

Article

Life Assessment of Deep-Sea Observation Windows under Different Design Considerations

Zhihao He ¹, Fang Wang ^{1,*}, Jinfei Zhang ¹, Bingxiong Zhao ², Yu Wu ¹, Ruilong Luo ¹ and Fengluo Chen ^{3,4}

¹ College of Engineering Science and Technology, Shanghai Ocean University, Shanghai 201306, China; zhihaohe1226@163.com (Z.H.); jf-zhang@shou.edu.cn (J.Z.); y_wu@shou.edu.cn (Y.W.); rlluo@shou.edu.cn (R.L.)

² Naval Architecture and Shipping College, Guangdong Ocean University, Zhanjiang 524088, China; bxzhao@gdou.edu.cn

³ State Key Lab of Marine Geology, Tongji University, Shanghai 200092, China; chenfengluo@126.com

⁴ China Merchants Marine and Offshore Research Institute Co., Ltd., Shenzhen 518067, China

* Correspondence: wangfang@shou.edu.cn

Abstract: As a key component of deep-sea manned submersibles, the observation window is usually constructed with polymethyl methacrylate (PMMA) material. During the design of the observation windows, the consideration of actual lifespan and its influential factors is insufficient. There are no clear provisions in the widely applied specifications. In this paper, based on the continuum damage mechanics model, combined with the viscoelastic relationship of PMMA material, a series of calculations were performed on the PMMA observation window. The parametric analysis of the fatigue crack-initiation life of the observation window at various thickness-to-diameter ratios (1.6, 1.4, 1.2, and 1.0), different friction coefficients (0.1, 0.2, and 0.3), and different transition arc radii (4000 mm and 6000 mm) was carried out. The calculated crack positions in the numerical mode used for validation closely align with those in the tested window. And simulation results show that the fatigue life of the observation window gradually decreases with the decrease in the thickness–diameter ratio and the increase in the friction coefficient. However, the increase in the transition arc radius will prolong the fatigue life of the observation window, which is higher than that of the original structure.

Keywords: observation window; manned submersible; fatigue life; polymethyl methacrylate (PMMA)



Citation: He, Z.; Wang, F.; Zhang, J.; Zhao, B.; Wu, Y.; Luo, R.; Chen, F. Life Assessment of Deep-Sea Observation Windows under Different Design Considerations. *J. Mar. Sci. Eng.* **2024**, *12*, 1017. <https://doi.org/10.3390/jmse12061017>

Academic Editor: Constantine Michailides

Received: 10 May 2024

Revised: 31 May 2024

Accepted: 14 June 2024

Published: 18 June 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Nowadays, with the advancement in ocean exploration and deep-sea devices, an increasing number of explorers and marine scientists have begun to dive and explore, which has gradually become an important development in the deep sea. Deep-sea manned submersibles represent high-end technologies in this field. The manned cabin stands as the pivotal component of the submersible. It primarily consists of pressure-resistant metal, with several observation windows made of transparent PMMA material [1]. Typically, there are a minimum of three observation windows in a manned cabin: the primary observation window and two supplementary lateral observation windows, as depicted in Figure 1. Compared to the metal hull, the design of the PMMA viewport window is equally important in guaranteeing the safety of the manned cabin [2]. The observation window not only provides means for submariners and scientists but also bears huge seawater pressure, together with the metal hull. The material and structural attributes of the observation window render it a vulnerable point within the manned cabin so that it assumes a pivotal role in the pressure hull's design.

There are various structural forms of observation windows, with three basic types being prevalent, including flat-circular shaped, frustum shaped, and spherical-sector shaped [3]. The observation windows of deep-sea manned submersibles in service are predominantly frustum-shaped structures. At present, the design of the observation window

relies on the Short-Term Critical Pressure (STCP) recommended by the ASME specification, although the observation window-design regulations for submersibles with a service depth exceeding 7000 m are artificially-set values, lacking a sufficient experimental basis. If the design is carried out strictly according to the parameters of the ASME specification, the observation window of the deep-sea submersible is hundreds of millimeters thick, and the metal wall-thickness transition section is very steep, which not only causes the weight to increase but also causes the strength of the metal part to decrease. Therefore, for deep-sea submersibles, whether it is necessary to design the window with such a large thickness under a high safety factor is a question worth re-evaluating, and some theoretical basis needs to be found. Strength and service life are two important indicators.

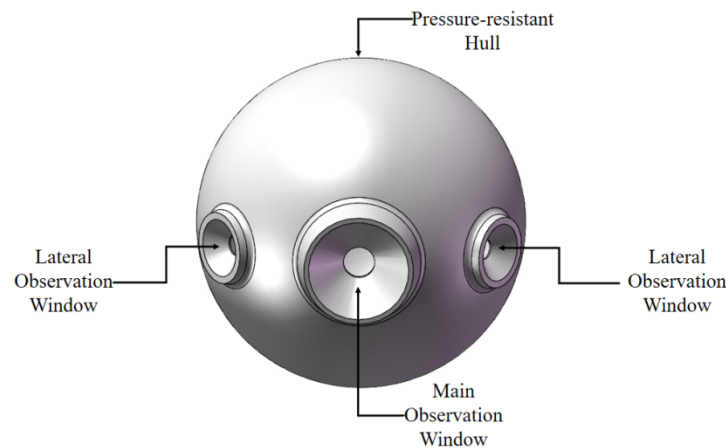


Figure 1. A main observation window and two lateral observation windows of the deep-sea manned submersible.

Generally, during the design phase, the strength is checked and the consideration of lifespan is insufficient. But there is a significant correlation between the two aspects. Many studies have mainly focused on strength analysis. For safety assessment, the design and analysis of PMMA windows necessitate the use of experimental methods as well as analytical and numerical analysis techniques. The empirical design method, although backed by numerous test results in the ASME specification, is deemed insufficient. Therefore, there is a growing emphasis on the research of analytical design methods. Yue and Tian [4] utilized the cone angle, thickness, and contact boundary-friction coefficient of the observation window as fundamental parameters to derive the stress state of frustum-shaped observation windows of various sizes, and optimized the structure form. Through finite element analysis and experimental research, the influence of parameters such as temperature, material nonlinearity, and others on the observation window is thoroughly discussed [5]. Zhu et al. [6] investigated the strength and stability of pressure-resistant shells featuring three different observation windows using theoretical and numerical methods. Through finite element analysis of the viewport window, Wang et al. [7] provided a precise calculation formula for the axial displacement of the PMMA observation window with varying thickness–diameter ratios under variable pressure and holding time. Du et al. [2] completed a study on the stress and deformation properties of thick tapered windows and compared them with experimental data and some existing data to discuss in depth the failure causes and design criteria of observation windows. Pranesh et al. [8,9] investigated the behavior of the observation window at its corner through numerical analysis and optimized the structure by using the fillet radius method and the biological growth method. Du et al. [10] conducted structural analysis and coordination research on the cone-edge spherical fan-shaped observation window, ultimately determining its optimal cone angle. Du et al. [11] further analyzed the local strength and coordination of the conical spherical-sector observation window by the ABAQUS contact finite element method, discussed the stress-concentration factor and displacement deformation under different cone angles, and

obtained the optimized cone angle design. Zhao et al. [12] explored two failure criteria for the observation window and conducted a numerical analysis to determine the initial failure pressure and failure position, which provided a reference for the design of a reasonable safety factor. Li et al. [13] employed a viscoelastic damage model to predict the viscoelastic behavior of the PMMA observation window through the entire operational process at varying water depths. Liu et al. [14] examined the creep and damage behavior of the PMMA observation window under constant seawater pressure and analyzed its creep-fatigue life using finite element analysis. Li et al. [15] proposed an evaluation method of stress accumulation and recovery of observation windows based on polarization imaging, which can provide new possibilities for stress detection of observation windows. Du et al. [16] analyzed the relaxation behavior of a multi-parameter PMMA observation window through an improved stress relaxation model and found that the numerical calculation outcomes closely aligned with experimental findings. Using the temperature dependent time-hardening creep model, He et al. [17] carried out a series of finite element analyses on the observation window, offering a method for analyzing and designing the window's creep behavior. Zheng et al. [18] characterized and measured the defects of the observation window, and gave the stress, strain and displacement distribution of the observation window glass during the hydrostatic external pressure test. Combined with the defect characteristics, the mechanism of the defects and the relationship between these types of defects were preliminarily explained. Hu et al. [19] determined the constitutive model of PMMA material by combining the relaxation curve of PMMA material compression, and studied the influence of geometric size on the viscoelastic response of the structure, as well as the response characteristics under different loading rates and friction coefficients. Liu and Li [20] proposed a damage potential function to derive the rate of the second-order damage tensor, and studied the creep behavior of the PMMA observation window under constant water pressure. Christodoulou and Kermanidis [21] used the concepts of local strain and fracture mechanics to evaluate the fatigue crack-initiation life at the root of a V-notch. The finite element method was used to determine the local stress-strain response at the root of the notch. Llavori et al. [22] proposed a numerical calculation method for the joint problem of fretting wear and fretting fatigue, which can study the interaction between crack and fretting contact and wear in detail. Wang et al. [23] established a calculation model of fatigue crack-initiation size caused by symmetrical cyclic-torsional alternating stress under low strain, and estimated the crack initiation size of the component.

Currently, much of the research is concentrated on the analysis of stress, creep deformation, and structural design of the observation window. However, the effects of large-thickness design specifications and the service life due to damage are often overlooked. The discussion on design safety factor is, accordingly, insufficient. At present, it is difficult to fully grasp the performance dispersion of the observation window through sufficient tests. The practice of solely increasing thickness to artificially enhance the safety factor for ensuring safety is not conducive to the overall performance optimization of the submersible. Moreover, it does not fundamentally address the safety issue. In this paper, the lifespan variation tendency of the windows under the effects of thickness associated with the safety factor will be explored, as well as taking the friction factor and transition arc diameter into account, aiming at providing some basis for whether the safety factor can be reasonably reduced. A series of designs beyond ASME specifications is undertaken based on reducing the thickness-to-diameter ratio of the observation window. Through the utilization of a damage model, finite element analysis is conducted on observation windows with varying thicknesses to investigate the damage evolution process and fatigue crack-initiation life. This study lays the groundwork for a deeper understanding of the observation window lifespan in service, with implications for enhancing safety assessments of existing submersibles and the design and manufacturing of underwater observation windows.

2. Material and Structures

2.1. Material Properties

The key factor for safety design is to select the appropriate observation window material to meet the requirements of both the necessary strength reserve and the observation range. PMMA is a synthetic transparent material renowned for its exceptional properties. It boasts high transparency and ease of machining, making it a favored choice for observation window manufacturing. The specific material performance parameters for testing are presented in Table 1.

Table 1. Main property parameters of PMMA.

Property	Value
Elastic modulus, E /MPa	3100
Tensile strength, σ_b /MPa	80.3
Yield strength, σ_y /MPa	78
Poisson's ratio, ν	0.36
Density, g/cm^3	1.19
Transmittance, %	91.43

2.2. Structures under Different Design Safety Factors

2.2.1. Design in Accordance with ASME Specification

The frustum-shaped structure emerges as the predominant design for observation windows in submersibles [24]. The small opening structure of the frustum-shaped observation window has minimal impact on the structural strength and stability of the manned cabin. In the presence of deep-sea hydrostatic pressure, the sealing performance of the conical contact surface exhibits greater stability and reliability when compared to a planar surface. The contact area between the window and the cone of the window seat is large, and the extrusion deformation of the observation window is small. Furthermore, stress distribution along the contact surface direction is more uniform, primarily comprising compressive stress. Additionally, observers can enjoy a clear and expansive field of view when positioned close to the observation window, as depicted in Figure 2.

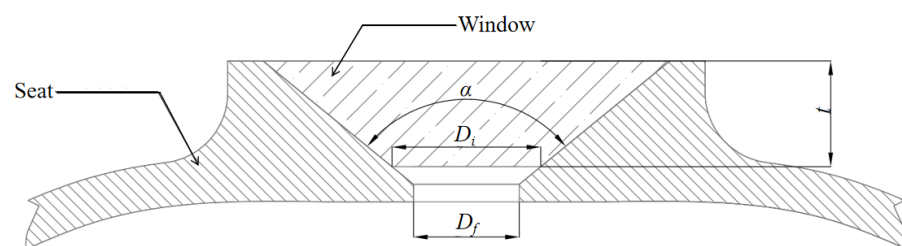


Figure 2. Frustum-shaped observation window.

D_i , D_f , t , and α are utilized to denote the inner diameter, outer diameter, thickness, and cone inclination of the observation window, respectively. In the present study, an observation window structure model suitable for depths of about eleven thousand meters (full-ocean-depth condition, with water pressure of 115 MPa) is firstly designed based on the ASME specification. Subsequently, adhering to the technical requirements for the development of full-ocean-depth manned submersibles, two types of observation windows with outer diameters (D_f) of 200 mm and 120 mm are typically designed. As per the ASME specification [3], the structural parameters of the observation window operating under a pressure of 115 MPa must meet the following criteria:

$$\alpha = 90^\circ \quad (1)$$

$$D_i / D_f = 1.26 \quad (2)$$

$$t / D_i = 1.6 \quad (3)$$

In the deep-sea environment, the high pressure exerted on the manned submersible's cabin causes the PMMA observation window to undergo axial displacement, ranging from several millimeters to even dozens of millimeters. When designing the observation window, a specific space is typically reserved at its bottom. The dimensions of this reserved space are determined by the maximum displacement anticipated during service. Additionally, this space directly impacts the weight and safety of the manned cabin. The bottom window seat of the observation window with an outer diameter of 200 mm is reserved for 15 mm, while the bottom window seat of the observation window with an outer diameter of 120 mm is reserved for 10 mm, to fulfill usage requirements. This implies that the corresponding inner diameters are 230 mm and 140 mm, respectively. Therefore, when the inner diameter of the PMMA observation window is 200 mm, the thickness of the observation window is 368 mm. Similarly, the observation window thickness is 225 mm when the outer diameter is 120 mm. The specific structure of the observation window is shown in Figure 2.

2.2.2. Design with Decreasing Safety Factor

By increasing the thickness of the observation window, the design safety factor is artificially enhanced to ensure safety. However, this approach leads to a steep increase in the metal shell thickness in the window transition section. Consequently, this increases the structural weight, which is detrimental to the overall performance optimization of the submersible. This design concept of employing large-thickness observation windows does not fundamentally address the safety issue. The design process should fully consider the creep deformation of the observation window and the deformation coordination between the viewport window and the window seat in the deep-sea hydrostatic pressure environment, to avoid the sealing failure caused by large deformation or the instability, or even failure, of the observation window structure. Therefore, it is decided to adopt the super-standard direct design concept, put forward a reasonable design safety factor, and use a safety assessment method for the observation window. The cone angle is guaranteed to be 90° , and the inner diameters are 230 mm and 140 mm. Four groups of observation window sizes with different thickness-to-diameter ratios are considered, as illustrated in Tables 2 and 3.

Table 2. The size of the frustum-shaped observation window with different thickness-to-diameter ratios (inner diameter of 230 mm).

Cone Angle ($2\alpha/^\circ$)	Thickness (t/mm)	Inner Diameter (D_i/mm)	Thickness-to-Diameter Ratios (t/D_i)
90	368	230	1.6
90	322	230	1.4
90	276	230	1.2
90	230	230	1.0

Table 3. The size of the frustum-shaped observation window with different thickness-to-diameter ratios (inner diameter of 140 mm).

Cone Angle ($2\alpha/^\circ$)	Thickness (t/mm)	Inner Diameter (D_i/mm)	Thickness-to-Diameter Ratios (t/D_i)
90	225	140	1.6
90	196	140	1.4
90	168	140	1.2
90	140	140	1.0

The size of another observation window is designed. The inner diameter is $D_i = 130$ mm; the cone angle is $\alpha = 90^\circ$, and the thickness is 153 mm. An arc transition with a radius of 2000 mm is applied at the lower part of the frustum. The model is mounted onto the window seat using the assembly method specified for the observation window. The inner circumference of the window seat is sealed with the low-pressure base to uphold a low-pressure environment.

3. Damage Evolution Model

Under the deep-sea hydrostatic pressure, the actual deformation of the observation window includes extrusion deformation and creep deformation. During the load-sustaining stage under prolonged high-stress level, the creep phenomenon of PMMA observation windows becomes particularly pronounced. PMMA exhibits typical viscoelastic behavior, differing from metal materials in its heightened sensitivity to environmental factors and external loads. Consequently, a damage model tailored to the viscoelastic properties of PMMA material is developed [25]. The viscoelasticity is represented by the spring-damper ternary viscoelastic model, as depicted in Figure 3.

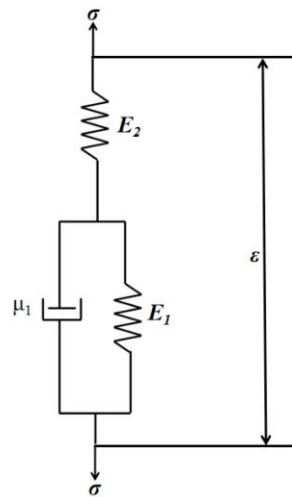


Figure 3. The three-element viscoelastic model.

