

Article

Investigation of Crack Propagation and Failure of Liquid-Filled Cylindrical Shells Damaged in High-Pressure Environments

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Abstract: Cylindrical shell structures have excellent structural properties and load-bearing capacities in fields such as aerospace, marine engineering, and nuclear power. However, under high-pressure conditions, cylindrical shells are prone to cracking due to impact, corrosion, and fatigue, leading to a reduction in structural strength or failure. This paper proposes a static modeling method for damaged liquid-filled cylindrical shells based on the extended finite element method (XFEM). It investigated the impact of different initial crack angles on the crack propagation path and failure process of liquid-filled cylindrical shells, overcoming the difficulties of accurately simulating stress concentration at crack tips and discontinuities in the propagation path encountered in traditional finite element methods. Additionally, based on fluid-structure interaction theory, a dynamic model for damaged liquid-filled cylindrical shells was established, analyzing the changes in pressure and flow state of the fluid during crack propagation. Experimental results showed that although the initial crack angle had a slight effect on the crack propagation path, the crack ultimately extended along both sides of the main axis of the cylindrical shell. When the initial crack angle was 0°, the crack propagation path was more likely to form a through-crack, with the highest penetration rate, whereas when the initial crack angle was 75°, the crack propagation speed was slower. After fluid entered the cylindrical shell, it spurted along the crack propagation path, forming a wave crest at the initial ejection position.

Keywords: crack propagation; structural failure; extended finite element method; fluid-filled cylindrical shell; fluid-structure interaction



Citation: Zhang, H.; Tan, D.; Xu, S.; Hu, T.; Qi, H.; Li, L. Investigation of Crack Propagation and Failure of Liquid-Filled Cylindrical Shells Damaged in High-Pressure Environments. *J. Mar. Sci. Eng.* **2024**, *12*, 921. <https://doi.org/10.3390/jmse12060921>

Academic Editor: Leszek Chybowski

Received: 9 May 2024

Revised: 22 May 2024

Accepted: 25 May 2024

Published: 30 May 2024



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1. Introduction

The liquid-filled cylindrical shell structure is a classic engineering structure with excellent performance, widely used in fields such as underwater vehicles and marine pipelines [1–7]. Influenced by internal fluid impact, corrosion, and fatigue, cracks can easily develop on the surface or inside of cylindrical shells, leading to failure. Additionally, once fluid-filled cylindrical shells like high-pressure pipelines are damaged by cracks, the cost of repair or replacement is high [8–13]. Therefore, studying the crack propagation and failure processes of damaged fluid-filled cylindrical shells under high-pressure conditions is crucial in optimizing design and enhancing safety.

The immersed particle method (IPM) is a method often used to simulate structures that fracture under impact loading [14–18]. It uses a meshless particle method for fluids and structures and is suitable for dealing with complex FSI problems including crack extension and penetration [19,20]. Meanwhile, many researchers have used the crack particles method (CPM) to simulate dynamic fracture of metals [21]. CPM does not require an explicit representation of the crack topology, which makes it suitable for dynamic fracture and fragmentation problems [22]. However, the particle approach requires a large amount

of computational resources and is not favorable for dealing with the multivariate crack path problem. In addition, the dual-horizon peridynamics method (DH-PDM) has been gaining attention in recent years. It can be used to analyze the material fracture problem by introducing two independent field-of-view concepts that naturally include the changing field-of-view dimensions, and completely solving the “ghost force” problem in the traditional peridynamics [23]. However, DH-PDM, as a relatively new technique, lacks sufficient experimental data to support its applicability in material nonlinearity. In contrast, the extended finite element method (XFEM) has an advantage in computational efficiency by adapting to crack extension through local remeshing. Additionally, it captures the singularities at the crack tip through local enrichment functions, which is beneficial for modeling nonlinear patterns of complex cracks [24]. XFEM does not require additional mesh encryption at the crack tip. Although XFEM has been widely used to solve discontinuous displacement field problems, its performance in fluid-filled cylindrical shells has not been extensively studied [25–29].

Material damage criteria, including crack initiation criteria and damage evolution criteria, are used to study damage formation and evolution in fluid-filled cylindrical shell models [30]. The damage initiation criteria suitable for XFEM include the maximum principal stress (Maxps) or strain (Maxpe), maximum nominal stress or strain, sub-nominal stress or strain, and user-defined damage initiation criteria [31].

Selecting appropriate damage parameters is crucial for improving model simulation accuracy [32]. Liu [33] studied the toughness crack propagation of X80 pipeline steel and found the maximum principal strain criterion more suitable for numerical analysis. Motamedi and others [34] used XFEM to analyze the fracture performance of polysulfone and unidirectional glass fiber composites, successfully predicting crack propagation paths under different loads. Okodi [35] used XFEM with maximum principal strain and fracture energy as damage parameters to analyze crack propagation in pipelines. Compared to the actual material strength, the maximum principal stress resulted in higher predictions of crack propagation. Ameli and others [36] studied the critical maximum principal stress values of X42 pipelines, which aligned well with experimental data. However, the crack initiation stress was about 4.3 times the yield stress of X42, suggesting that a strain-based damage criterion might be more suitable for predicting toughness fractures. Under high-pressure conditions, high-strength materials in fluid-filled cylindrical shells often undergo ductile rather than brittle fracture. Caleyron [37] used the SPH method to establish a fluid-structure interaction model for a damaged fluid-filled cylindrical thin-shell structure, predicting the failure modes of fluid-filled tank-like containers under impact loads and analyzing the failure forms of the damaged fluid-filled cylindrical thin-shell structure. Ozdemir [38] used a meshless method to study the buckling behavior of cylindrical shells with penetrating cracks, examining the effects of through-cracks on the buckling coefficients and modal shapes of cylindrical shells, and modeling fluid-structure interaction for cylindrical shells with through-cracks to compare results, validating the effectiveness of the meshless method in this research.

In the current research on damaged liquid-filled cylindrical shell structures, the maximum principal strain criterion used does not consider the material's nature and microstructure, and it only evaluates damage based on local strain, which cannot accurately reflect the true fracture behavior of the material. Therefore, this research studied the crack propagation and failure process of damaged liquid-filled cylindrical shells. It employed the XFEM method with the maximum principal stress criterion (Maxps) as the damage parameter to analyze crack propagation and failure of liquid-filled cylindrical shells under high-pressure conditions, and investigated the impact of crack parameters on structural failure. Additionally, based on fluid-structure interaction theory, a dynamic model for damaged liquid-filled cylindrical shells was established to analyze the crack propagation process under the influence of fluid, as well as the changes in fluid pressure and flow state.

2. Mathematical Model

For the purpose of theoretical modeling, the following assumptions need to be made: the shell material is isotropic; the overall deformation is linear-elastic; the effects of rotational inertia, in-plane inertia, and transverse shear deformation of thin-walled cylindrical shells are neglected; and the internal fluid is incompressible.

2.1. Element Decomposition Method

The element decomposition method divides the overall solution domain into several independent discrete units, processes the approximation function of each unit, and then integrates all the discrete units into an accurate overall shape function [39,40]. Each discrete unit in the solution domain contains a unit decomposition function, and φ_i of all discrete units in the solution domain needs to satisfy [41]:

$$\sum_i \varphi_i(x) = 1 \quad (1)$$

In the above equation, i is each discrete unit in the solution domain; $\varphi_i(x)$ is the unit decomposition function of each discrete unit. The unit decomposition method requires that the sum of the unit decomposition function of each discrete unit is always 1.

