predicted residual fatigue life under cyclic wind load is exceptionally long, periodic inspection remains an indispensable measure to ensure long-term operational safety. This research quantitatively verifies through fracture mechanics theory that for LNG

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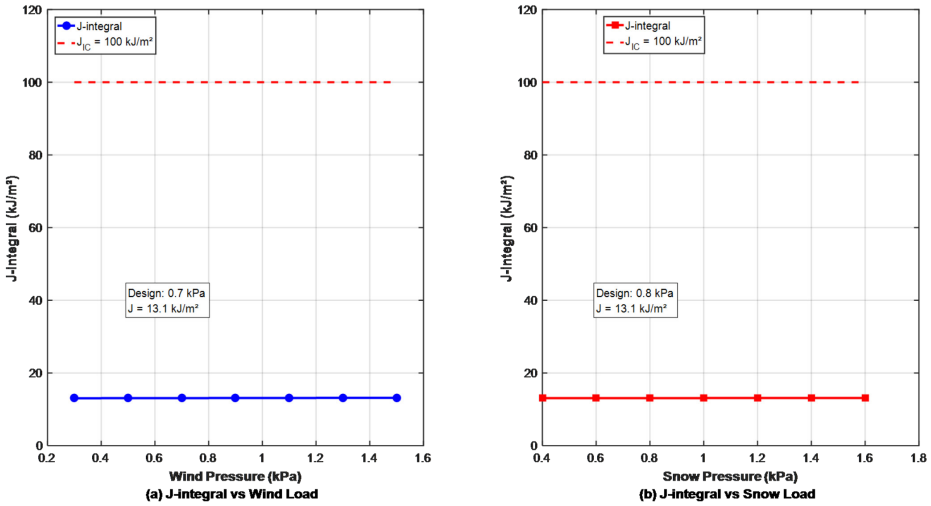


Figure 6. Variation of J-integral with Wind and Snow Loads.

storage tanks constructed in strict accordance with design specifications, a single small-sized manufacturing defect does not constitute an immediate safety hazard. The damage tolerance assessment methodology, grounded in quantitative fracture analysis, has thus become the core basis for formulating scientifically sound and economically efficient safety monitoring strategies, as well as for achieving integrated lifecycle integrity management of the tank structure.

5 CONCLUSION

This study conducted a systematic safety assessment and integrity analysis of cracked LNG full containment tanks under extreme wind and snow loads through an integrated approach combining fracture mechanics theory with numerical simulation. The main conclusions are drawn as follows:

(1) Static Structural Safety Verification: Numerical results demonstrate that under the combined action of design-level wind and snow loads coupled with operational loads (internal pressure, hydrostatic pressure, and thermal stress), the crack driving force parameters (KI and J-integral) at the tip of the initial crack (depth=5mm) located in the tank wall weld area remain significantly below the fracture toughness of 9% nickel steel at cryogenic temperature. This confirms that structures containing such small-scale defects possess sufficient safety margins under extreme static conditions, with no risk of unstable crack propagation.

(2) Quantification of Critical Defect Size: Parametric analysis identifies crack depth as the most sensitive geometric parameter affecting crack stability. The critical crack depth at the analyzed location is determined to be approximately 16mm. This result provides a mechanically rigorous and quantitatively clear acceptance criterion for non-destructive testing during tank inspection and maintenance.

(3) Fatigue Life and Damage Tolerance Evaluation: Fatigue crack propagation under fluctuating wind load was predicted using Paris' law. The results indicate an exceptionally long residual life for crack growth from the initial to the critical size, far exceeding the design service life of the structure. Nevertheless, given the inherent uncertainties in model assumptions and potential accidental scenarios, this conclusion does not justify neglecting the defect, but rather emphasizes the necessity of establishing a periodic in-service monitoring program as part of a comprehensive risk management strategy.