The three-element viscoelastic model is expressed as follows:

$$\sigma = E_1 \epsilon_1 + \mu_1 \dot{\epsilon}_1 \quad (4)$$

$$\sigma = E_2 \epsilon_2 \quad (5)$$

$$\epsilon = \epsilon_1 + \epsilon_2 \quad (6)$$

where Equation (4) E_1 is the instantaneous elastic modulus and Equation (5) E_2 is the time-delay elastic modulus. Among them, ϵ_1 is the elastic strain, ϵ_2 is the time-delay elastic strain, μ_1 is the viscoelastic coefficient, and $\dot{\epsilon}_1$ is the viscoelastic strain rate. Next,

$$\sigma = E_1(\epsilon - \epsilon_2) + \mu_1(\dot{\epsilon} - \dot{\epsilon}_2) = E_1\left(\epsilon - \frac{\sigma}{E_2}\right) + \mu_1\left(\dot{\epsilon} - \frac{\dot{\sigma}}{E_2}\right) \quad (7)$$

$$\left(1 + \frac{E_1}{E_2}\right)\sigma + \frac{\mu_1}{E_2}\dot{\sigma} = E_1\epsilon + \mu_1\dot{\epsilon} \quad (8)$$

Equation (8) multiplied by E_1 and divided by $E_1 + E_2$ can result in the following form:

$$\sigma + \frac{\mu_1}{E_1 + E_2}\dot{\sigma} = \frac{1}{\frac{1}{E_1} + \frac{1}{E_2}}\epsilon + \frac{\mu_1}{1 + \frac{E_1}{E_2}}\dot{\epsilon} \quad (9)$$

where $\dot{\sigma}$ and $\dot{\epsilon}$ are the time change rates of stress and strain.

The damage to materials or structures arises from the propagation of micro-damage, constituting an irreversible process of energy dissipation. Typically, the damage variable D is employed to depict the evolution process of macro-damage. Currently, the prevailing method involves assessing damage by monitoring the degradation of Young's modulus [26].

Under cyclic loading, the degradation of mechanical properties of isotropic materials can be manifested as stiffness degradation. The damage variable D is defined as

$$D = 1 - \frac{E_D}{E} \quad (10)$$

where E represents the elastic modulus of the undamaged material, MPa; E_D is the equivalent elastic modulus with damage, MPa; and the variation range of D is 0~1.

Under uniaxial stress, the elastic specific-strain energy of the damaged element can be expressed as the following formula:

$$W_D = \frac{1}{2E_D}\sigma^2 = \frac{1}{2E(1-D)}\sigma^2 \quad (11)$$

where σ is the stress, E is the elastic modulus, and D is the damage value.

At this time, the damaged driving force of the material can be expressed as follows:

$$Y = -\frac{\partial W_D}{\partial D} = \frac{1}{2E(1-D)^2}\sigma^2 = \frac{W_D}{1-D} \quad (12)$$

According to the law of thermodynamics, the damage evolution equation of materials under various conditions can be expressed as the following formula [25]:

$$\frac{dD}{dN} = a \left[\frac{(Y_{\max}^{1/2} - Y_{th}^{1/2})}{1-D} \right]^b \quad (13)$$

$$\begin{cases} Y_{\max} = \frac{\sigma_{\max}^2}{2E(1-D)^2} \\ Y_{th} = \frac{\sigma_{th}^2}{2E(1-D)^2} \end{cases} \quad (14)$$

Among them, a , b are the material parameters of PMMA; $Y_{\max}$, and Y_{th} are the maximum damage driving force and the damage driving-force threshold; N is the number of cycles; D is the damage value; E is the elastic modulus; $\sigma_{\max}$ is the maximum stress; and σ_{th} is the stress threshold. The damage evolution-equation parameters of the PMMA material are shown in Table 4 [25].

Table 4. Fatigue parameters for simulation.

a	b	σ_{th} (MPa)
1.654×10^{-3}	2.039	52.98

4. Fatigue Life Assessment

4.1. Observation Window Structure and Finite Element-Analysis Process

The design of PMMA observation windows for manned submersibles primarily relies on standard design practices and model testing of typical structural forms. The understanding of the internal response state of the observation window is not clear enough, and the design method of the observation window based on analysis is lacking, which limits the design of the observation window of the manned submersible. Finite element analysis technology has been found to have extensive application in marine engineering structure design and safety analysis. Utilizing finite element analysis to compute the response state of manned submersible observation windows under ultra-high water pressure aids in enhancing our comprehension of stress distribution and local stress-concentration phenomena within the observation window. The application of an eight-node linear hexahedron element in ABAQUS 2022 software to create a three-dimensional model is shown in Figure 4. In the finite element calculations, the material of the window seat is defined

as titanium alloy, with an elastic modulus of 124,000 MPa and a Poisson's ratio of 0.3, consistent with the material properties of the actual manned submersible pressure cabin. In the deep-sea high-pressure environment, lubricating materials such as silicone grease are injected between the observation window seat and the PMMA window, but the sliding friction still exists, which will produce a certain amount of friction stress. The boundary conditions encompass the friction coefficient governing the contact between the viewport window and the window seat. Furthermore, a fixed constraint is imposed at the bottom of the window seat to replicate the support offered by the pressure cabin. The external load is then applied to the outer surface of both the viewport window and the window seat, as shown in Figure 4. In the deep-sea environment, the actual external seawater pressure is about 113.8 MPa under 11,000 m below the surface. However, for enhanced safety, the design pressure is set to 115 MPa for analysis purposes. As shown in Figure 5, the mesh convergence analyses of the observation window and the window seat are performed, respectively. The mesh size of the observation window is set to 20 mm, while the mesh size of the window seat is configured to 25 mm. Assuming that the submersible reaches the design working pressure every time for conservative consideration, Figure 6 briefly describes the simplified trapezoidal loading history. To accurately simulate the actual load conditions, the user-defined DLOAD subroutine is used to simulate the real load conditions, allowing the adjustment of load holding-time settings and different load pressure settings. The numerical analysis and calculation are performed under the Windows 11 operating system. The CPU model is Intel (R) Core (TM) i7-12700H 2.30 GHz and the GPU model is NVIDIA RTX 3060.

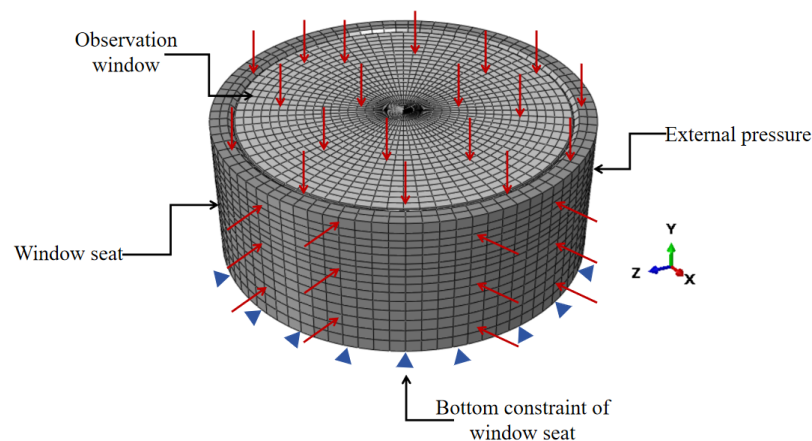


Figure 4. Finite element model of the cone-shaped observation window.

The fatigue cumulative-damage value is computed using the viscoelastic damage evolution model of PMMA material. The crack-initiation life of the structure is identified when the damage value reaches $D = 1$. By considering $D = 1$ at the critical location as the failure criterion, the safety of the observation window can be assessed. The flow chart depicting the finite element numerical simulation of the fatigue crack-initiation life of the viewport window is presented in Figure 7. The PMMA material constants are first input into ABAQUS as initial conditions, followed by the calculation of stress distribution within the observation window using the finite element method. In the initial increment step, the material's elastic modulus is set to E . Subsequently, after the first increment, the cumulative damage value D for each element is computed, along with obtaining the stress information. With each increment step, the material stiffness gradually deteriorates, and the constitutive relationship is continuously adjusted based on the degraded stiffness matrix, to compute the stress–strain field. The finite element calculation terminates once the damage value D reaches 1, indicating material failure and the appearance of an initial crack on the surface. At this point, the current fatigue life is extracted.

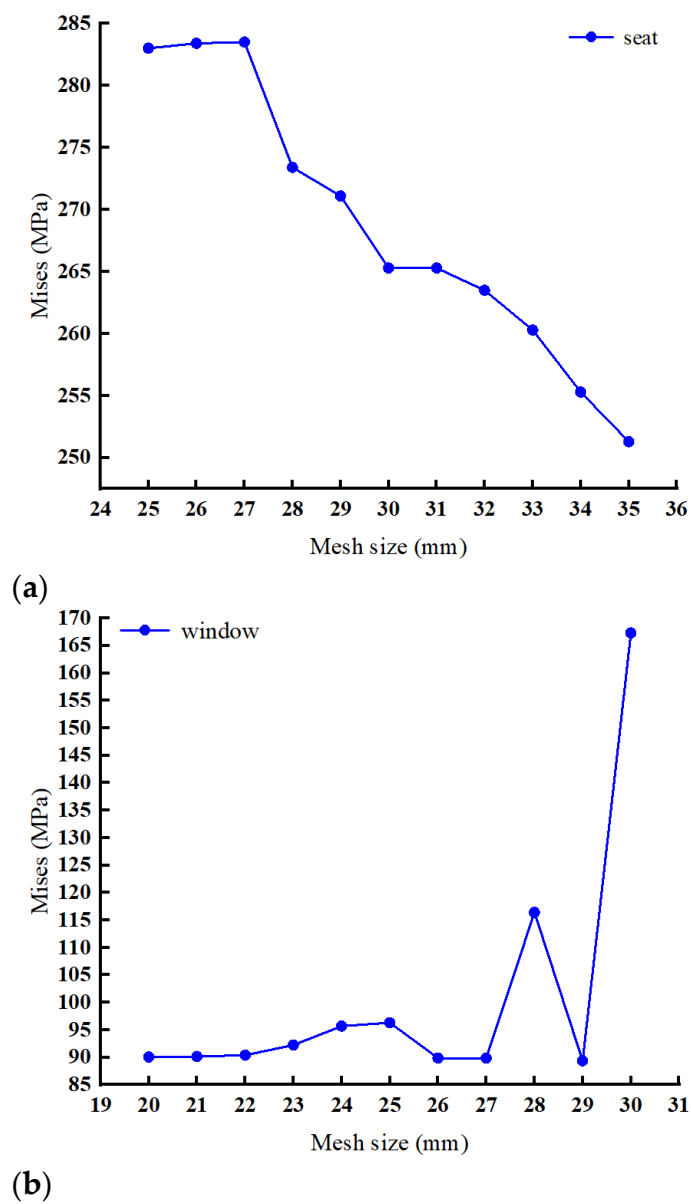


Figure 5. Mesh convergence analysis results. (a) The window seat; (b) the observation window.

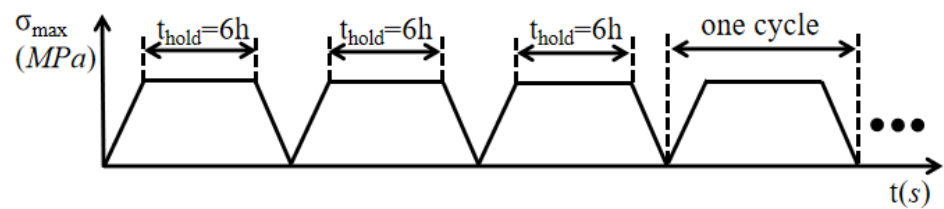


Figure 6. The simplified loading history.

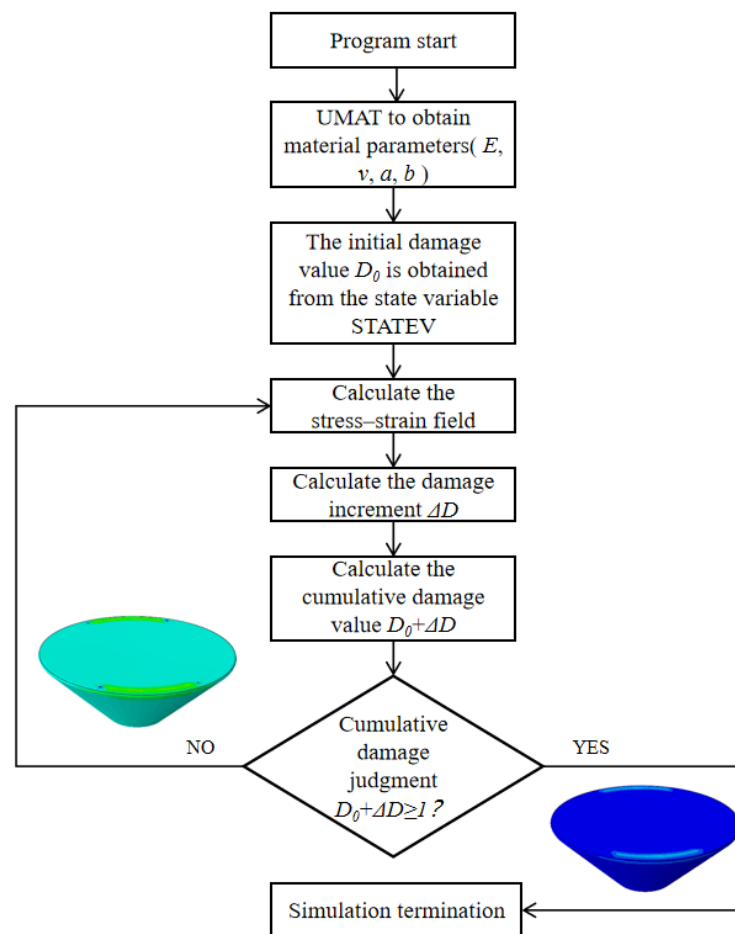


Figure 7. Finite element-calculation flow chart.

4.2. Life Assessment of Observation Windows

4.2.1. Life Assessment of Observation Window Designed by ASME Specification

The fatigue failure of PMMA often starts from the craze, and the craze continues to grow and then the craze microfiber ruptures to form microcracks. The concatenation of microcracks produces large cracks or cavitations, resulting in the overall macroscopic fracture of the material. The test model is installed on the window seat with reference to the assembly method of the observation window. The displacement sensor is set inside the observation window model to measure the displacement of the center of the inner surface of the window. The pressing speed is not more than 4.5 MPa/min, and 5 MPa is pressed each time. Specific operations: (1) assemble window seat and base, paste the sensor; (2) put the test model into the pressure bucket and cover the pressure bucket cover; and (3) press according to the design state. The pressing speed is not more than 4.5 MPa/min, and each pressing is 5 MPa; wait for 2 min to press again, until 115 MPa, then read the sensor data from the computer. The specific pressure chamber and the tested window with strain gauges are shown in Figure 8. The fatigue crack-initiation life is calculated according to the size of the observation window designed according to the ASME specification in Section 2.2. A frustum-shaped observation window with a transition radius of $R = 2000$ mm is utilized for the numerical analysis. A uniform load of 115 MPa was applied to the exterior of the observation window with a friction coefficient of 0.1, and a fixed restraint was applied to the underside of the window seat. In both the finite element analysis and actual observation window tests, a significant fracture area has been identified near the sealing ring, with cracks exceeding 10 cm in length, as depicted in Figure 9. Figure 10 shows that the fatigue crack-initiation life of the observation window with an inner diameter of 230 mm, designed according to the ASME specification, is 1532 cycles. The initial crack occurs at the fillet

transition at the contact between the viewport window and the window seat, as well as on the outer surface of the observation window. The fatigue crack-initiation life of the observation window with an inner diameter of 140 mm, designed according to the ASME specification, is 2155 cycles. The initial crack occurs at the fillet transition of the contact between the upper surface of the observation window and the window seat, as shown in Figure 11.

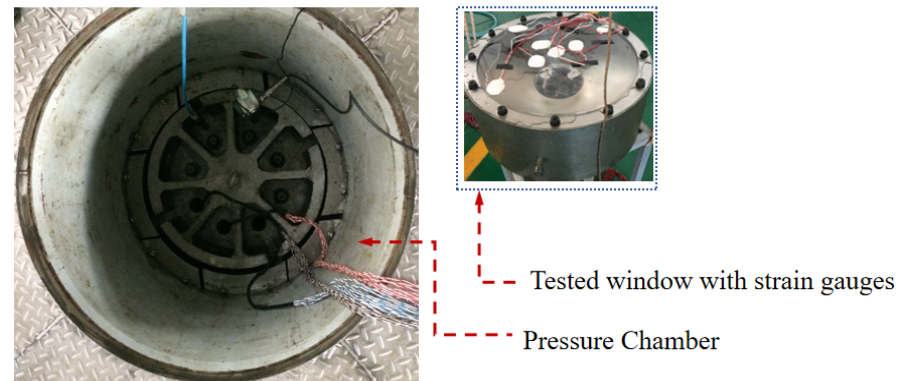


Figure 8. The pressure chamber and the tested window with strain gauges.