The unit decomposition function $\varphi_i(x)$ in the above equation has different functional forms. The form function used by the finite element method is one of the discrete unit decomposition functions. Through the form function, the finite element method is able to calculate the displacement at any position in the discrete unit. The displacement expression of the finite element method is shown as follows [42],

$$u(x) = \sum_{i=1}^n N_i(x) u_i \quad (2)$$

where u denotes the displacement field inside the discrete cell; i is the cell node; $N_i(x)$ is the finite element shape function of each cell node; and u_i is the displacement of each cell node.

2.2. Extended Finite Element Method Expansion

The extended finite element method is an improved method of finite element method for discontinuous problems [33]. Equation (2) is the displacement solution equation of the traditional finite element method. The extended finite element method introduces an expansion term $\psi(x)$ on this basis, which is specifically used to describe the displacement field of discontinuous surfaces. The expression for solving the discontinuous displacement field $u^h(x)$ at any place in the solution domain based on the extended finite element method is [43]:

$$u^h(x) = \sum_{i=1}^n N_i(x) u_i + \psi(x) \quad (3)$$

where $N_i(x)$ is the finite element shape function of each unit node; u_i is the displacement of each unit node, and $\psi(x)$ is an expansion function added to describe the intermittent discontinuity field. Further, a cell decomposition of the expansion term $\psi(x)$, Equation (3), can be expressed as [44]:

$$u^h(x) = \sum_{i=1}^n N_i(x) u_i + \sum_{j=1}^m N_j(x) \varphi(x) q_j \quad (4)$$

Equation (4) is the generalized displacement field description form of the extended finite element method; the former term $\sum_{i=1}^n N_i(x) u_i$ is the displacement field solution of the traditional finite element, and the latter term $\sum_{j=1}^m N_j(x) \varphi(x) q_j$ is the expansion term of

the extended finite element for describing the discontinuous field. Where j denotes the nodal cells of the discontinuous field, q denotes the total number of cells added to the interrupted discontinuous field; $\varphi(x)$ denotes the enrichment function that corrects the displacement field of the discontinuous cell; and q_j denotes the displacement field of the discontinuous cell.

The unit classification of the crack-containing damage model based on the extended finite element method is shown in Figure 1. The black solid curve represents the expanding crack; the white area is the ordinary continuous unit; the orange area is the crack unit; and the red area is the crack tip unit. Based on this, the displacement field expression of the extended finite element method for the crack extension problem can be further rewritten [45]:

$$u^{xfem}(x) = u^F(x) + u^H(x) + u^{tip}(x) \quad (5)$$

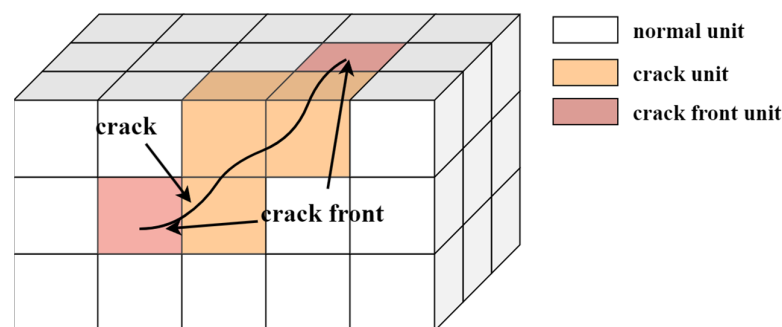


Figure 1. Schematic classification of crack-containing damage model units based on the extended finite element method.

In the above equation, $u^F(x)$ is the conventional finite element method displacement field function, i.e., the ordinary continuous cell displacement field; $u^H(x)$ denotes the cracked cell displacement field; and $u^{tip}(x)$ denotes the cracked tip cell displacement field.

Further, the displacement field anywhere in the solution domain of the crack extension problem can be expressed as [46]:

$$u^{xfem}(x) = \sum_{i=1}^l N_i(x)u_i + \sum_{j=1}^m N_j(x)H(x)p_j + \sum_{k=1}^n N_k(x)F(x)q_k \quad (6)$$

In Equation (6), i, j, k represent the ordinary continuous unit, crack unit, and crack tip unit, respectively; l, m, n represent the total number of ordinary continuous units, crack units, and crack tip units, respectively; $N_i(x), N_j(x), N_k(x)$ represent the shape function of ordinary continuous unit i , crack unit j , and crack tip unit k , respectively; $H(x)$ is a step function for the characterization of the intermittency of the cracks, and the specific form is shown in Equation (7). $F(x)$ is a crack tip enhancement function, and the specific form is shown in Equation (8).

$$H(x) = \begin{cases} 1, & (x - x^*) \cdot \mathbf{n} \geq 0 \\ -1, & (x - x^*) \cdot \mathbf{n} < 0 \end{cases} \quad (7)$$

$$F(x) = \left[\sqrt{\rho} \sin \frac{\psi}{2} \sqrt{\rho} \cos \frac{\psi}{2} \sqrt{\rho} \sin \psi \sin \frac{\psi}{2} \sqrt{\rho} \sin \psi \cos \frac{\psi}{2} \right] \quad (8)$$

In Equation (7), x is the integration point; x^* is the closest point of the crack to the integration point; $x - x^*$ is the shortest distance of the integration point from the crack. In Equation (8), expressing the crack tip enhancement function, ρ and ψ are the polar coordinates of the crack tip.

2.3. Maximum Principal Stress Criterion (Maxps)

The material is subjected to different stresses at different locations, and if the stress exceeds the compressive strength of the material at a certain location, the structure will be damaged, and this location is the crack damage initiation location [47]. Usually, the maximum principal stress method uses the compressive strength as the critical maximum principal stress. The expression for the maximum principal stress law to determine the damage initiation is shown as follows [48],

$$f = \left\{ \frac{\langle \sigma_{\max} \rangle}{\sigma_{\max}^o} \right\} \quad (9)$$

where $\sigma_{\max}^o$ denotes the critical maximum principal stress; $\langle \sigma_{\max} \rangle$ is a relation of the value of the maximum principal stress of the material $\sigma_{\max}$, the value of which is related to the direction of the maximum stress. $\langle \sigma_{\max} \rangle$ is shown as follows [49].

$$\begin{cases} \langle \sigma_{\max} \rangle = 0 & \text{if } \sigma_{\max} < 0 \\ \langle \sigma_{\max} \rangle = \sigma_{\max} & \text{if } \sigma_{\max} \geq 0 \end{cases} \quad (10)$$

Equation (10) indicates that the maximum stress value $\sigma_{\max}$ is valid when the maximum stress in the material is positive, otherwise it is 0. This indicates that the crack initiation location will not start to expand when only stressed.

$$1 \leq f \leq 1 + f_{\Delta} \quad (11)$$

Cracks in damaged fluid-filled cylindrical shells satisfy the maximum principal stress criterion and begin to expand when the result of the calculation in Equation (9), f , satisfies Equation (11). f_{Δ} is a correction factor, and in general it is sufficient to take 0.05.