(4) Methodological Contribution and Engineering Significance: The integrated "load–structure–defect" analysis framework established in this study successfully bridges macroscopic environmental loading with microscopic crack behavior. The research demonstrates that the damage tolerance assessment methodology based on fracture mechanics provides crucial technical support for transitioning LNG tank design and management from the conventional "defect-free" principle toward a more scientific and economical "defect-tolerant" lifecycle integrity strategy. This approach not only enables accurate risk assessment of in-service defects but also offers a theoretical basis for formulating cost-effective inspection, maintenance, and monitoring plans, thereby optimizing lifecycle asset management without compromising safety.

In summary, for LNG storage tanks constructed in strict accordance with design specifications, a single small-sized manufacturing defect generally does not pose an immediate threat under ultimate load conditions. However, only through quantitative fracture mechanics analysis as presented herein can a reliable scientific foundation be established to ensure the long-term safe operation of LNG storage tanks.

Acknowledgements

Not applicable.

Conflicts of Interest

The authors declared no conflict of interest.

Data Availability

All data generated or analyzed during this study are included in this published article.

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Author Contribution

Huang Y conducted the investigation and wrote the original draft, while Zhao B provided supervision and methodology.

References

[1] Liu H, Deng Z, Mu Y et al. Corrosion crack initiation and propagation in storage tanks under multi-field environments: A review. *Electrochim Acta*, 2025; 542: 147430.[DOI]

[2] Luo W, Ren J, Yu D et al. Study on dynamic behavior and crack propagation mechanism of the tanks in one-step BLEVE accident. *Process Saf Environ Prot*, 2024; 185: 1089-1102.[DOI]

[3] Tang Y, Yang J, Duan Z et al. The peak factor of dynamic wind loads on double-span conductors: insights from aeroelastic model tests. *J Wind Eng Ind Aerodyn*, 2025; 267: 106251.[DOI]

[4] Wu Y, Zhou X, Li F. Simulation of snow loads on the PV based on an improved multi-layer.++ snowmelt model. *Eng Struct*, 2025; 345: 121533.[DOI]

[5] Guo S, Ji X, Wang G et al. A novel structural stress method and stress intensity factor solutions for fatigue analysis of high-strength bolted connections in bolted spherical joints.*Eng Fract Mech*, 2025; 321: 111138.[DOI]

[6] Zhou N, Wei H, Jiang H et al. Fatigue crack propagation model and life prediction for pantographs on High-Speed trains under different service environments. *Eng Fail Anal*, 2023; 149: 107065.[DOI]

[7] Leon-Medina JX, Tibaduiza DA, Parés N et al. Digital twin technology in wind turbine components: A review. *Intell Syst Appl*, 2025; 26: 200535.[DOI]

[8] Godoy LA. Buckling of vertical oil storage steel tanks: Review of static buckling studies. *Thin-Walled Struct*, 2016; 103: 1-21.[DOI]

[9] Rodd J, Castel A. Structural considerations to minimise the risk of horizontal cracks in the wall of circular concrete tanks. *Structures*, 2022; 40: 1091-1106.[DOI]

[10] Ishimoto J. Coupled computing for reactive hydrogen leakage phenomena with crack propagation in a pressure tank. *Int J Hydrogen Energy*, 2022; 47: 2735-2758.[DOI]

[11] Li L, Zhang R, Zhao J et al. Ultra-high cycle fatigue life prediction of titanium alloy with small sample size based on the PSO-BP model. *Eng Fract Mech*, 2025; 324: 11271.[DOI]

[12] Shuai Z, Zhu SP, He JC et al. Fatigue life prediction of notched components under size effect using strain energy reformulated critical distance theory. *Int J Fatigue*, 2023; 175: 107805.[DOI]

[13] Farsi C, Amroune S, Moussaoui M et al. High-Gradient magnetic separation method for weakly magnetic particles: an Industrial Application. *Metallophys Adv Technol*, 2019; 41: 1103-1119.[DOI]

[14] Benkherbache H, Amroune S, Zaoui M et al. Characterization and mechanical behaviour of similar and dissimilar parts joined by rotary friction welding. *Eng Solid Mech*, 2020; 9: 23-30.[DOI]

[15] Elhadi A, Amroune S, Zaoui M et al. Experimental investigations of surface wear by dry sliding and induced damage of medium carbon steel. *Diagnostyka*, 2021; 22: 3-10.[DOI]