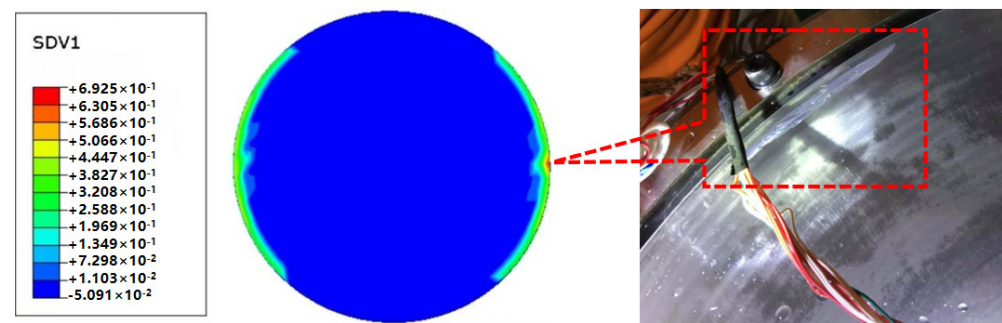


Figure 9. Finite element analysis and physical comparison diagram of observation-window crack.

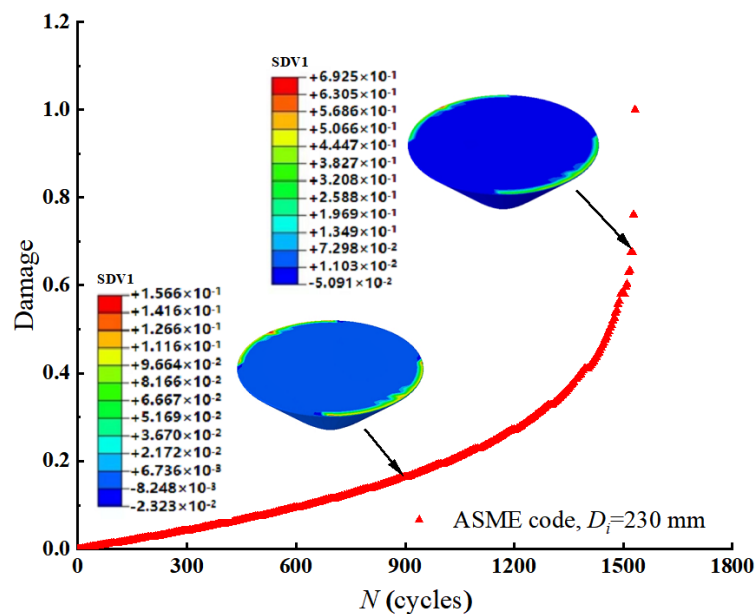


Figure 10. Fatigue crack-initiation life under ASME specification design ($D_i = 230$ mm).

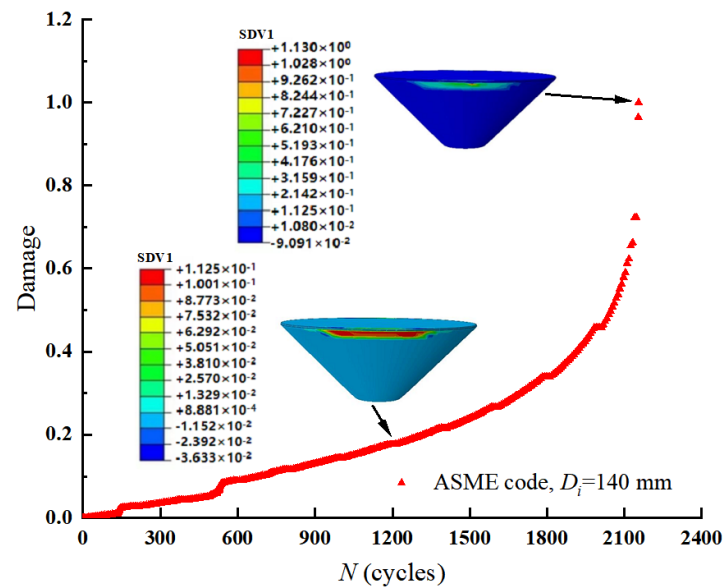


Figure 11. Fatigue crack-initiation life under ASME specification design ($D_i = 140$ mm).

The influence of the friction coefficient between the PMMA observation window and the window seat on the fatigue crack-initiation life under the condition of maintaining the load was analyzed by setting up two groups of conditions with different friction coefficients of 0.2 and 0.3. The calculation results are shown in Figures 12 and 13. The fatigue crack-initiation life of the observation window with an inner diameter of 230 mm is 1532 cycles, 1258 cycles, and 449 cycles, respectively, when the friction coefficient is 0.1, 0.2, and 0.3. The fatigue crack-initiation life of the observation window with an inner diameter of 140 mm at the friction coefficients of 0.1, 0.2, and 0.3 are 2155 cycles, 1459 cycles, and 653 cycles, respectively. The cloud diagram shows that different friction coefficients affect the fatigue crack-initiation life of the observation window. The larger the friction coefficient, the smaller the fatigue crack-initiation life. It can also be found that under different friction coefficients, the initial crack position of the observation window has also changed, from the transition fillet on the upper surface of the viewport window to the contact position between the transition arc and the seat, because the larger the friction coefficient, the stronger the constraint.

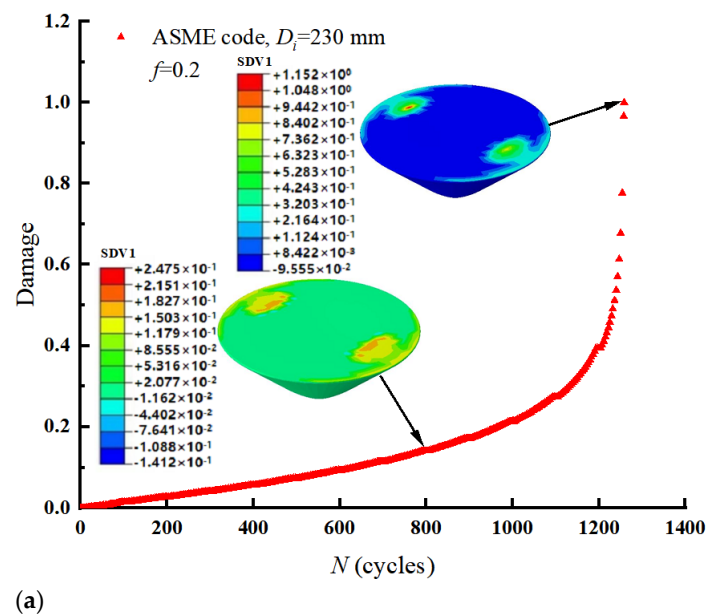
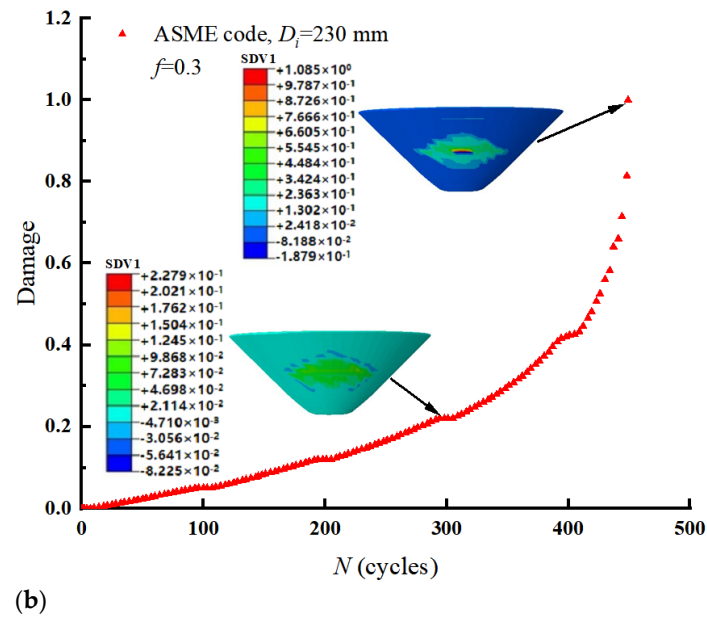
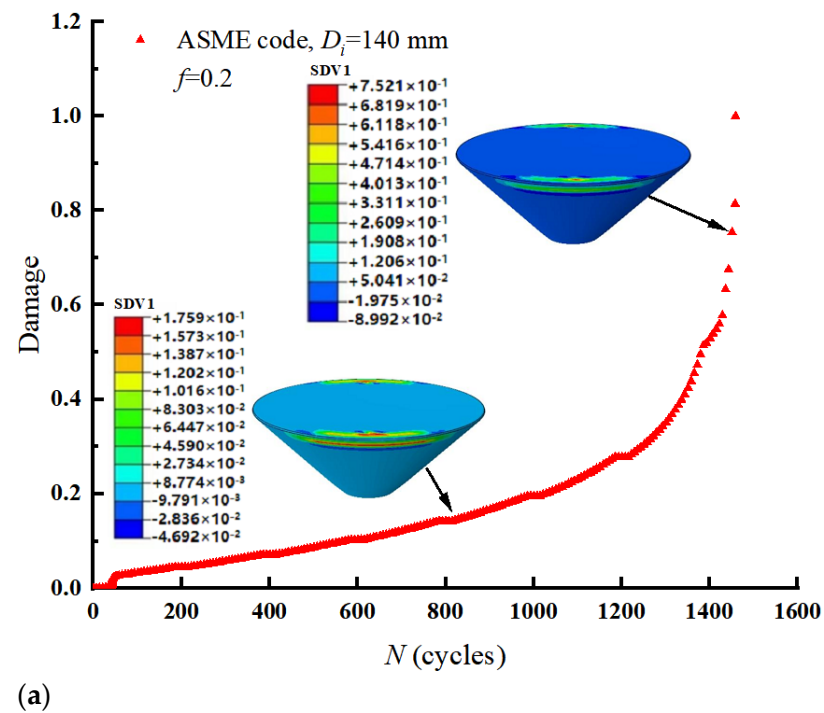


Figure 12. Cont.



(b)

Figure 12. (a) The crack-initiation life of the observation window (friction coefficient is 0.2, $D_i = 230$ mm); (b) The crack-initiation life of the observation window (friction coefficient is 0.3, $D_i = 230$ mm).



(a)

Figure 13. Cont.

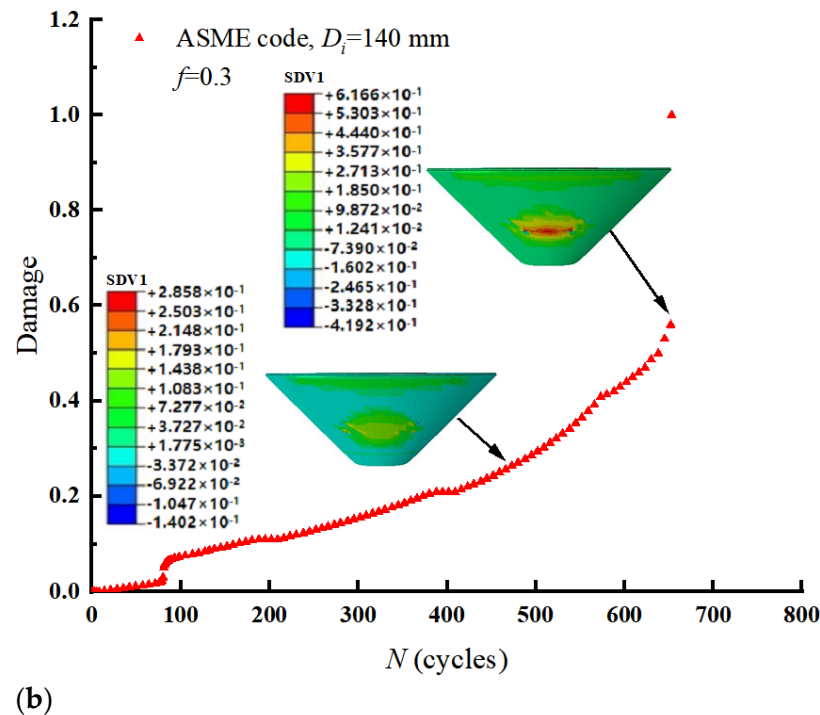
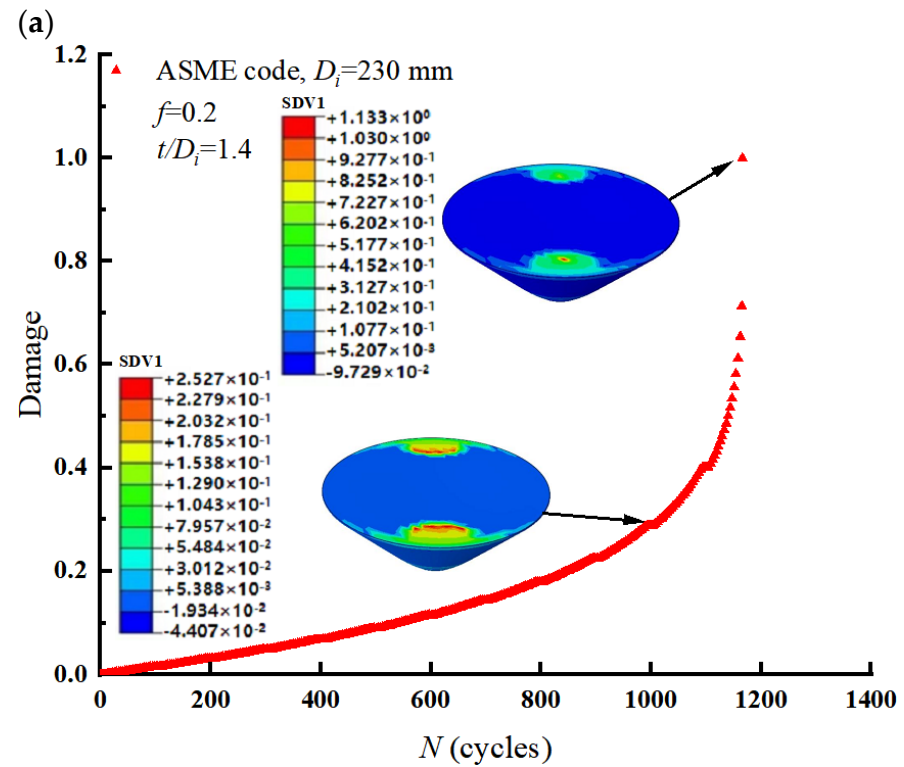
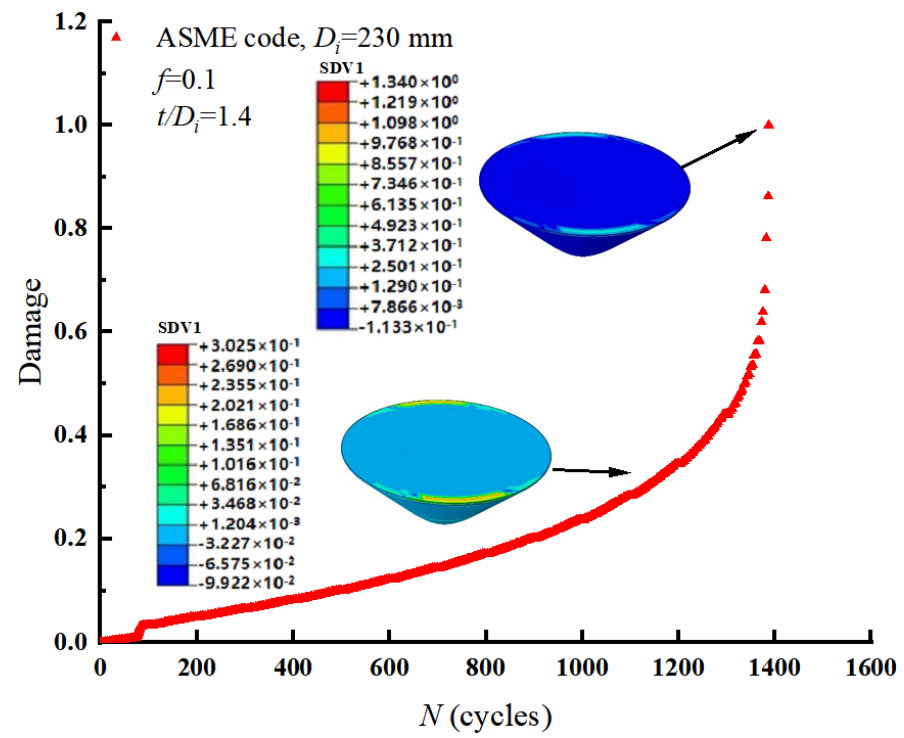


Figure 13. (a) The crack-initiation life of the observation window (friction coefficient is 0.2, $D_i = 140$ mm); (b) The crack-initiation life of the observation window (friction coefficient is 0.3, $D_i = 140$ mm).