The displacement-based crack damage evolution criterion predicts the crack damage evolution by observing the amount of material displacement. It is categorized into two types: linear and exponential evolution; Equations (12) and (13) show the expressions for linear and exponential evolution, respectively.

$$D = \frac{u_m(u_{\max} - u_0)}{u_{\max}(u_m - u_0)} \quad (12)$$

$$D = 1 - \left\{ \frac{u_0}{u_{\max}} \right\} \left\{ 1 - \frac{1 - \exp\left(-\alpha \left(\frac{u_{\max} - u_0}{u_m - u_0} \right)\right)}{1 - \exp(-\alpha)} \right\} \quad (13)$$

where u_m is the displacement of the damaged fluid-filled cylindrical shell unit in the current state; u_0 is the initial displacement of the unit when the crack in the damaged fluid-filled cylindrical shell starts to expand; $u_{\max}$ is the maximum displacement of the damaged fluid-filled cylindrical shell in the process of crack expansion, and a denotes a dimensionless parameter.

2.4. The Equation of Fluid Motion within a Crack in a Damaged Fluid-Filled Cylindrical Shell

The fluid motion within a crack in a damaged fluid-filled cylindrical shell is depicted in Figure 2. As the fluid within the cylindrical shell moves radially toward the crack, the direction of the fluid motion is parallel to the plane of the cylindrical shell's crack, constituting tangential flow. When the fluid enters the crack, that is, into the damage-enriched elements, the flow transitions to a normal direction perpendicular to the crack plane. The tangential flow within the crack of the damaged fluid-filled cylindrical shell is described by the Newtonian flow formula, as shown in Equation 14; the formulas for calculating the normal flow within the crack are presented in Equations (16) and (17).

$$qd = -k_t \nabla p \quad (14)$$

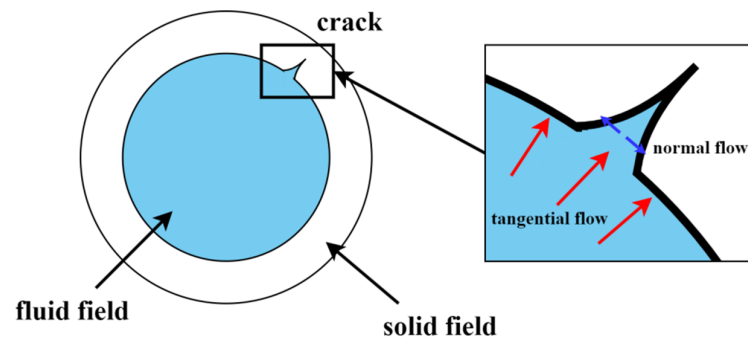


Figure 2. Fluid movement in damaged fluid-filled cylindrical shell.

In the above expression, q denotes the volumetric flow rate of the fluid within the enriched element; ∇p represents the pressure gradient across the crack plane of the cylindrical shell; d signifies the opening displacement of the cylindrical shell's crack plane; k_t indicates the permeability coefficient, which is defined in the Newtonian flow formula as shown as follows [50].

$$k_t = \frac{d^3}{12\mu} \quad (15)$$

In the equation, μ represents the fluid viscosity.

$$q_u = c_u (p_f - p_u) \quad (16)$$

$$q_d = c_d (p_f - p_d) \quad (17)$$

In the equation, q_u and q_d represent the volumetric flow rates of the fluid at the upper and lower surfaces of the crack plane after entering the crack in the cylindrical shell, respectively; c_u and c_d denote the filtration coefficients at the upper and lower surfaces of the crack plane, respectively; p_u and p_d indicate the pore pressures at the upper and lower surfaces, respectively; p_f signifies the fluid pressure within the crack of the cylindrical shell.

2.5. The Fluid-Structure Interaction Control Equation for a Damaged Fluid-Filled Cylindrical Shell

The core concept of a dynamic model that encompasses both fluid and solid domains is the conservation of relevant physical parameters at the interface where the fluid and solid meet. For a damaged fluid-filled cylindrical shell, conservation of stress, displacement, temperature, and heat flux at the interface between the cylindrical shell region and the fluid region on the inner wall of the shell enables the coupling of the fluid and solid domains [51,52].

$$\begin{cases} \tau_f \cdot n_f = \tau_s \cdot n_s \\ T_f = T_s \\ u_f = u_s \\ q_f = q_s \end{cases} \quad (18)$$

In Equation (16), τ_f and τ_s respectively represent the stresses at the interface between the fluid domain and the solid domain; T_f and T_s respectively denote the temperatures at the interface between the fluid domain and the solid domain; u_f and u_s respectively indicate the displacements at the interface between the fluid domain and the solid domain; q_f and q_s respectively signify the heat fluxes at the interface between the fluid domain and the solid domain.

2.6. The Solution Method for Fluid-Structure Interaction in a Damaged Fluid-Filled Cylindrical Shell

The computational methods for fluid-structure interaction (FSI) solutions are divided into direct and indirect FSI approaches. The direct FSI approach provides an intuitive and accurate method for solving FSI problems by solving the fluid and solid domains simultaneously within a single solver. The control equations for the direct FSI approach are presented as follows [53].

$$\begin{pmatrix} T_{ff} & T_{fs} \\ T_{sf} & T_{ss} \end{pmatrix} \begin{pmatrix} \Delta X_f^t \\ \Delta X_s^t \end{pmatrix} = \begin{pmatrix} F_f \\ F_s \end{pmatrix} \quad (19)$$

In the equation, T_{ff} represents the system matrix for the fluid domain; T_{ss} represents the system matrix for the solid domain; T_{sf} and T_{fs} denote the coupling matrices between the fluid and solid domains; t indicates the time step for analysis; ΔX_f^t and ΔX_s^t respectively represent the solution values for the fluid and solid domains; F_f and F_s respectively denote the external forces acting on the fluid and solid domains. As the solutions for the fluid and solid domains are solved within the same control equation, their solution processes are synchronized, eliminating computational errors that might arise from asynchronous processing.

3. Numerical Simulation

The extended finite element software used in this paper was Abaqus 2022, the fluid-structure coupling software was Ansys 2022R1, and the extended finite element model was the finite element model of the cracked cylindrical shell.

3.1. Establishment of the Finite Element Model and Parameter Settings

The crack-containing model (shown in Figure 3) consisted of hexahedral units with a length of 100 mm, a diameter of 40 mm, and a thickness of 3 mm. According to the crack direction, it could be divided into circumferential and axial cracks. In this model, the crack width was 10 mm, the crack length was 17 mm, and the crack depth was 1.5 mm. The boundary conditions of the solid pipe were fixed at both ends at a distance of 100 mm. In order to ensure the simulation accuracy, considering the process of crack penetration through the cylindrical shell wall, the region near the initial crack of the cylindrical shell model was densely meshed and the radial mesh was layered.

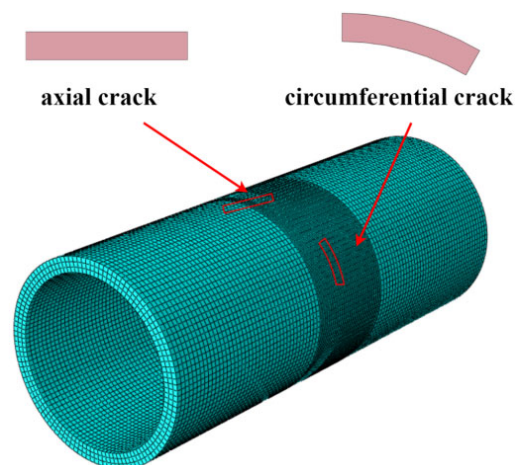


Figure 3. Finite element modeling of cylindrical shell containing cracks.