4.2.2. Life Assessment of the Observation Window to Reduce the Safety Factor

In light of the excessive thickness of the observation windows as per the ASME specification, which could potentially compromise the strength of the metal components of the manned cabin and increase structural weight, a finite element analysis of the fatigue crack-initiation life of the observation window is conducted using reduced thickness based on the design dimensions outlined in Section 2.2. The cone angle is 90° ; the inner diameter is 230 mm, and the external load is 115 MPa. Three groups of observation windows with different thickness-to-diameter ratios (1.4, 1.2, 1.0) and different friction coefficients (0.1, 0.2, 0.3) are taken for analysis, as shown in Figures 14–16. Another group of finite element analyses, in addition to those of the observation window diameter, changed this measurement to 140 mm; the remaining analysis conditions are consistent with the above, as shown in Figures 17–19. The finite element analysis results of the fatigue crack-initiation life of the observation window under various thickness-to-diameter ratios and different friction coefficients are presented in Table 5. As the thickness-to-diameter ratio decreases and the friction coefficient increases, the fatigue crack-initiation life of the observation window decreases. Notably, particular attention should be given to the finite element calculation results obtained when the observation window thickness and inner diameter size are identical. When the ratio of thickness to diameter is 1, the crack-initiation life of the observation window structure with varying inner diameters is higher when the friction coefficient is 0.2 than that when the friction coefficient is 0.1. Based on the finite element calculation results, it can be concluded that, for observation window structures designed with a thickness-to-diameter ratio of 1 in real-world scenarios, a friction coefficient of 0.2 would be more favorable for long-term usage.



(b)

Figure 14. Cont.

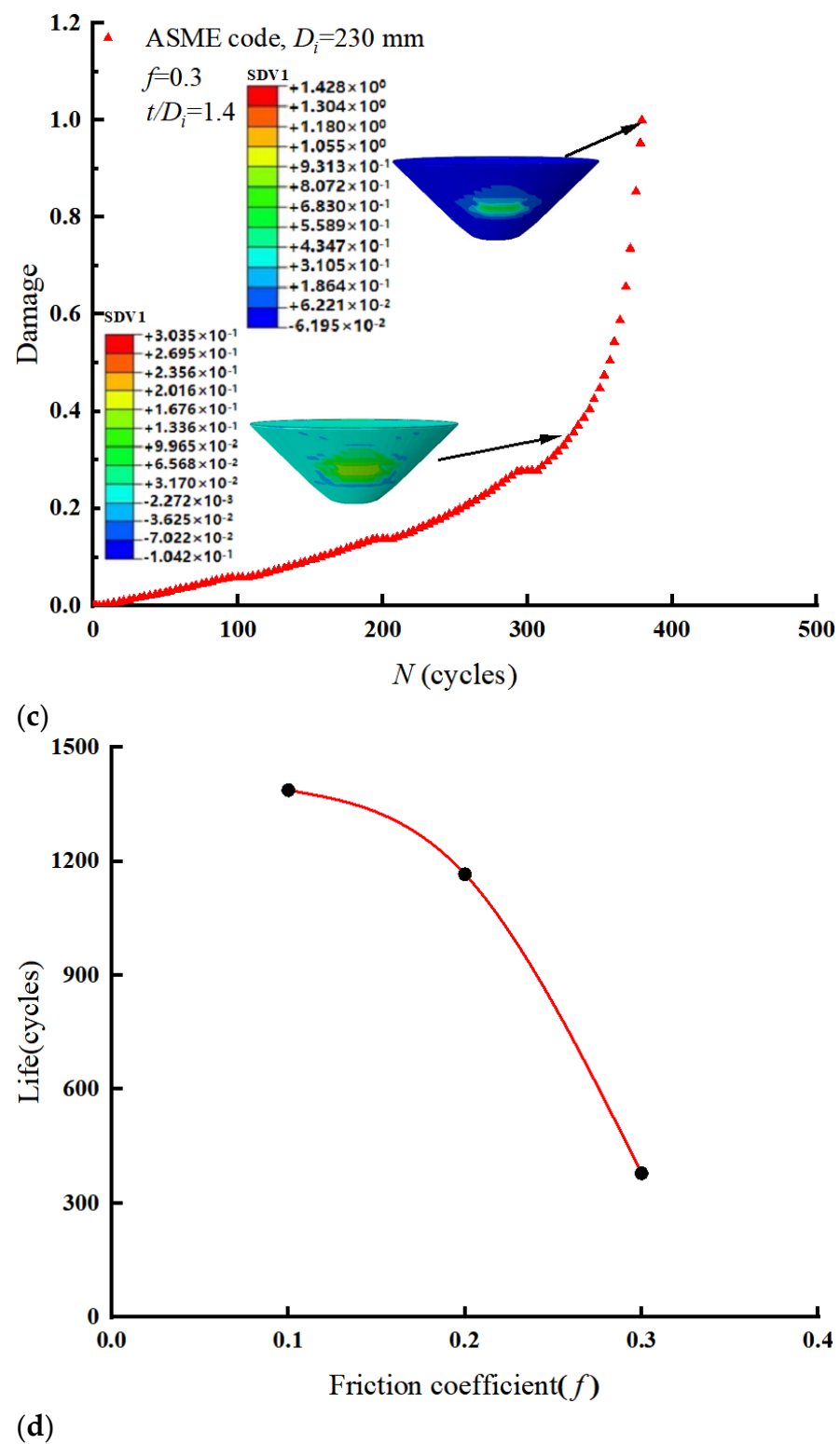
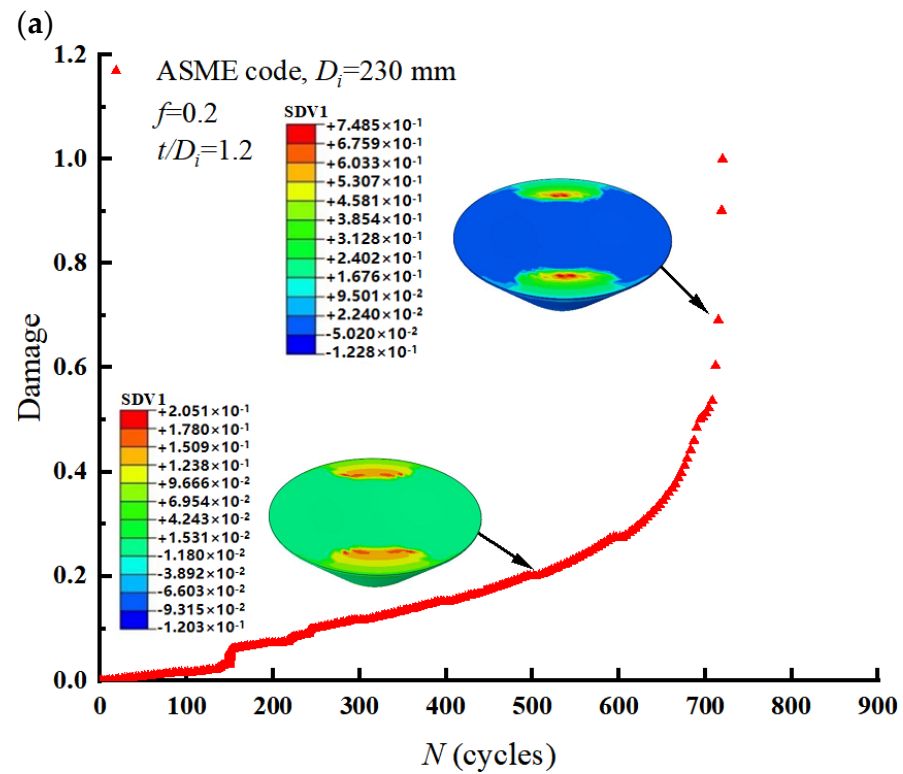
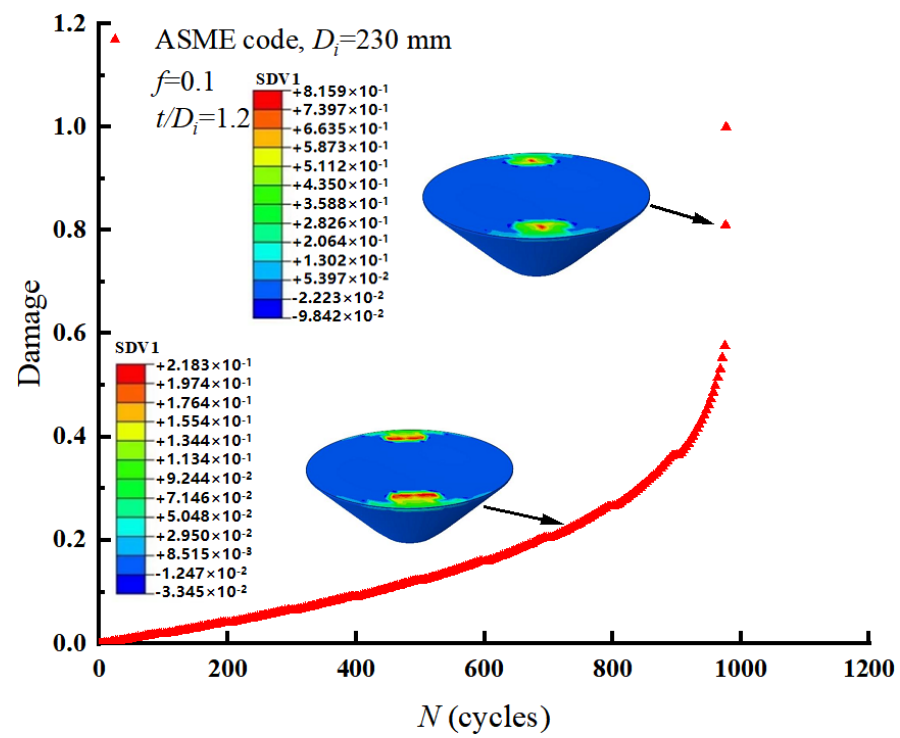


Figure 14. (a) The crack-initiation life of the observation window (friction coefficient is 0.1, $D_i = 230$ mm, $t/D_i = 1.4$); (b) the crack-initiation life of the observation window (friction coefficient is 0.2, $D_i = 230$ mm, $t/D_i = 1.4$); (c) the crack-initiation life of the observation window (friction coefficient is 0.3, $D_i = 230$ mm, $t/D_i = 1.4$); (d) life decreasing curve with increasing friction coefficient.



(b)

Figure 15. Cont.

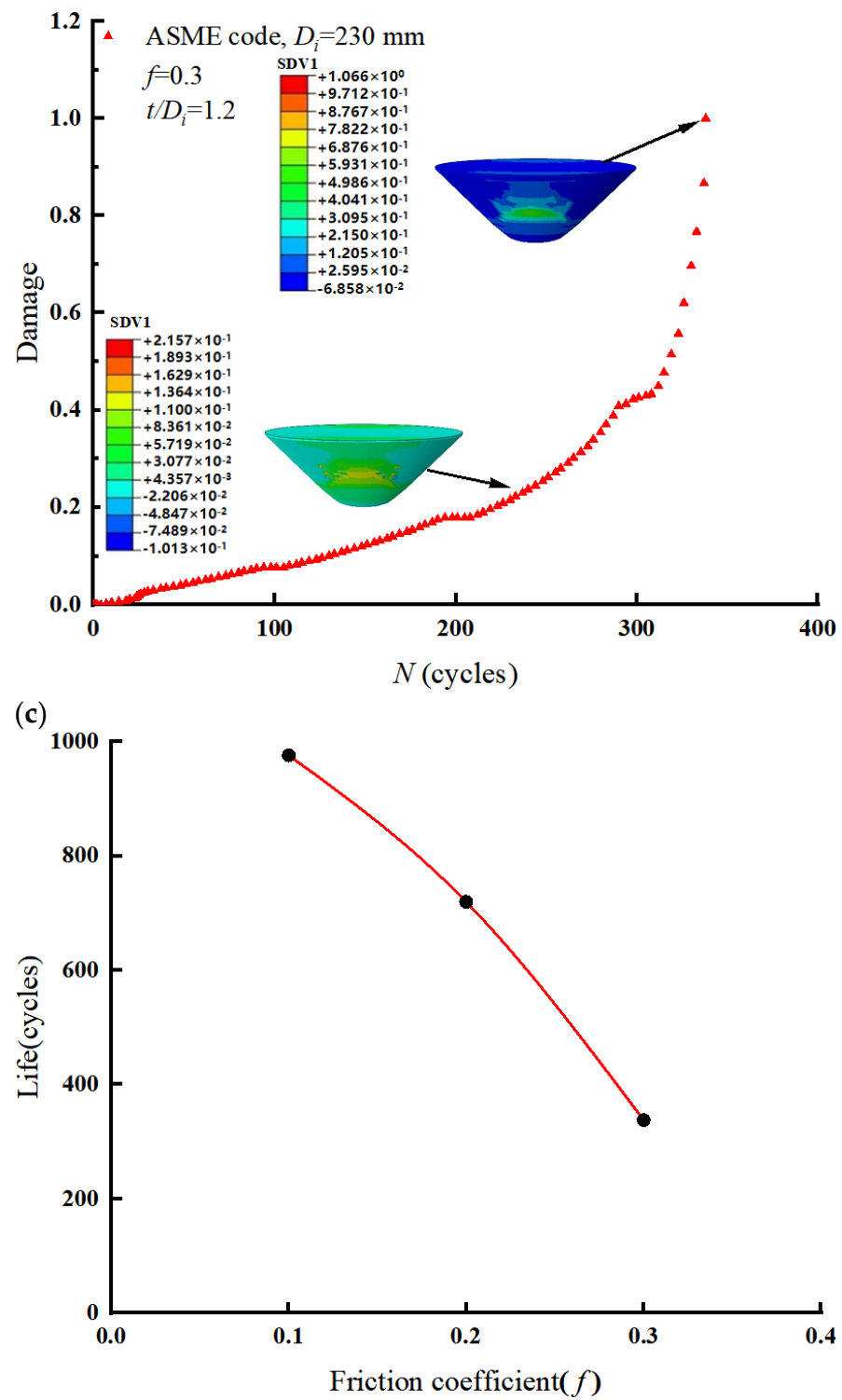
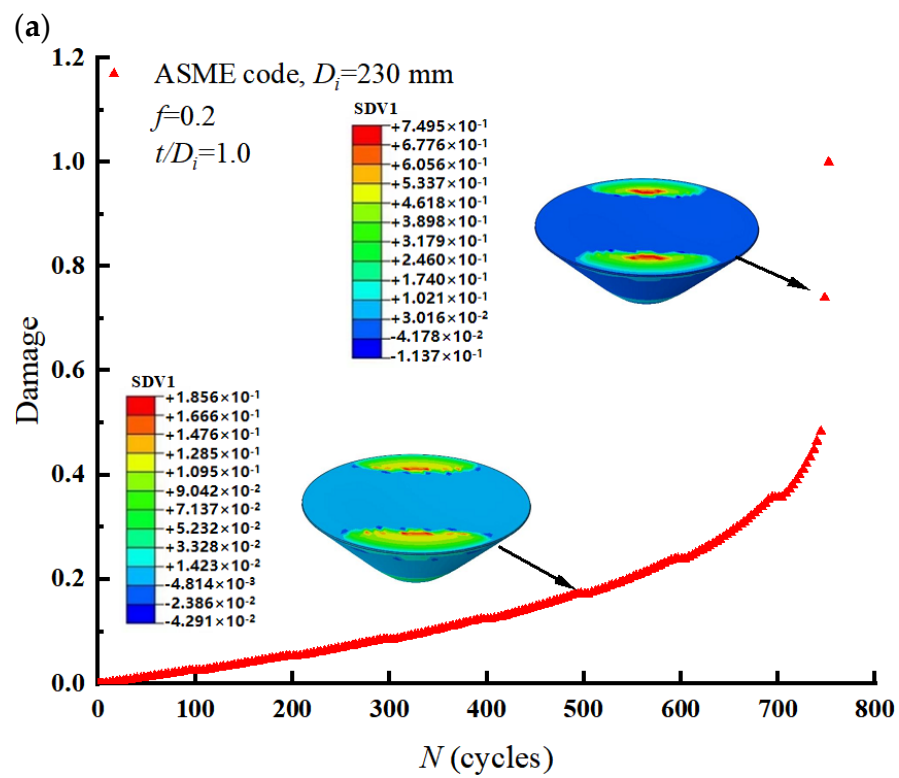
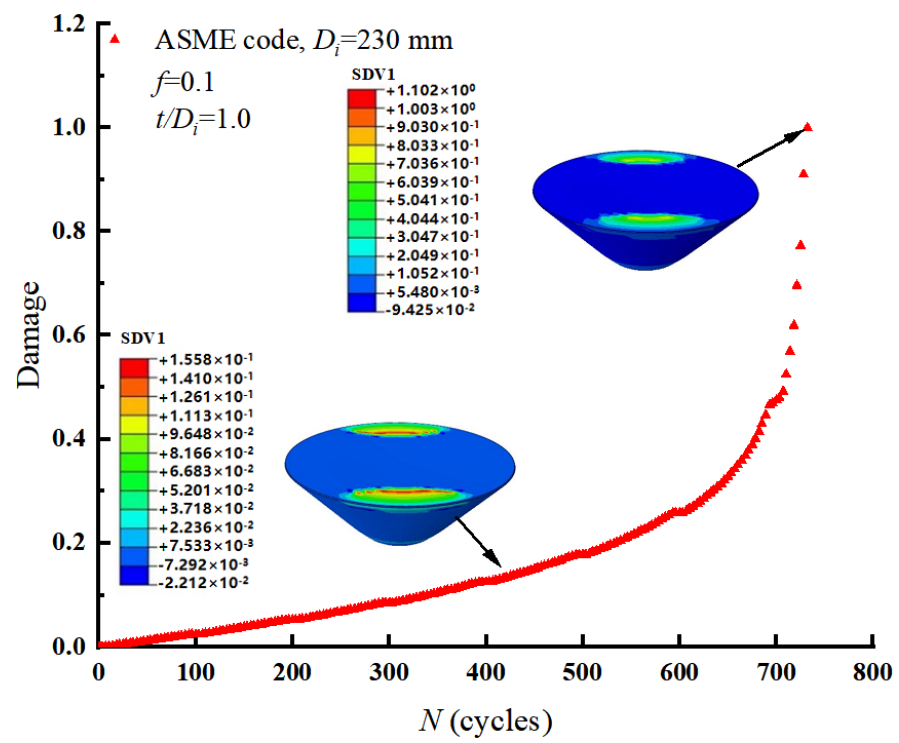
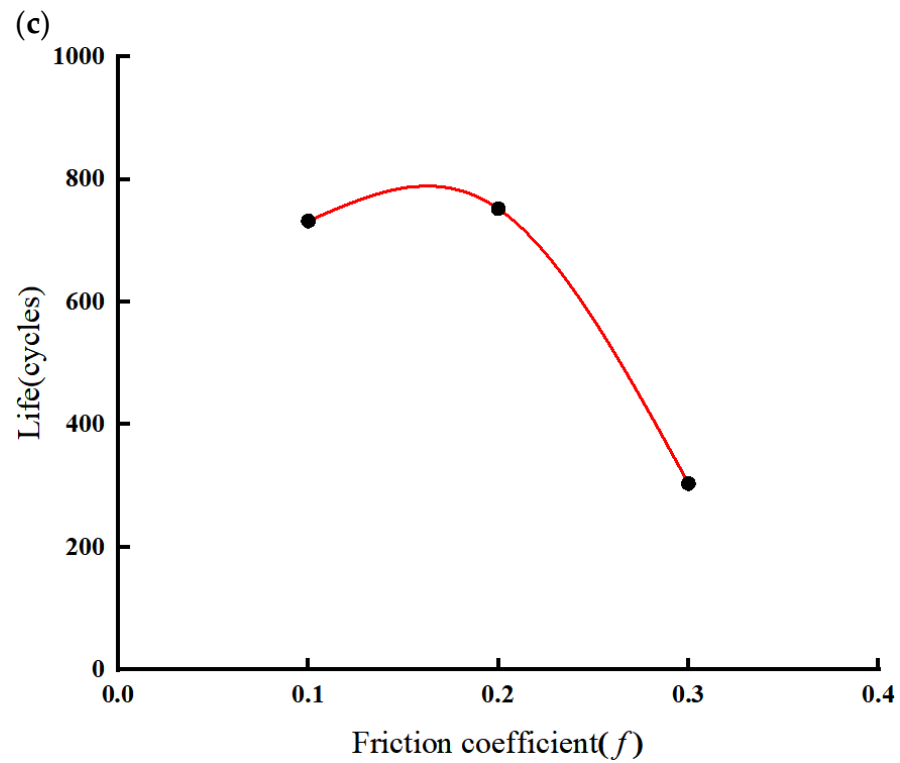
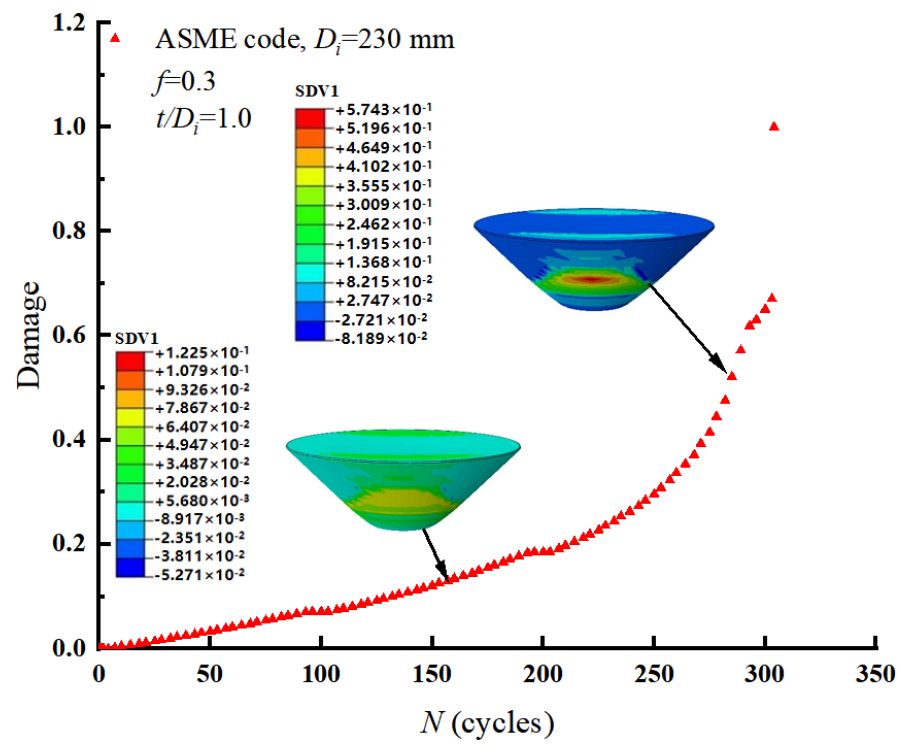


Figure 15. (a) The crack-initiation life of the observation window (friction coefficient is 0.1, $D_i = 230$ mm, $t/D_i = 1.2$); (b) the crack-initiation life of the observation window (friction coefficient is 0.2, $D_i = 230$ mm, $t/D_i = 1.2$); (c) the crack-initiation life of the observation window (friction coefficient is 0.3, $D_i = 230$ mm, $t/D_i = 1.2$); (d) life decreasing curve with increasing friction coefficient.



(b)

Figure 16. Cont.



(d)

Figure 16. (a) The crack-initiation life of the observation window (friction coefficient is 0.1, $D_i = 230$ mm, $t/D_i = 1.0$); (b) the crack-initiation life of the observation window (friction coefficient is 0.2, $D_i = 230$ mm, $t/D_i = 1.0$); (c) the crack-initiation life of the observation window (friction coefficient is 0.3, $D_i = 230$ mm, $t/D_i = 1.0$); (d) life decreasing curve with increasing friction coefficient.

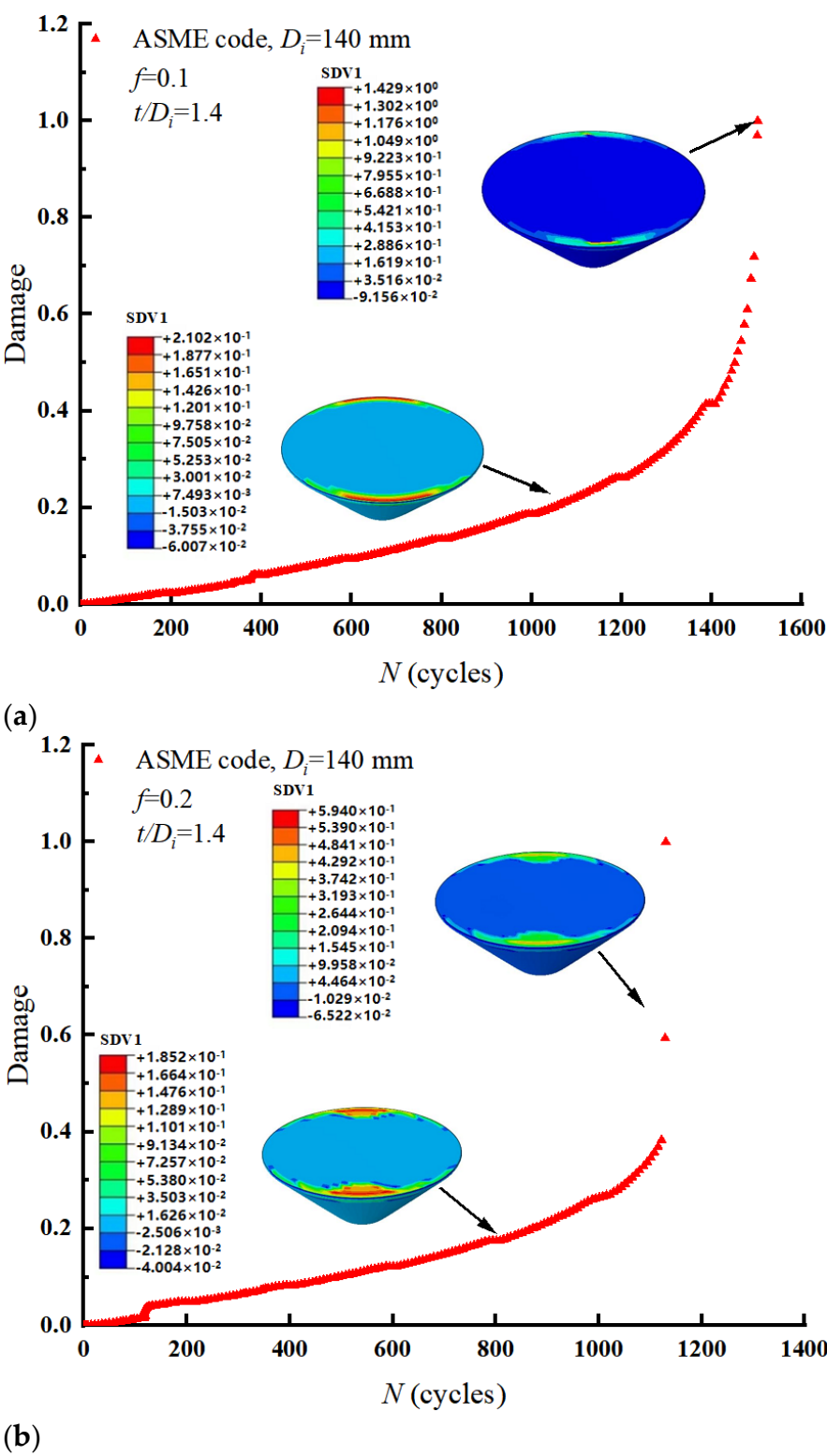


Figure 17. Cont.

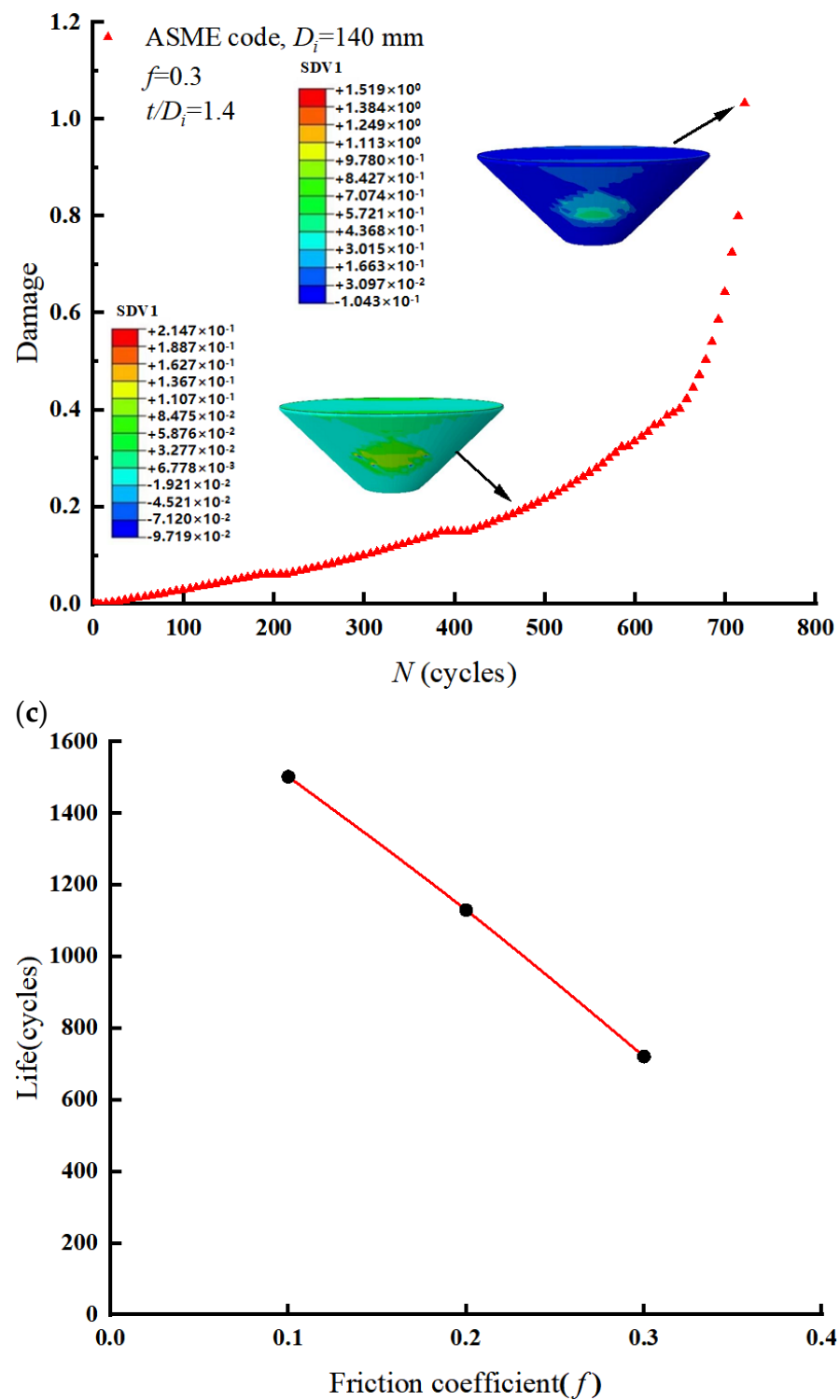
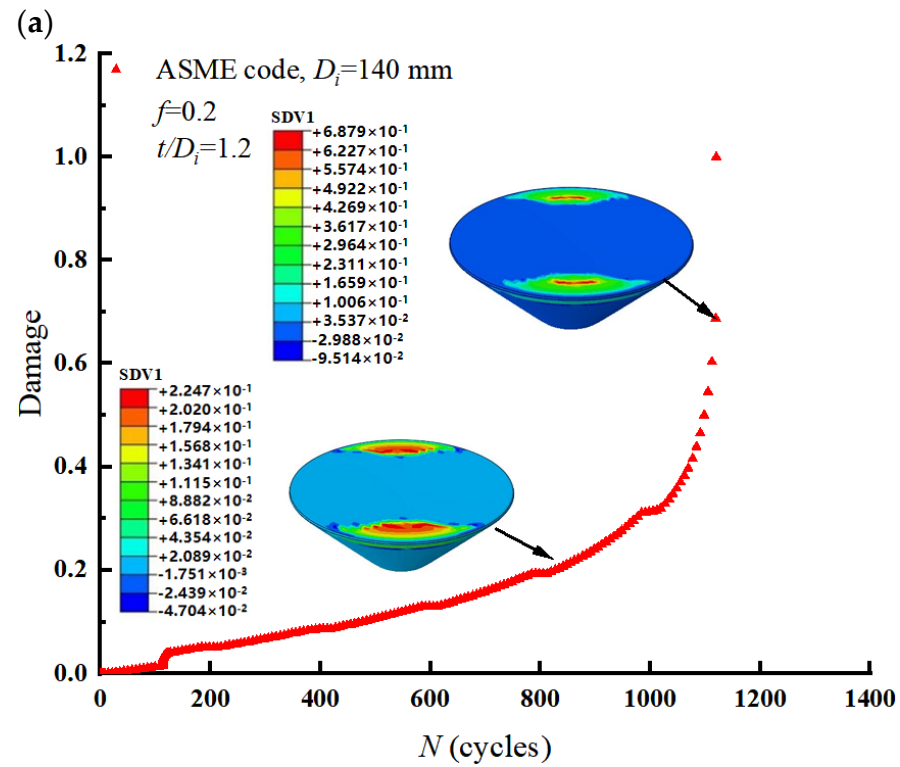
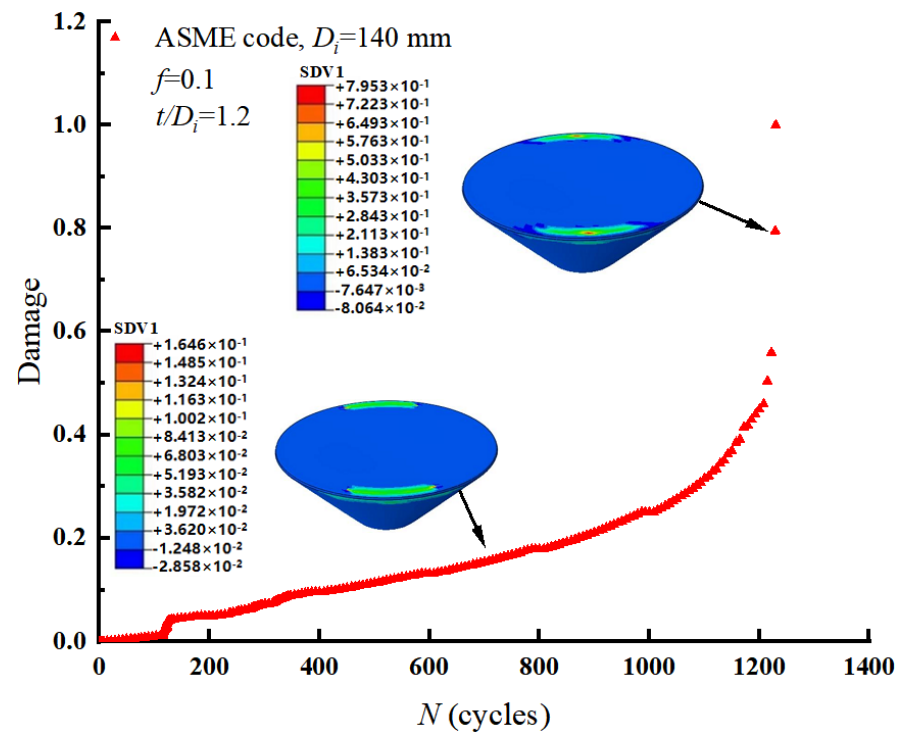