The dynamics model of a damaged fluid-filled cylindrical shell based on fluid-structure interaction is shown in Figure 4. The model comprised four parts: the cylindrical shell, the liquid, the crack, and a stop block. The material of the cylindrical shell was SAF2205 duplex stainless steel, which is increasingly used as a structural material for pressure vessels in nuclear energy, oil and gas, and marine engineering, among other fields [54,55]. The specific

material parameters are listed in Table 1. Water was chosen as the experimental fluid. To ensure that the fluid pressure inside the cylindrical shell met the requirements for crack propagation in the damaged fluid-filled cylindrical shell, one end of the shell was set as the fluid inlet, and a stop block was placed at the other end to prevent the experimental fluid from leaving the damaged cylindrical shell. The inlet boundary was the pressure inlet, and the initial pressure increased from 50 MPa to 10 MPa/s in the calculation process. As the experimental fluid continuously entered the shell, the fluid pressure rose until the crack in the damaged fluid-filled cylindrical shell penetrated, causing the fluid to burst out.

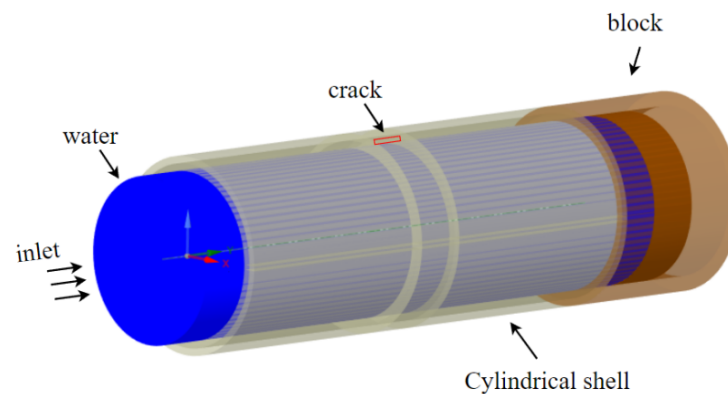


Figure 4. Damaged liquid-filled cylindrical shell dynamics modeling.

Table 1. Mechanical property parameters of SAF2205.

Mechanical Property	Parameter Values (Units)
Intensity	7.98 (g/cm ³)
Young's modulus	550 (MPa)
Tensile strength	750 (MPa)
Poisson's ratio	0.3
Elastic modulus	200 (GPa)
Elongate	0.25
Durometer	290/30.5 (Brinell/Rockwell)
Corrosion resistance factor (PREN)	35.4

The mesh division was carried out separately for the fluid and solid regions. Specifically, the fluid region comprised 72,448 elements, while the cylindrical shell region contained 64,588 elements. Since the baffle was not the focus of this study, it was only given a basic mesh division with 7332 elements. To ensure more accurate crack propagation, the mesh around the crack in the damaged cylindrical shell model was refined. In order to better simulate the process of crack propagation from the inner to the outer wall in the damaged fluid-filled cylindrical shell, a multi-layer mesh division was also implemented radially on the cylindrical shell. This allowed the crack to gradually extend from the inner wall to the outer wall. To ensure the accuracy of the fluid burst flow state when the crack penetrated the cylindrical shell, the mesh near the crack in the fluid domain was also refined. The mesh division of the fluid region and the cylindrical shell region, which are the main subjects of this study, is illustrated in Figure 5.

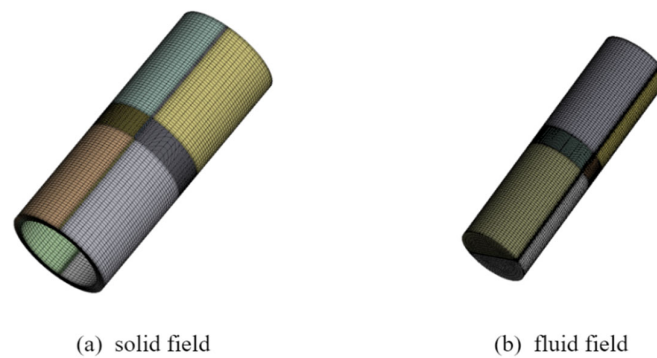


Figure 5. Meshing of the solid and fluid domains of the damaged liquid-filled cylindrical shell.

The boundary conditions were set with both ends of the cylindrical shell and the baffle fixed, and the interface between the damaged cylindrical shell and the fluid region was designated as a fluid-structure interaction (FSI) contact surface. One end of the fluid-filled cylindrical shell, not obstructed by the baffle, was established as the experimental fluid inlet. The fluid velocity started at 0 and increased linearly, with an increment of 2 m/s per second, until the crack penetrated the damaged fluid-filled cylindrical shell, leading to the shell's failure. The dynamic finite element model of the damaged fluid-filled cylindrical shell, based on fluid-structure interaction, is illustrated in Figure 6.

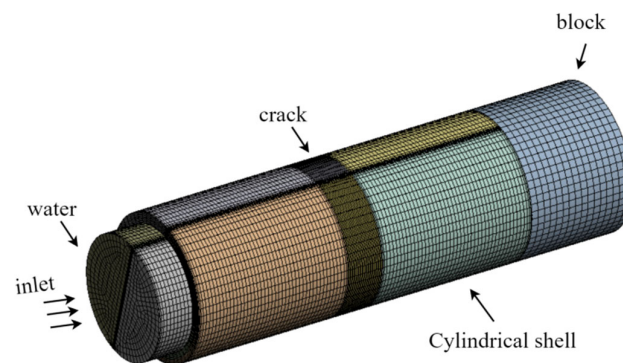


Figure 6. Fluid-solid interaction based finite element model of damaged liquid-filled cylindrical shell dynamics.

3.2. Mesh Independence Verification

In order to ensure the calculation accuracy, the mesh quality was above 0.8. At the same time, the iteration step length was 0.01 s and the number of steps was 1000 times.

The finite element model of the damaged cylindrical shell, containing circumferential and axial cracks (illustrated in Figure 7), underwent a mesh independence verification. We analyzed the stress values at the crack tips of cylindrical shell models with varying total numbers of elements under a 50 MPa tensile load (presented in Table 2). The results indicated that the model with 136,890 meshes contained very few error elements and critical elements. The stress value errors at the crack tips in damaged cylindrical shell models with different total numbers of elements were all less than 0.5% under tensile loading. This confirmed the mesh independence of the damaged cylindrical shell finite element model.

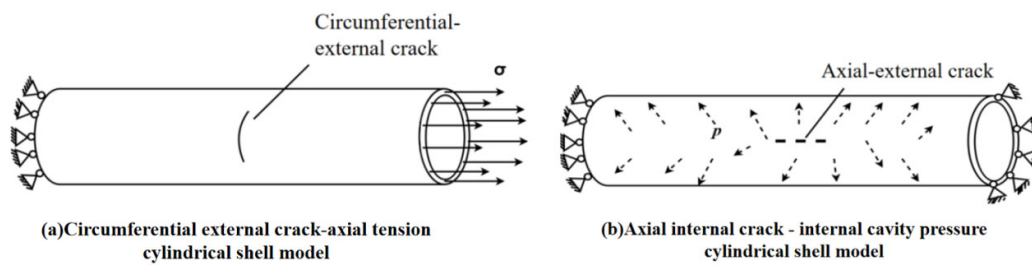


Figure 7. Cylindrical shell model for circumferential outward cracking-axial stretching and axial inward cracking-internal cavity pressure.

Table 2. Stress values at the crack tip under a 50 MPa tensile load for cylindrical shell models with different total numbers of elements.

Element Number	45,630 (n)	91,260 ($2n$)	136,890 ($3n$)	182,520 ($4n$)
S	55.404 MPa	55.503 MPa	56.105 MPa	55.902 MPa
err	−0.89%	−0.71%	0.36%	/

4. Results and Discussion

4.1. Effect of Crack Initial Angle on the Paths of Crack Propagation in Damaged Fluid-Filled Cylindrical Shells

The initial crack was a planar straight edge crack with a crack width of 10 mm and a depth of 1.5 mm. The crack propagation simulations of the damaged fluid-filled cylindrical shell were performed by respectively setting the initial crack angles to 0° , 15° , 30° , 45° , 60° , and 75° . Figure 8 shows the simulation results of crack propagation at each initial crack angle. It can be observed from the figure that, regardless of changes in the initial crack angle, after a period of propagation, the crack consistently extended along the axis of the damaged fluid-filled cylindrical shell.

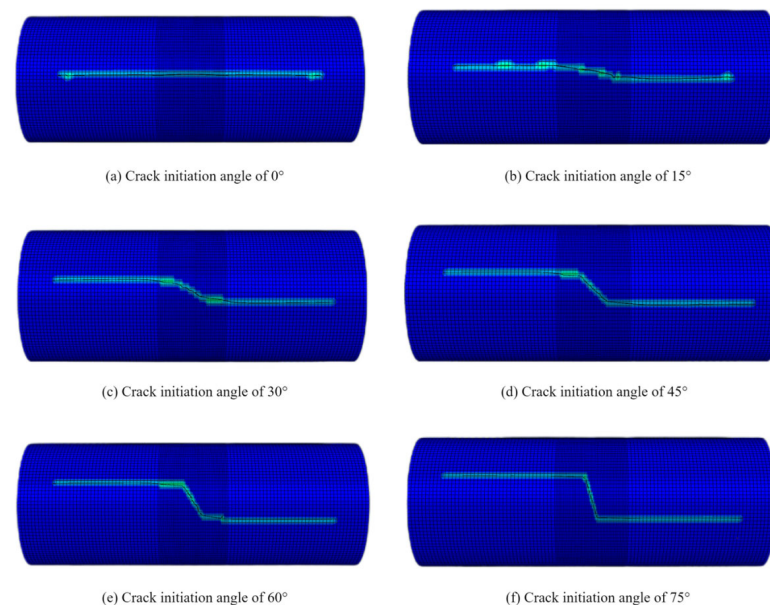


Figure 8. Results of crack propagation on the outer wall of a damaged fluid-filled cylindrical shell under different initial crack angles.

The results of crack propagation on the inner wall and the final morphology of the crack surfaces at different initial crack angles are shown in Figures 9 and 10. Observation of the crack propagation on the inner wall under different initial crack angles and the final

results of crack propagation on the outer wall shows that they were basically similar. The crack surfaces were generally flat, although in some cases the propagation speed of the inner wall cracks was slightly faster than that of the outer wall. However, the overall trend remained consistent.

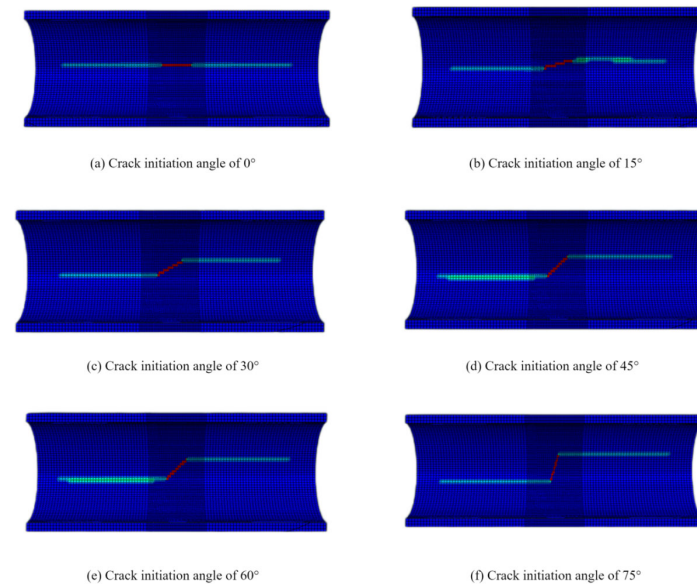


Figure 9. Results of crack propagation on the inner wall of a damaged fluid-filled cylindrical shell under different initial crack angles.

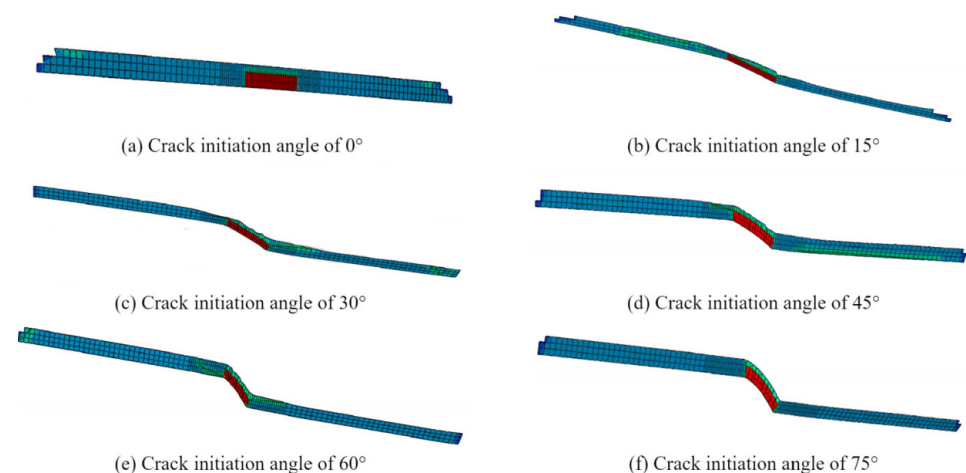


Figure 10. Final morphology of cracked surface of damaged fluid-filled cylindrical shell with different initial crack angles.

As indicated by the above figures, the initial crack angle of crack propagation influenced the direction of cracks in the damaged fluid-filled cylindrical shell during the initial stages of propagation. The direction of crack growth gradually shifted from the initial crack angle towards the axis of the cylindrical shell. However, after a brief period, the crack invariably extended outward along the axis of the cylinder. During the phase before the crack penetrated the outer wall of the cylindrical shell, the crack propagation speed was relatively slow. Once the crack breached the outer wall, the outer wall crack propagated faster, following a similar path to the inner wall crack, and then continued at a consistent speed. Since the inner wall was directly subjected to pressure, the crack propagation path may have advanced a few grid units faster than that on the outer wall. At the end of the

propagation, the crack patterns on the inner and outer walls of the damaged fluid-filled cylindrical shell were consistent, and the crack surfaces were smooth.