Figure 17. (a) The crack-initiation life of the observation window (friction coefficient is 0.1, $D_i = 140$ mm, $t/D_i = 1.4$); (b) the crack-initiation life of the observation window (friction coefficient is 0.2, $D_i = 140$ mm, $t/D_i = 1.4$); (c) the crack-initiation life of the observation window (friction coefficient is 0.3, $D_i = 140$ mm, $t/D_i = 1.4$); (d) life decreasing curve with increasing friction coefficient.



(b)

Figure 18. Cont.

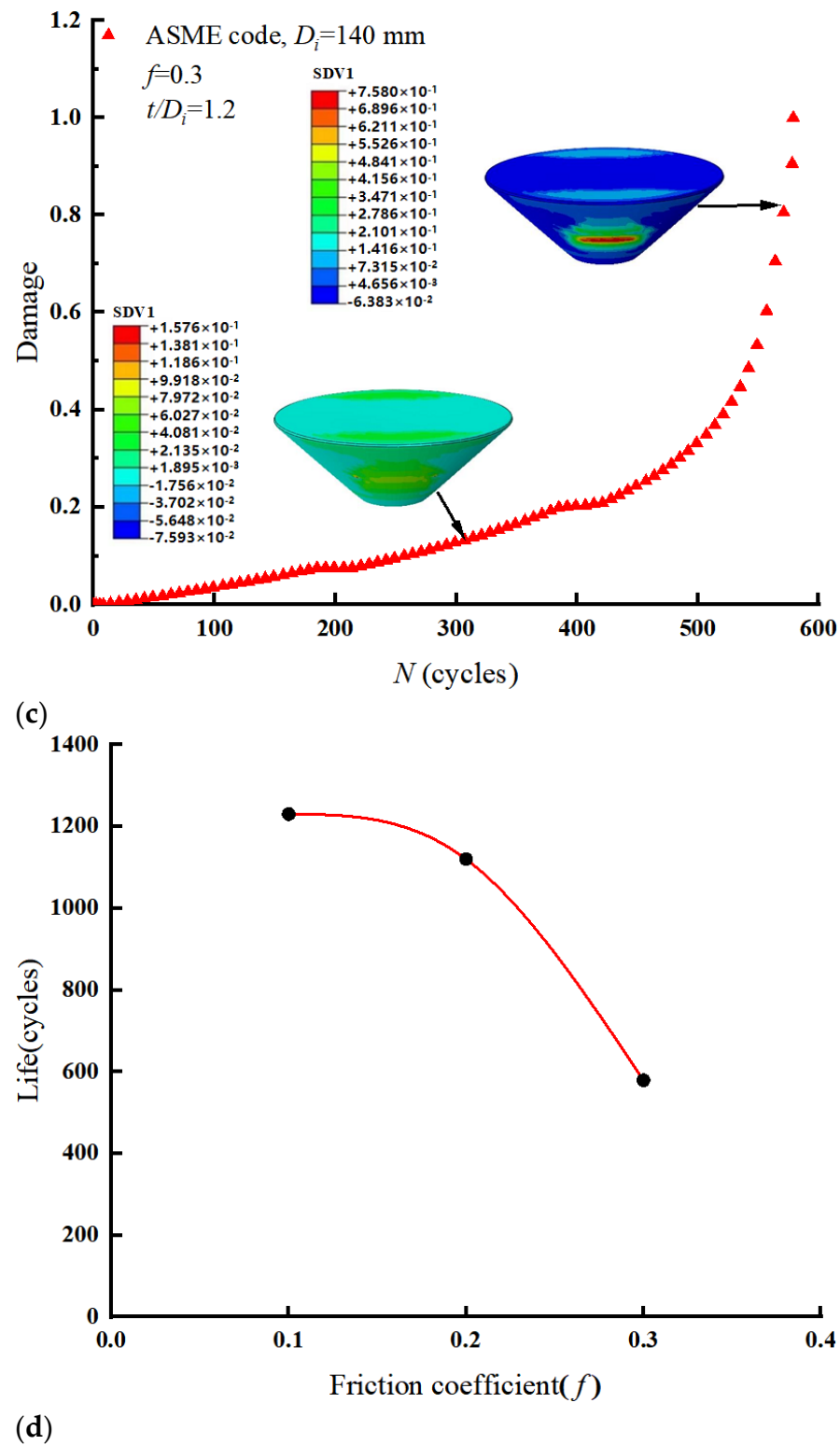


Figure 18. (a) The crack-initiation life of the observation window (friction coefficient is 0.1, $D_i = 140$ mm, $t/D_i = 1.2$); (b) the crack-initiation life of the observation window (friction coefficient is 0.2, $D_i = 140$ mm, $t/D_i = 1.2$); (c) the crack-initiation life of the observation window (friction coefficient is 0.3, $D_i = 140$ mm, $t/D_i = 1.2$); (d) life decreasing curve with increasing friction coefficient.

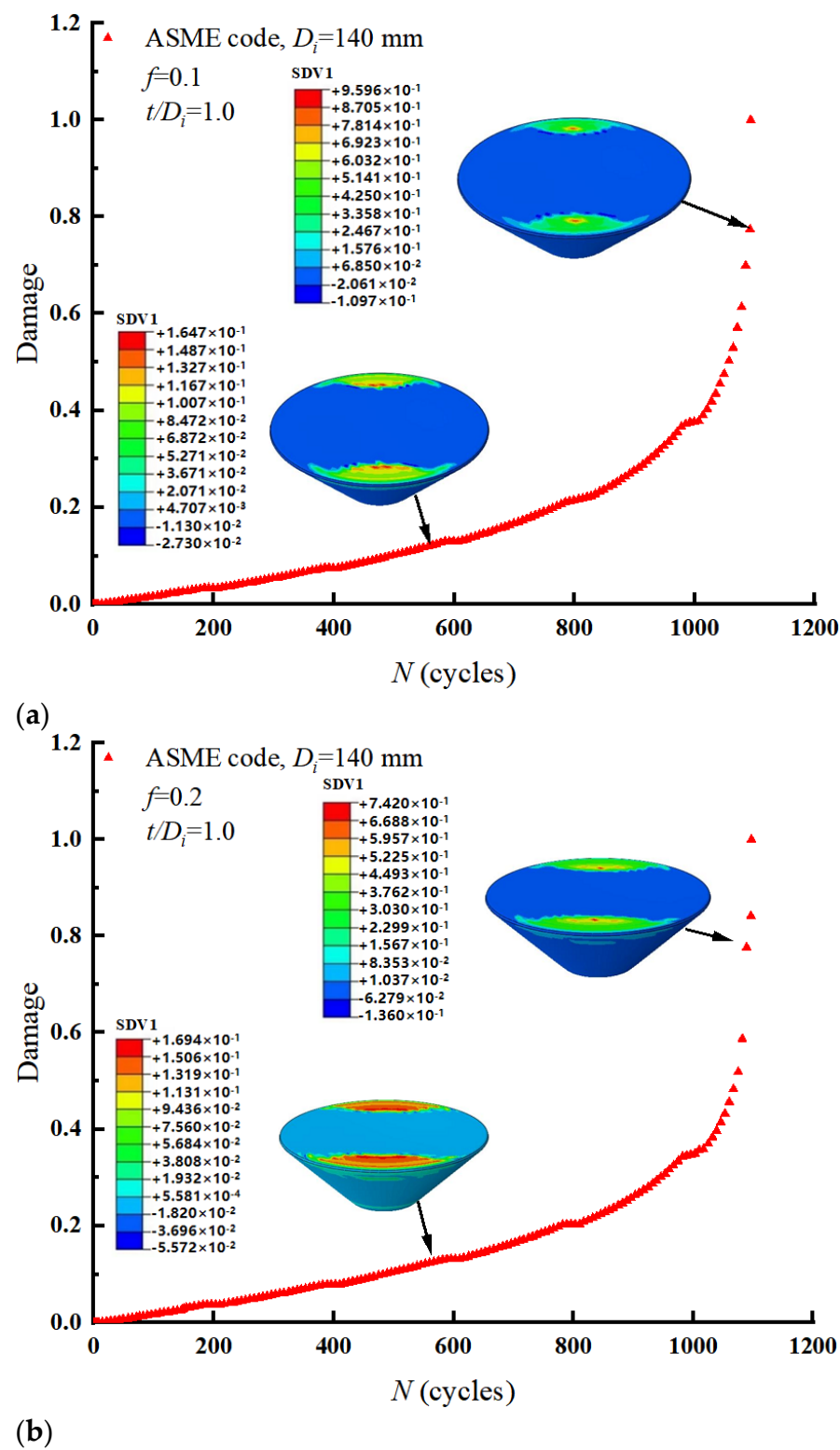
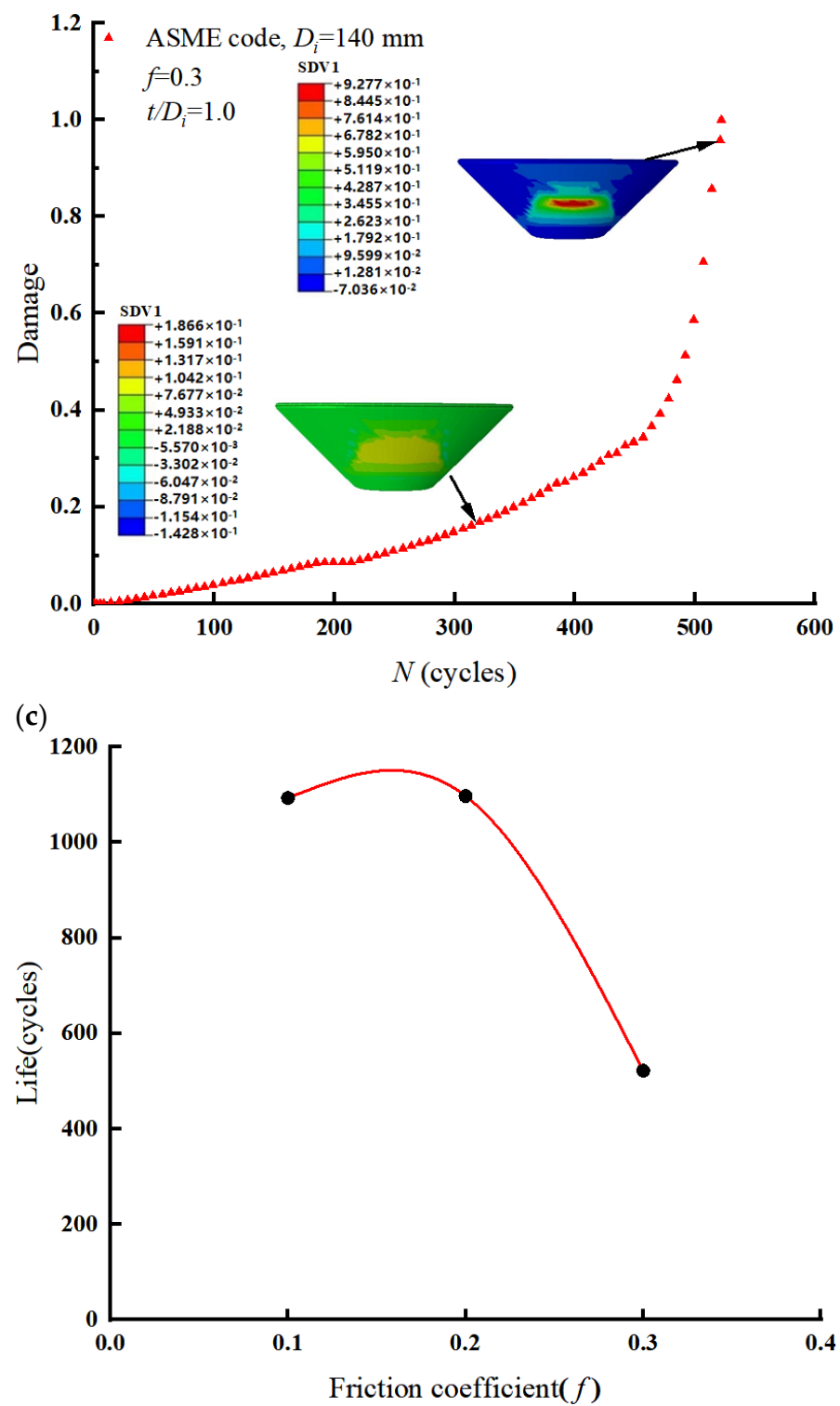


Figure 19. Cont.



(d)

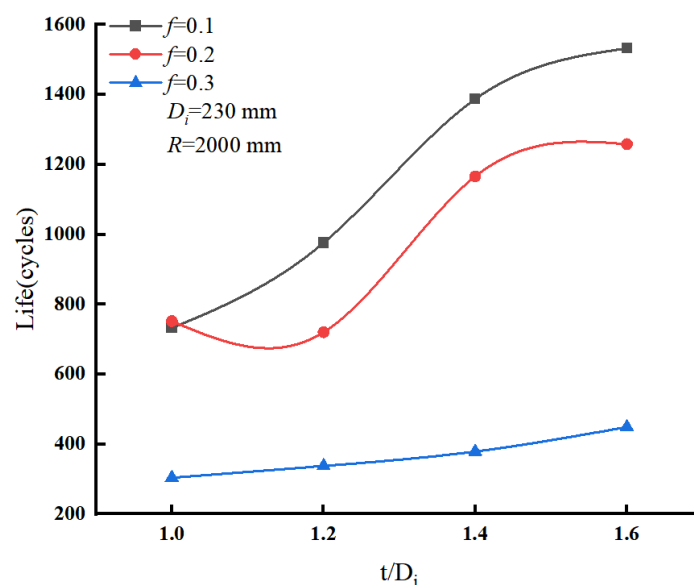
Figure 19. (a) The-crack initiation life of the observation window (friction coefficient is 0.1, $D_i = 140$ mm, $t/D_i = 1.0$); (b) the crack-initiation life of the observation window (friction coefficient is 0.2, $D_i = 140$ mm, $t/D_i = 1.0$); (c) the crack-initiation life of the observation window (friction coefficient is 0.3, $D_i = 140$ mm, $t/D_i = 1.0$); (d) life decreasing curve with increasing friction coefficient.

Table 5. The finite element calculation results of different thickness–diameter ratios and different friction coefficients.

D_i (mm)	t/D_i	f	Life (Cycles)
230	1.4	0.1, 0.2, 0.3	1387, 1166, 379
230	1.2	0.1, 0.2, 0.3	976, 720, 338
230	1.0	0.1, 0.2, 0.3	732, 752, 304
140	1.4	0.1, 0.2, 0.3	1502, 1130, 721
140	1.2	0.1, 0.2, 0.3	1230, 1120, 579
140	1.0	0.1, 0.2, 0.3	1093, 1097, 522

4.2.3. Life Assessment under Different Design Considerations

Based on available data from manned submersibles, assuming each dive reaches the designated working depth of 11,000 m and if there are 200 cycles of diving operations annually, it is estimated that the PMMA observation window of the manned submersible would need replacement every 5 years, corresponding to a fatigue life of 1000 cycles. According to Figures 20 and 21, if the thickness–diameter ratio is greater than 1, and only when the friction coefficient is 0.2, the observation window with an inner diameter of 230 mm does not meet the conditions for 1000 times the fatigue life. The frustum-shaped observation window exhibits high stress concentration at the edge of its inner surface due to its structural characteristics. To mitigate this, a transition arc is incorporated for smoothing, aimed at improving stress distribution. Numerical analysis is conducted on observation windows designed with different transition arc radii, using a specific radius ($R = 4000, 6000$ mm). The radius is varied to observe its impact on the fatigue crack-initiation life of the observation window through finite element analysis. The results are summarized in Table 6. According to Figures 22 and 23, in the case of a certain thickness–diameter ratio ($t/D_i = 1.2$), with the increase in the transition arc radius and the decrease in the friction coefficient, the fatigue crack-initiation life of the observation window will also increase. It is worth noting that, from the finite element calculation results of Figures 20 and 21, under the observation window structure with an inner diameter of 230 mm and a thickness-to-diameter ratio of 1.0, the fatigue crack-initiation life when the friction coefficient is 0.2 is larger than that when the friction coefficient is 0.1. Under the observation window structure with an inner diameter of 140 mm and a friction coefficient of 0.3, the fatigue crack-initiation life is the largest when the thickness-to-diameter ratio is 1.4.

**Figure 20.** Relationship between thickness–diameter ratio and life ($D_i = 230$ mm).

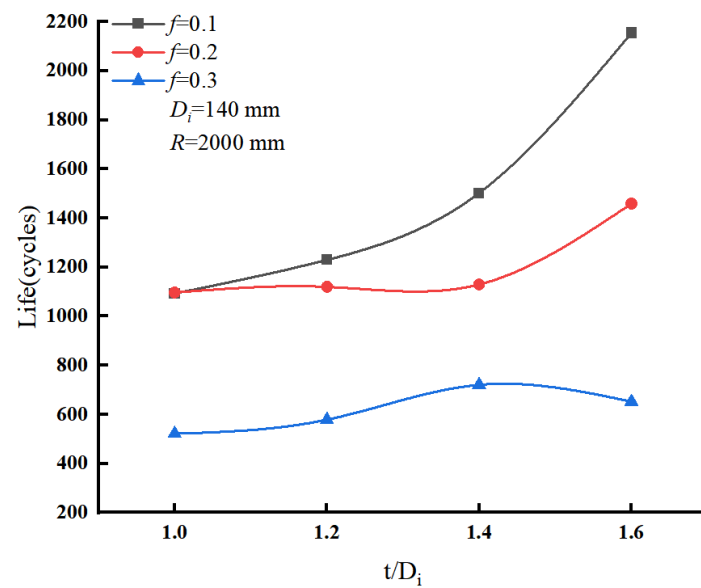


Figure 21. Relationship between thickness–diameter ratio and life ($D_i = 140$ mm).

Table 6. The finite element calculation results of different transition arc radii and different friction coefficients.

D_i (mm)	R (mm)	f	Life (Cycles)
230	4000	0.1	1089
230	4000	0.2	1087
230	4000	0.3	786
230	6000	0.1	1765
230	6000	0.2	1292
230	6000	0.3	717

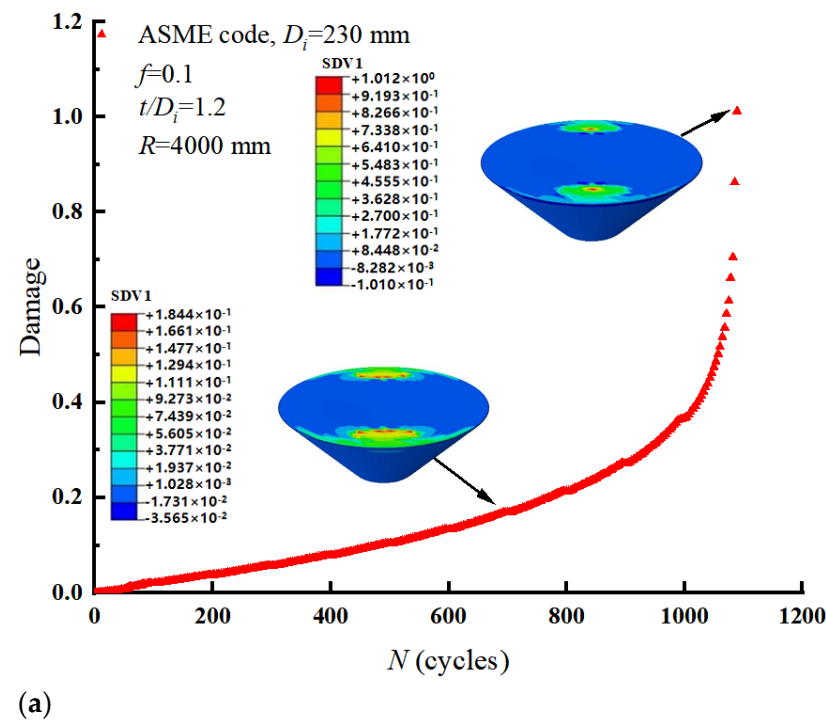
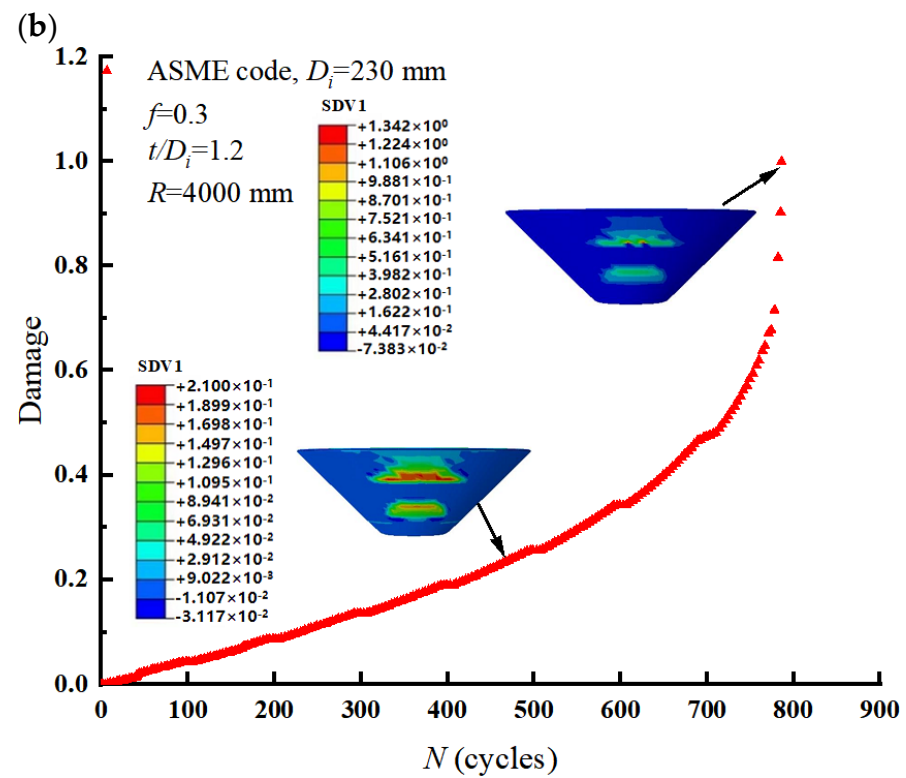
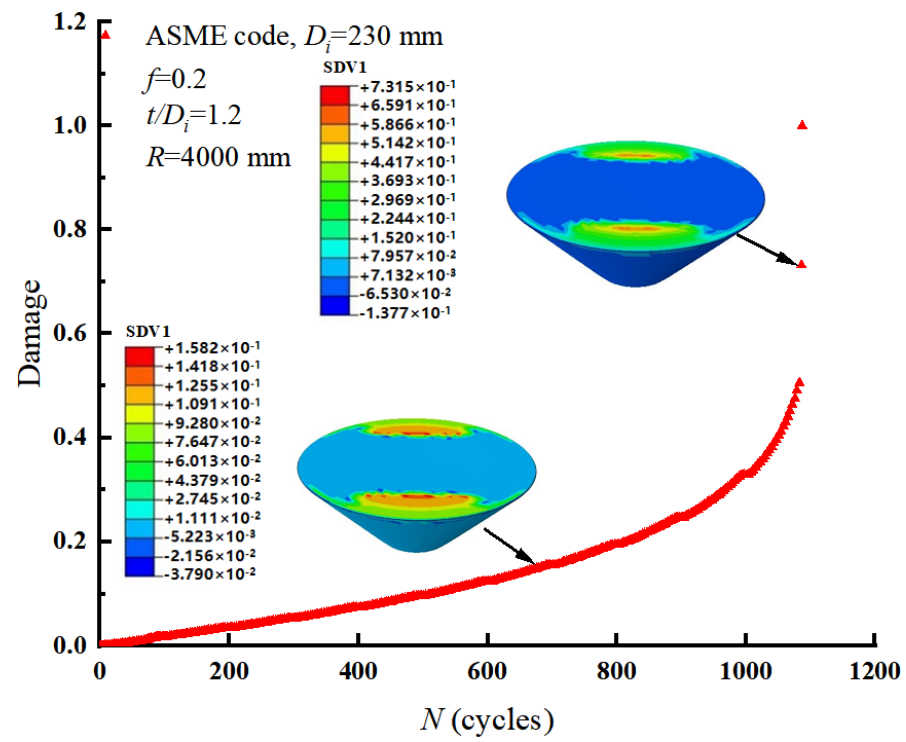


Figure 22. Cont.



(c)

Figure 22. Cont.

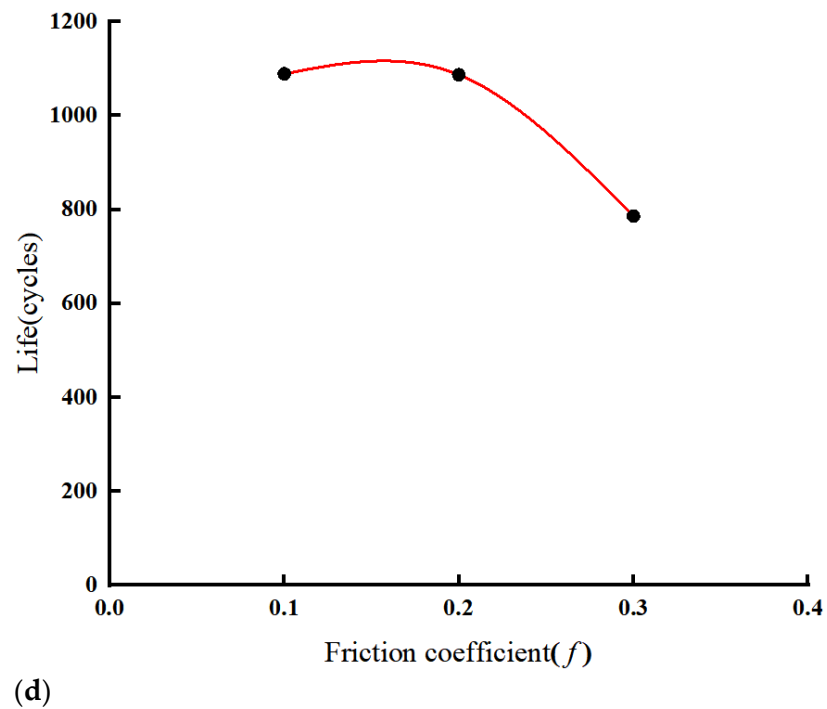


Figure 22. (a) The crack-initiation life of the observation window (friction coefficient is 0.1, $D_i = 230$ mm, $t/D_i = 1.2$, $R = 4000$ mm); (b) the crack-initiation life of the observation window (friction coefficient is 0.2, $D_i = 230$ mm, $t/D_i = 1.2$, $R = 4000$ mm); (c) the crack-initiation life of the observation window (friction coefficient is 0.3, $D_i = 230$ mm, $t/D_i = 1.2$, $R = 4000$ mm); (d) life decreasing curve with increasing friction coefficient.

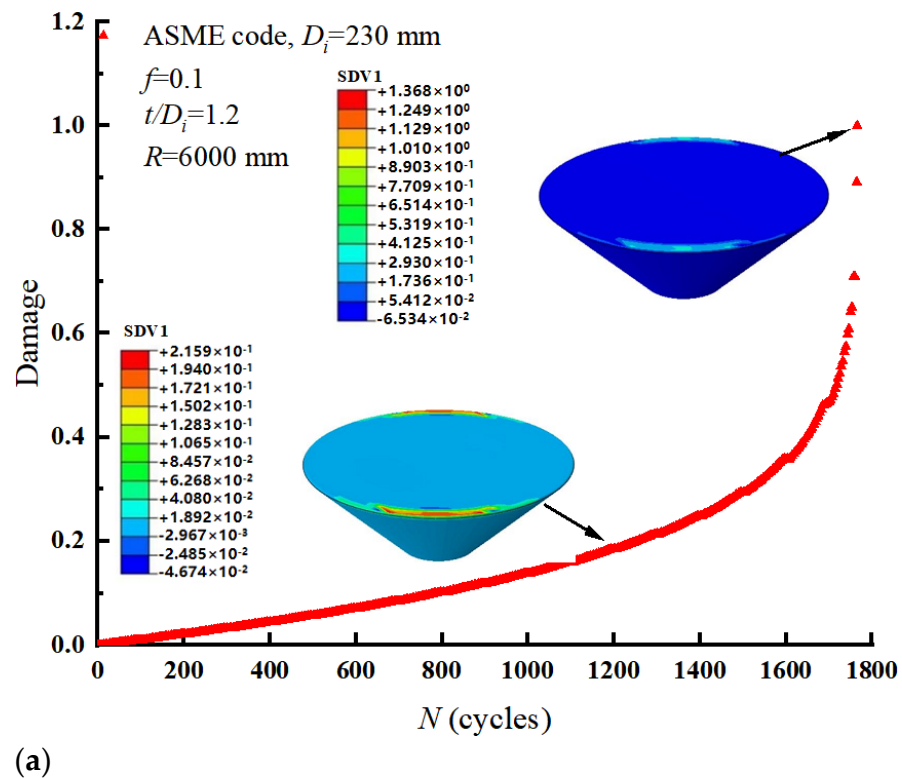
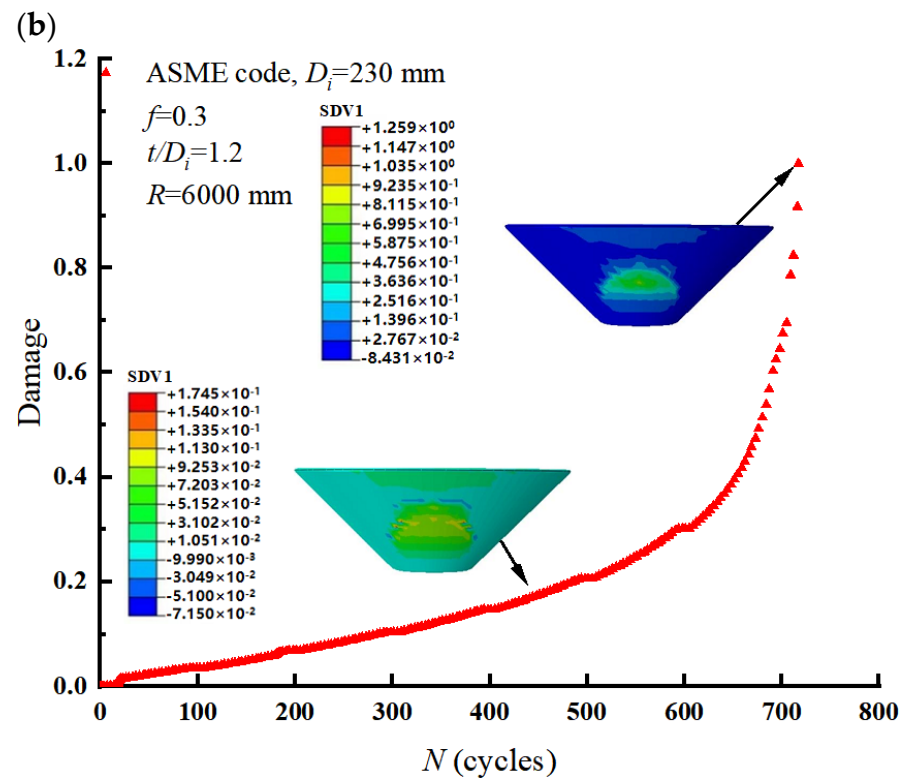
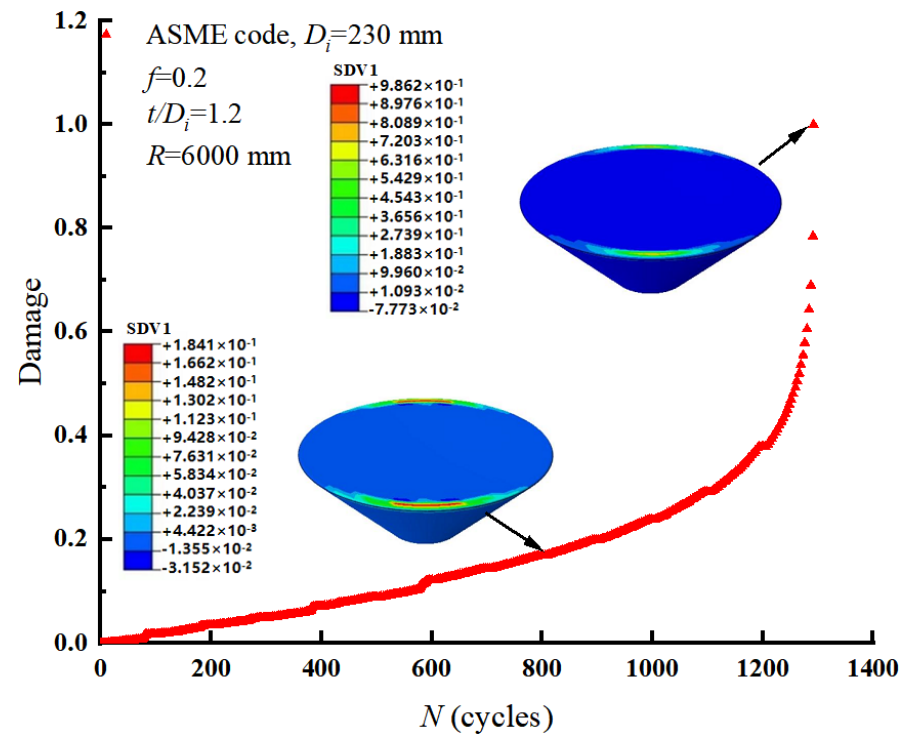
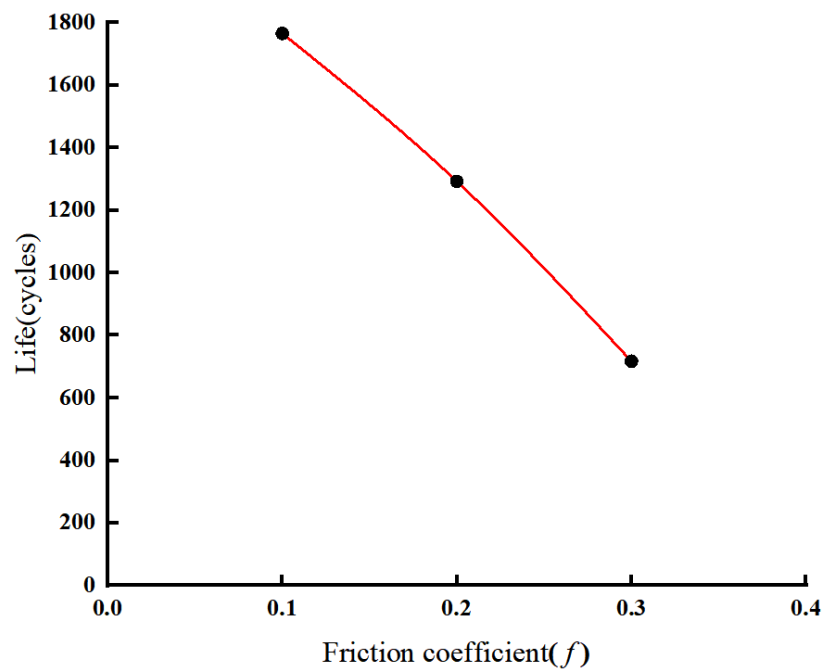