4.2. Effect of Initial Crack Angle on the Failure Process of Damaged Fluid-Filled Cylindrical Shells

The crack depth in the damaged cylindrical shell was set to be 2.00 mm, and the crack width was set to be 10 mm. The effects of different initial crack angles on the crack penetration velocity in the damaged fluid-filled cylindrical shell were investigated by adjusting the initial crack angles to be 0° , 15° , 30° , 45° , 60° , and 75° . Figure 11 shows the time-displacement curves of the crack penetration unit in the outer wall of the damaged fluid-filled cylindrical shell model with different initial crack angles.

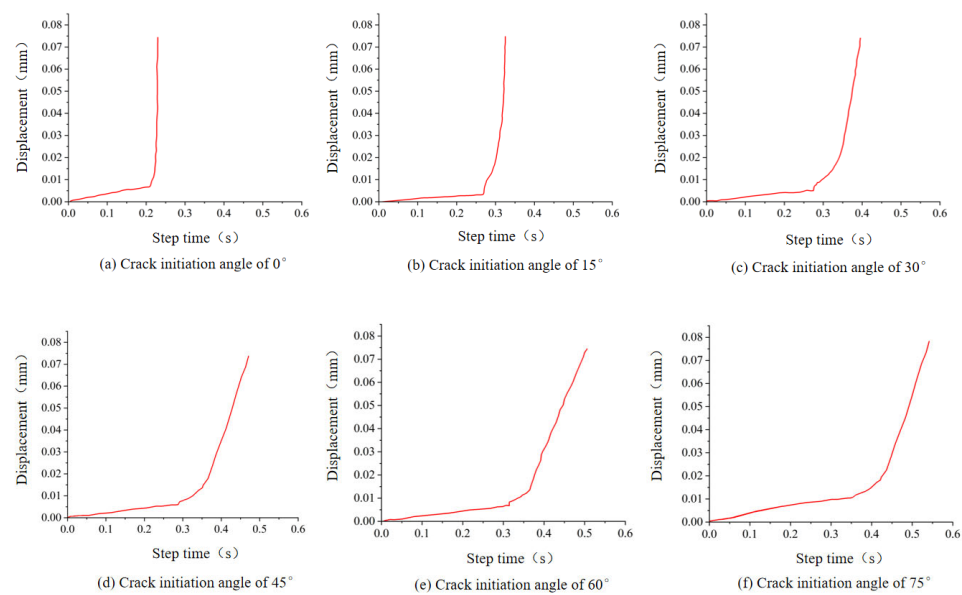


Figure 11. Time-displacement curves for crack penetration units in a damaged fluid-filled cylindrical shell at different initial crack angles.

The time-displacement curves from the damaged fluid-filled cylindrical shell models at different initial crack angles indicate that as the initial crack angle increased, the time of abrupt change in the time-displacement curve of the outer wall units was delayed, and the slope after the abrupt change also gradually decreased. This preliminary observation suggested that the crack penetration speed in the damaged fluid-filled cylindrical shell decreased as the initial crack angle increased. By analyzing the data from the time-displacement curves of crack penetration units at various initial angles, we recorded the times of abrupt changes, the onset of plastic deformation t_b , and the occurrence of crack penetration t_s . These findings are plotted and presented in Table 3 and Figure 12.

Table 3. Times of plastic deformation and crack penetration for outer wall units of a damaged cylindrical shell at different initial crack angles.

Initial Crack Angles	0°	15°	30°	45°	60°	75°
t_b	0.2251	0.2694	0.2750	0.2887	0.3127	0.3519
t_s	0.2455	0.2827	0.2903	0.3088	0.3315	0.3740

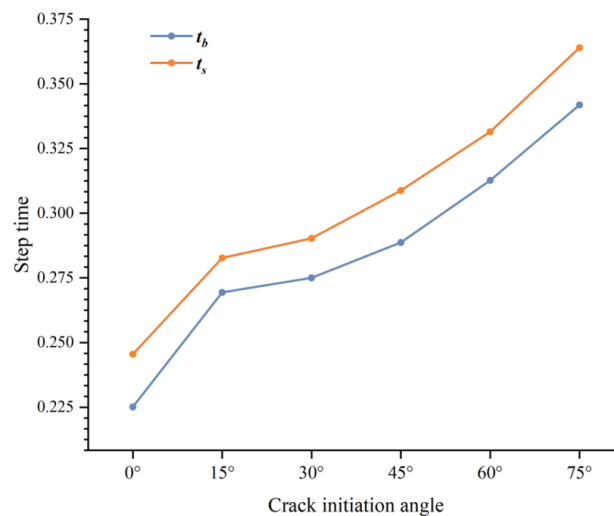


Figure 12. Time required for crack penetration in a damaged fluid-filled cylindrical shell at different initial crack angles.

Figure 12 shows that as the initial crack angle increased, the rate of plastic deformation and crack penetration in the damaged fluid-filled cylindrical shell model gradually decreased. Additionally, the difference between the time of plastic deformation of the outer wall units and the time of crack penetration remained consistently around 0.02 s when the internal crack began to expand. When the initial crack angle was 0°, the crack penetrated the cylindrical shell model the fastest. Between 15° and 60°, the slope was smaller and the increase in time was slower; whereas at the extremes of 0° and 75°, the slope was steeper, and the crack penetration time increased rapidly. Due to the internal fluid pressure, cracks always extended toward both ends along the axis of the cylindrical shell. Therefore, when the initial crack angle was 0°, it aligned with the path of crack propagation in the damaged cylindrical shell, resulting in the fastest crack penetration. Conversely, when the initial crack angle was 75°, the direction of the crack differed significantly from the propagation direction, resulting in slower crack penetration.

For fluid-filled cylindrical shell structures, the maximum internal pressure that the structure can withstand is a critical parameter that must be determined to ensure the safe and normal operation of the structural components. The initial crack was set to have a depth of 2.25 mm and a width of 10 mm, represented by a through-thickness straight-edged crack. The maximum bearable internal pressure at the onset of internal crack propagation in the damaged cylindrical shell was defined as p_b , and the maximum bearable internal pressure at the time of crack penetration through the damaged cylindrical shell was defined as p_t , and the crack initiation angles were taken to be 0°, 15°, 30°, 45°, 60°, and 75°, respectively. The maximum internal pressures that can be sustained by the damaged fluid-filled cylindrical shells at different initial crack angles are shown in Table 4 and Figure 13.

Table 4. Maximum bearable fluid pressure in a damaged fluid-filled cylindrical shell model at different initial crack angles.

Initial Crack Angles	0°	15°	30°	45°	60°	75°
p_b	88.903	102.732	110.435	119.584	126.001	135.255
p_t	99.172	113.620	122.941	129.092	136.217	147.308

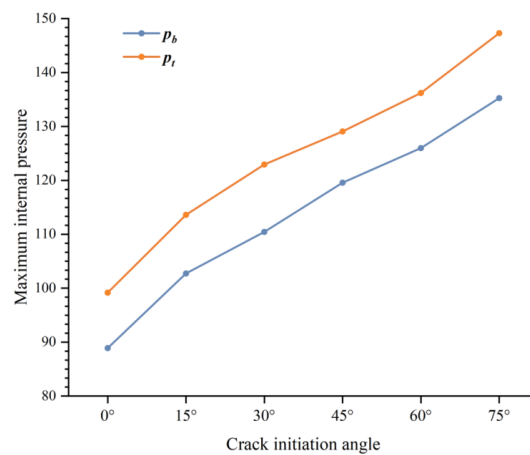


Figure 13. Maximum bearable fluid pressure in damaged fluid-filled cylindrical shells with various initial crack angles.

The charts indicate that as the initial crack angle increased, the maximum fluid pressure that the damaged fluid-filled cylindrical shell could withstand also gradually increased. Additionally, the difference between the maximum internal pressure p_b that could be borne at the onset of crack propagation and the maximum internal pressure p_t at the time of crack penetration was approximately 10 MPa. Moreover, the pattern of change in the maximum sustainable internal pressure related to the initial crack angle mirrored the trend observed in the crack penetration speed. When the initial crack angle was in the middle range, the change in maximum bearable pressure was minimal, and the slope of the curve was relatively flat. In contrast, at the extremes, specifically at 0° and 75°, the variation in maximum bearable fluid pressure was more significant. Particularly at an initial crack angle of 0°, the change was most pronounced with a maximum internal pressure decay of about 14.448 MPa, a decay rate of 12.7%, and a decay value of approximately 13.829 MPa, with a decay rate of 13.46%.

Since the path of crack propagation in a damaged fluid-filled cylindrical shell typically extends along the axis of the cylinder towards both ends, cracks are most likely to propagate and cause the shell to rupture when the initial crack direction aligns with the propagation path. Under these conditions, the maximum fluid pressure that the damaged cylindrical shell can withstand reaches its lowest value.

4.3. Analysis of Fluid Flow States in Damaged Fluid-Filled Cylindrical Shells Based on Fluid-Structure Interaction Experiments

Research on fluid domain elements within a dynamic model involves analyzing the experimental fluid in damaged fluid-filled cylindrical shells. This study focused on the maintenance of pressure in the experimental fluid during the crack propagation and failure processes in damaged fluid-filled cylindrical shells, as well as the flow state of the fluid when it bursts through the shell wall upon complete crack penetration.

The process of experimental fluid bursting from a damaged cylindrical shell with axial cracks upon crack penetration is shown in Figure 14. When the crack penetrated, it first initiated at the center of the crack, causing the experimental fluid to burst out sharply from the penetration point and gradually rise. At this moment, the internal pressure of the experimental fluid within the cylindrical shell was not lost; instead, as the crack path continued to expand, stress concentrated at the crack tip, causing fluid to burst out of the newly formed cracks as shown in Figure 14c, where the stress in the area near the shell's crack was significantly higher than in other areas. Subsequently, as the crack continued to expand, a substantial amount of experimental fluid began to burst out, and the damaged fluid-filled cylindrical shell gradually lost its pressure-bearing capability, with the pressure of the experimental fluid gradually dropping to zero. During this process, the initial

bursting location of the experimental fluid remained the point of greatest displacement. Figure 15 shows the displacement of the experimental fluid in the fluid-filled cylindrical shell with axial cracks during the bursting process. It can be seen that the initial burst of experimental fluid occurred at the point of greatest displacement.

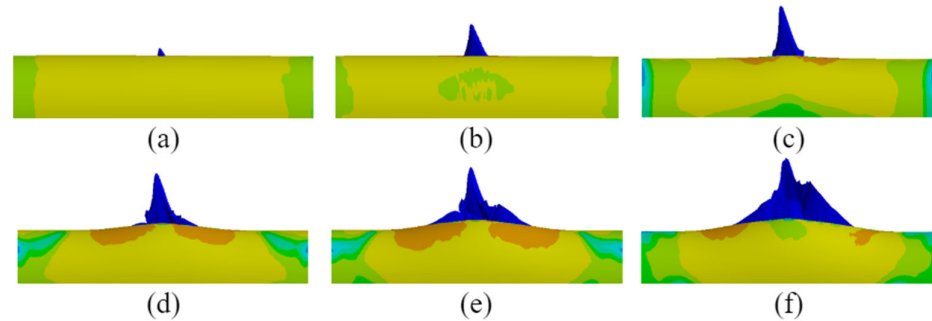


Figure 14. Flow pattern of experimental fluid bursting out of a fluid-filled cylindrical shell containing axial cracks when the cracks penetrate. (a) 0.02 s; (b) 0.04 s; (c) 0.06 s; (d) 0.08 s; (e) 0.10 s; (f) 0.12 s.

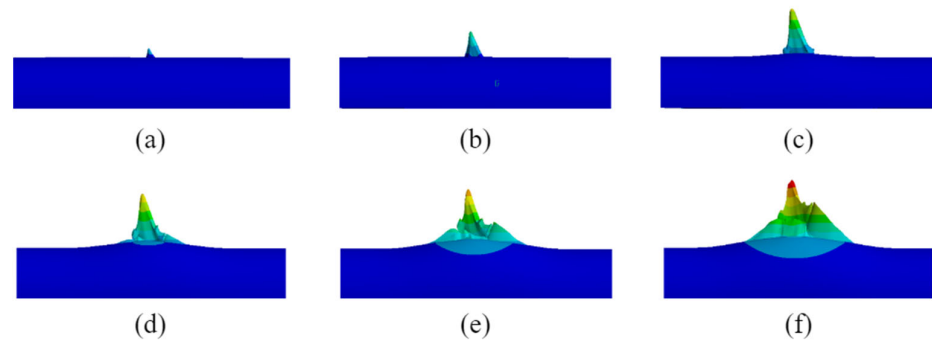


Figure 15. Experimental fluid displacement processes bursting out during crack penetration in cylindrical shells containing axial cracks filled with fluid. (a) 0.02 s; (b) 0.04 s; (c) 0.06 s; (d) 0.08 s; (e) 0.10 s; (f) 0.12 s.

The process of experimental fluid bursting from a fluid-filled cylindrical shell with circumferential cracks under an acceleration of 10 m/s^2 is illustrated in Figure 16. When the crack penetrated, the experimental fluid burst along the initial crack path in a sharp, peak-like manner, as shown in Figure 16a–c. As the crack continued to expand, vulnerable units appeared on both sides of the circumferential crack. These vulnerable units bent due to the fluid pressure, causing a sudden increase in crack area, which paradoxically led to a decrease in the height of the bursting experimental fluid, as shown in Figure 16d,e. Subsequently, the cracks formed at the tips of the two circumferential cracks converged into a wider crack due to the fracture of vulnerable units, and the experimental fluid re-emerged in a manner similar to bursting beneath axial cracks, with the center of the crack still showing the greatest displacement of the experimental fluid. After a certain duration of fluid bursting and the formation of a larger crack face in the cylindrical shell, as shown in Figure 16h,i, the stress on the cylindrical shell was significantly reduced compared to before, resulting in shell failure and loss of pressure-bearing capacity.