Figure 23. Cont.



(c)

Figure 23. Cont.



(d)

Figure 23. (a) The crack-initiation life of the observation window (friction coefficient is 0.1, $D_i = 230$ mm, $t/D_i = 1.2$, $R = 6000$ mm); (b) the crack-initiation life of the observation window (friction coefficient is 0.2, $D_i = 230$ mm, $t/D_i = 1.2$, $R = 6000$ mm); (c) the crack-initiation life of the observation window (friction coefficient is 0.3, $D_i = 230$ mm, $t/D_i = 1.2$, $R = 6000$ mm); (d) life decreasing curve with increasing friction coefficient.

5. Summary and Conclusions

The deep sea presents a high-pressure environment, imposing a significant challenge on the pressure-resistant capacity of manned submersibles, which is crucial for equipment and diver safety underwater. Among the critical components, the observation window stands out as one of the primary structural elements of the manned cabin. The nature of the PMMA material causes the structure to be weak. The design of the observation window represents a pivotal aspect in ensuring the integrity of the overall structure. However, the existing design curve outlined in the ASME specification has certain limitations. The conventional approach of enhancing safety by broadening the safety factor range by a larger window thickness does not necessarily contribute to the optimal performance of the submersible. Consequently, conducting thorough safety design and life analysis of the observation window structure to connect the relationship of lifespan and window geometry becomes imperative.

In addressing the aforementioned problems, this paper undertakes finite element analysis to assess the fatigue life of PMMA observation windows. Employing a cumulative damage approach, the methodology assumes that crack initiation signifies the entirety of the observation window's lifespan, without accounting for crack-propagation life. Throughout the calculation process, considerations include the viscoelastic properties of PMMA material, varying thickness-to-diameter ratios, varying friction coefficients of the observation window, and distinct transition arc radii of the PMMA observation window.

Based on the aforementioned factors, firstly, the design of the observation window is carried out according to the recommendation of the ASME specification. Two kinds of observation windows with different inner diameters are designed, which are 230 mm and 140 mm, respectively. By integrating the damage model with the material's constitutive relationship, the PMMA observation window was analyzed using the computational program proposed in this study. The finite element calculation results were then compared with experimental findings. As depicted in Figure 9, the finite element analysis results closely

align with the crack positions observed in the experimental process, thereby validating the reliability of the computational program presented in this paper. Then, with consideration beyond the ASME specification, changing thickness-to-diameter ratios (1.6, 1.4, 1.2, and 1.0) and friction coefficients (0.1, 0.2, and 0.3), the life of the observation window is evaluated. The results show that when the thickness–diameter ratio is 1.4, D_i is 140 mm, and the friction coefficient is 0.1, the fatigue life is up to 1502 cycles. Compared with the lowest fatigue life of 732 cycles, it increases by 105%. When the radius of the transition arc increases to 6000 mm, its fatigue life is up to 1765 cycles. However, the fatigue life at the friction coefficient of 0.3 (717 cycles) is not as high as the fatigue life of the transition arc radius of 4000 mm (786 cycles). With the decrease in the thickness–diameter ratio, the fatigue life of the structure decreases gradually. As the friction coefficient increases, the fatigue life of the observation window gradually decreases. The structure of the observation window with a thickness-to-diameter ratio of 1.2 and an inner diameter of 230 mm was improved. Two distinct transition arc radii (4000 mm, 6000 mm) were designed. It was observed that, with the augmentation of the transition arc radius, the fatigue crack-initiation life of the observation window also increased, representing an improvement over the previous structure.

The observation window PMMA is prone to crazing due to surface scratches and abrasions. The crazing not only reduces the light transmittance of PMMA, but also reduces the material strength, which in turn affects the service life of the observation window. PMMA crack-propagation research can be carried out to predict the residual fatigue life of the observation window. Aiming at the viscoelastic mechanical behavior of the observation window plexiglass, this paper proposes a viscoelastic constitutive model that can be used under full-sea-depth pressure. And, considering the influence of external factors, under the condition of accurately grasping the viscoelastic properties, other factors can be further studied for the viscoelastic behavior of organic glass. Based on assuming that the fatigue life of the observation window is 1000 cycles, the thickness of the observation window can be moderately reduced through finite element calculation and analysis, which can also meet its structural safety and use times. Under a specific structure, the service life of the observation window can also be increased by increasing the design of the transition arc radius. In this paper, the fatigue crack-initiation life of observation windows with different structures is analyzed. The purpose of improving the life of observation windows can be achieved by improving the structural design or improving the material properties, which can provide a reference for the design and service life of PMMA observation windows.

Author Contributions: Conceptualization, F.W.; methodology, Z.H. and F.W.; software, Z.H., Y.W.; validation, Z.H., J.Z. and B.Z.; formal analysis, Z.H.; investigation, Z.H.; resources, Z.H., R.L. and F.W.; data curation, J.Z. and R.L.; writing—original draft preparation, Z.H.; writing—review and editing, F.W. and F.C.; visualization, F.W.; supervision, F.W. All authors have read and agreed to the published version of the manuscript.

Funding: This work is supported by the National Natural Science Foundation of China (Grant No. 52071203) and the National Key Research and Development Program of China (Grant No. 2021YFC2800600).

Data Availability Statement: The data can be requested from the corresponding author.

Acknowledgments: The authors would like to express their gratitude for the support of the Fishery Engineering and Equipment Innovation Team of Shanghai High-level Local University.

Conflicts of Interest: Author Fengluo Chen was employed by China Merchants Marine and Offshore Research Institute Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Nomenclature

E	The elastic modulus of the material	σ_b	The tensile strength of the material
σ_y	The yield strength of the material	ν	The Poisson's ratio
D_i	The inner diameter of the observation window	D_f	The outer diameter of the observation window
t	The thickness of the observation window	α	The cone angle of the observation window
t/D_i	Thickness-to-diameter ratios	E_1	The instantaneous elastic modulus
E_2	The time-delay elastic modulus	ε_1	The elastic strain
ε_2	The time-delay elastic strain	μ_1	The viscoelastic coefficient
$\dot{\varepsilon}_1$	The viscoelastic strain rate	$\dot{\sigma}, \dot{\varepsilon}$	The time change rates of stress and strain
D	The damage value	E_D	The equivalent elastic modulus with damage
a, b	The material parameters	$Y_{\max}$	The maximum damage driving force
Y_{th}	The damage driving-force threshold	$\sigma_{\max}$	The maximum stress
σ_{th}	The stress threshold	f	The coefficient of friction

References

1. Stachiw, J.D. *Handbook of Acrylics for Submersibles, Hyperbaric Chambers and Aquaria*; Best Publishing: Flagstaff, AZ, USA, 2003.
2. Du, Q.H.; Hu, Y.; Cui, W.C. Safety assessment of the acrylic conical frustum viewport structure for a deep-sea manned submersible. *Ships Offshore Struct.* **2017**, *12* (Suppl. 1), S221–S229. [\[CrossRef\]](#)
3. ASME PVHO-1; Safety Standard for Pressure Vessels for Human Occupancy: In-Service Guidelines. American Society of Mechanical Engineers: New York, NY, USA, 2023.
4. Yue, K.; Tian, C.L. Stress analysis of deep-sea view-port windows and its optimization. *Jiangnan Univ. (Nat. Sci. Ed.)* **2011**, *10*, 58–62. (In Chinese)
5. Wang, F.; Wang, W.W.; Zhang, Y.K.; Du, Q.H.; Jiang, Z.; Cui, W.C. Effect of temperature and nonlinearity of PMMA material in the design of observation windows for a full ocean depth manned submersible. *Mar. Technol. Soc. J.* **2019**, *53*, 27–36. [\[CrossRef\]](#)
6. Zhu, Y.M.; Liang, W.W.; Zhao, X.L.; Wang, X.R.; Xia, J. Strength and stability of spherical pressure hulls with different viewport structures. *Int. J. Press. Vessel. Pip.* **2019**, *176*, 103951. [\[CrossRef\]](#)
7. Wang, F.; Wang, M.Q.; Wang, W.W.; Yang, L.; Zhang, X.Z. Time-dependent axial displacement of PMMA frustums designed for deep-sea manned cabin based on finite element analysis. *Ships Offshore Struct.* **2021**, *16*, 827–837. [\[CrossRef\]](#)
8. Pranesh, S.B.; Kumar, D.; Anantha Subramanian, V.; Sathianarayanan, D.; Ramadass, G.A. Structural analysis of spherical pressure hull viewport for manned submersibles using biological growth method. *Ships Offshore Struct.* **2018**, *13*, 601–616.
9. Pranesh, S.B.; Kumar, D.; Anantha Subramanian, V.; Sathianarayanan, D.; Ramadass, G.A. Numerical and experimental study on the safety of viewport window in a deep sea manned submersible. *Ships Offshore Struct.* **2020**, *15*, 769–779. [\[CrossRef\]](#)
10. Du, Q.H.; Wang, L.; Cui, W.C. Structural compatibility analysis of spherical sector view-port with conical seat. *J. Ship Mech.* **2011**, *15*, 101–108. (In Chinese)
11. Du, Q.H.; Jiang, H.G.; Hu, X.K. Creep behavior analysis of conical observation window for human occupied vehicle based on ABAQUS. *J. Ship Res.* **2022**, *17*, 108–116. (In Chinese)
12. Zhao, B.X.; Wang, F.; Liu, W.; Zhang, J.; Wang, M.Q.; Cui, W.C. Failure process analysis of frustum windows for deep-sea manned cabin. *Ships Offshore Struct.* **2022**, *17*, 676–686. [\[CrossRef\]](#)
13. Li, J.X.; Liu, P.F.; Tong, X.Y. A simplified method for studying cyclic creep behaviors of deep-sea manned submersible viewport windows. *Int. J. Press. Vessel. Pip.* **2021**, *194*, 104565. [\[CrossRef\]](#)
14. Liu, P.F.; Li, J.X.; Wang, S.B.; Leng, J.X. Finite element analysis of viscoelastic creep behaviors of deep-sea manned submersible viewport windows. *Int. J. Press. Vessel. Pip.* **2020**, *188*, 104218. [\[CrossRef\]](#)
15. Li, H.N.; Liao, R.; Zhang, H.L.; Ma, G.L.; Guo, Z.M.; Tu, H.B.; Chen, Y.; Ma, H. Stress Detection of Conical Frustum Windows in Submersibles Based on Polarization Imaging. *Sensors* **2022**, *22*, 2282. [\[CrossRef\]](#) [\[PubMed\]](#)
16. Du, Q.H.; Lei, Q.; Liu, F.Y.; Liu, W.; Liu, W.L. Stress relaxation and structural performance analysis of conical viewport for deep-sea submersible. *Ocean Eng.* **2024**, *295*, 116837. [\[CrossRef\]](#)
17. He, Z.H.; Wang, F.; Wang, H.X.; Zhao, B.X. Parametric Analysis on Creep Deformation of Deep-Sea PMMA Observation Window. *Appl. Sci.* **2024**, *14*, 1040. [\[CrossRef\]](#)
18. Zheng, M.Y.; Jiang, X.Y.; Wu, G.Q.; Zhang, X.W.; Ding, Y.; Yan, Y. Research on Damage and Defects of Deep-Sea Submersible Acrylic Windows. *Ship Eng.* **2022**, *44*, 8–13+30. (In Chinese)
19. Hu, X.K.; Du, Q.H.; Jiang, H.G. Study on PMMA viscoelastic constitutive model and structural performance of deep-sea submersible observation window. *Manuf. Autom.* **2023**, *45*, 93–99. (In Chinese)

20. Liu, P.F.; Li, J.X. Anisotropic viscoelasticity/damage coupled thermodynamic model for transparent polymer. *Eng. Fract. Mech.* **2023**, *292*, 109639. [[CrossRef](#)]
21. Christodoulou, P.I.; Kermanidis, A.T. A Combined Numerical-Analytical Study for Notched Fatigue Crack Initiation Assessment in TRIP Steel: A Local Strain and a Fracture Mechanics Approach. *Metals* **2023**, *13*, 1652. [[CrossRef](#)]
22. Llavori, I.; Zabala, A.; Urchegui, M.A.; Tato, W.; Gómez, X. A coupled crack initiation and propagation numerical procedure for combined fretting wear and fretting fatigue lifetime assessment. *Theor. Appl. Fract. Mech.* **2019**, *101*, 294–305. [[CrossRef](#)]
23. Wang, H.J.; Liu, X.T.; Wang, X.L.; Wang, Y.S. Numerical method for estimating fatigue crack initiation size using elastic-plastic fracture mechanics method. *Appl. Math. Model.* **2019**, *73*, 365–377. [[CrossRef](#)]
24. Lin, G.J.; Zhang, W.M.; Feng, Y.L.; Kang, Y.T. Review on viewport used in human occupied vehicle. *Ship Eng.* **2013**, *35*, 1–5+75. (In Chinese)
25. He, Z.H.; Wang, F.; Gaidai, O.; Qu, W.X. Lifetime assessment of deep-sea manned cabin with PMMA pressure-resistant hull prior to micro-cracks. *Ocean Eng.* **2024**, *306*, 118119. [[CrossRef](#)]
26. Lemaitre, J.; Chaboche, J.L. *Mechanics of Solid Materials*; Cambridge University Press: Cambridge, UK, 1994.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.