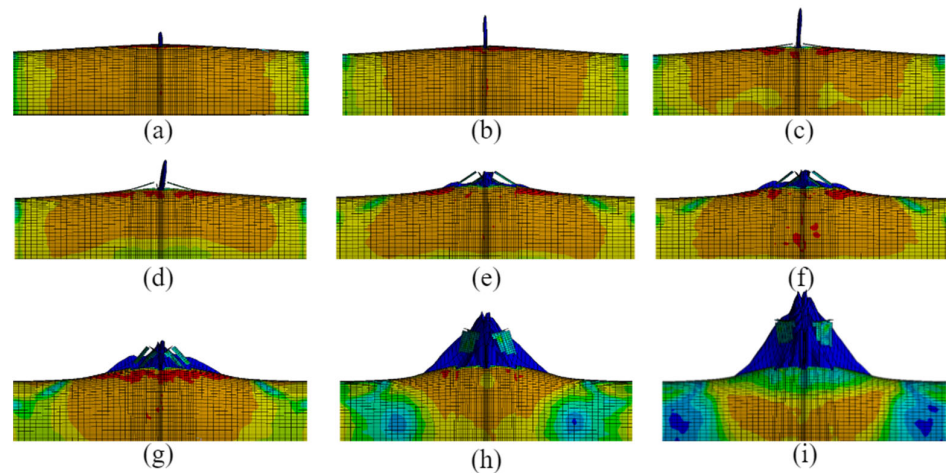


Figure 16. Flow patterns of experimental fluids bursting out when a circumferential crack-filled cylindrical shell is cracked through. (a) 0.02 s; (b) 0.04 s; (c) 0.06 s; (d) 0.08 s; (e) 0.10 s; (f) 0.12 s; (g) 0.14 s; (h) 0.16 s; (i) 0.18 s.

After completing the investigation into the changes in the flow state of the experimental fluid within the damaged fluid-filled cylindrical shell as the crack expanded, a study on the changes in fluid pressure inside the shell during the crack expansion process was conducted. Figure 17 shows the changes in the experimental fluid pressure inside the damaged fluid-filled cylindrical shell over time. In the model of the damaged cylindrical shell, the crack depth was 2.25 mm, and the crack width was 10 mm, and the initial crack angle was set to be 0° . The line graph of the experimental fluid pressure changes in the damaged cylindrical shell shows a gradual increase in internal fluid pressure due to the influx of fluid, as a baffle was placed at the outlet of the damaged cylindrical shell. When the stress at the crack tip on the inner wall of the damaged cylindrical shell exceeded the yield strength, plastic deformation occurred in the units near the crack tip, and the crack began to expand, with the internal experimental fluid pressure at that moment being 91.77 MPa. The experimental fluid pressure continued to increase as the crack expanded to penetrate the outer wall of the cylindrical shell, reaching its maximum value at 102.22 MPa.

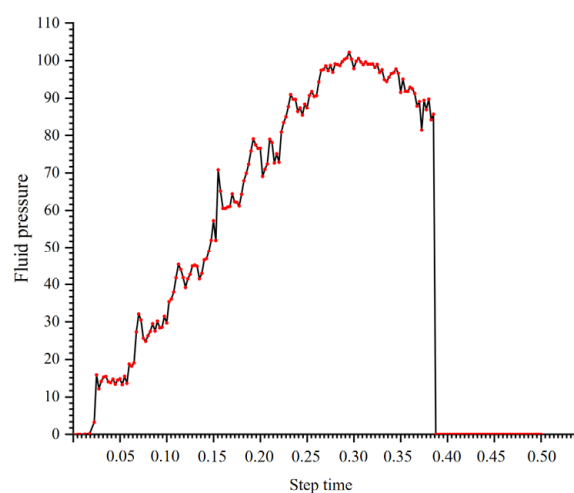


Figure 17. Experimental fluid pressure variation in damaged fluid-filled cylindrical shells containing axial cracks.

When using a dynamics model of a damaged fluid-filled cylindrical shell based on fluid-structure interaction for crack propagation, the fluid pressure inside the shell is extracted from the fluid domain elements, making the calculation of changes in the

experimental fluid pressure inside the shell more accurate. The line graph shows that after the fluid pressure inside the shell reached its maximum and the cylindrical shell's crack penetrated, the fluid did not immediately lose pressure but maintained it for a certain period. Once the crack expanded to a certain extent, the damaged fluid-filled cylindrical shell completely failed, at which point the fluid inside the shell lost pressure.

5. Experiment on Crack Propagation of Damaged Liquid-Filled Cylindrical Shells

5.1. Experimental Purpose and Plan

In previous studies on crack propagation in damaged liquid-filled cylindrical shells, theoretical model calculations were used to solve the problem. The experimental method is also an effective method for studying the crack propagation problem of damaged liquid-filled cylindrical shells. In view of this, this article established an experimental platform for observing the crack propagation behavior of damaged liquid-filled cylindrical shells.

In the previous chapters, when using theoretical models to calculate the crack propagation problem of damaged liquid-filled cylindrical shells, we found that a fluid pressure of approximately 100 MPa was required to induce crack propagation in a damaged liquid-filled cylindrical shell made of SAF2205 duplex steel with a wall thickness of 3 mm. The fluid pressure reached ultra-high pressure, and the existing experimental conditions did not meet the experimental requirements. Therefore, when conducting crack propagation on damaged liquid-filled cylindrical shells, in order to obtain clear and intuitive experimental results, the model of the test tube was modified to reduce the wall thickness to 0.5 mm. To ensure the accuracy of the experimental results, the pipe diameter was proportionally reduced, and the crack propagation results were remodeled and calculated based on the modified parameters of the test tube model.

The test tube assembly prepared for the liquid-filled crack propagation experiment is shown in Figure 18. There were a total of six test tube components in the test tube group, each prefabricated with cracks starting at 0° , 15° , 30° , 45° , 60° , and 75° . We observed the crack propagation path of the test specimens with different initial crack angles and the flow state of the experimental fluid when the crack penetrated the test specimens, and compared and verified these results with the theoretical model calculation results.



Figure 18. The test tubes in the damaged liquid-filled cylindrical shell crack propagation experiment.

5.2. Establishment of an Experimental Platform for Observing Crack Propagation in Damaged Liquid-Filled Cylindrical Shells

To meet the observation needs of crack propagation experiments on damaged liquid-filled cylindrical shells, a crack propagation observation experimental platform for damaged liquid-filled cylindrical shells was established. The experimental platform consisted of three subsystems: isolation support subsystem, fluid conveying subsystem, and image acquisition subsystem. The isolation support subsystem was used to complete the fixation of the test tube components and ensure the smooth operation of the experiment; the fluid transport subsystem was used to complete the cyclic flow of experimental fluids through-

out the entire experimental platform; the image acquisition subsystem was used to collect image data during the experimental process. The components of the isolation support subsystem, fluid transport subsystem, and image acquisition subsystem of the observation experimental platform for crack propagation in damaged liquid-filled cylindrical shells are shown in Figures 19–21.

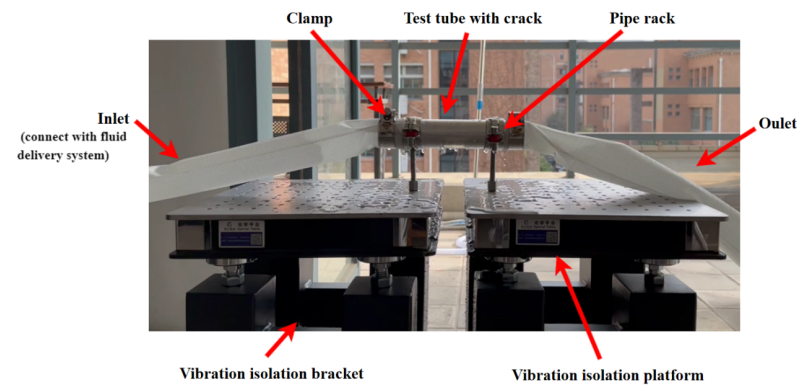


Figure 19. Experimental platform for observation of crack propagation of damaged liquid-filled cylindrical shell—vibration isolation support subsystem.

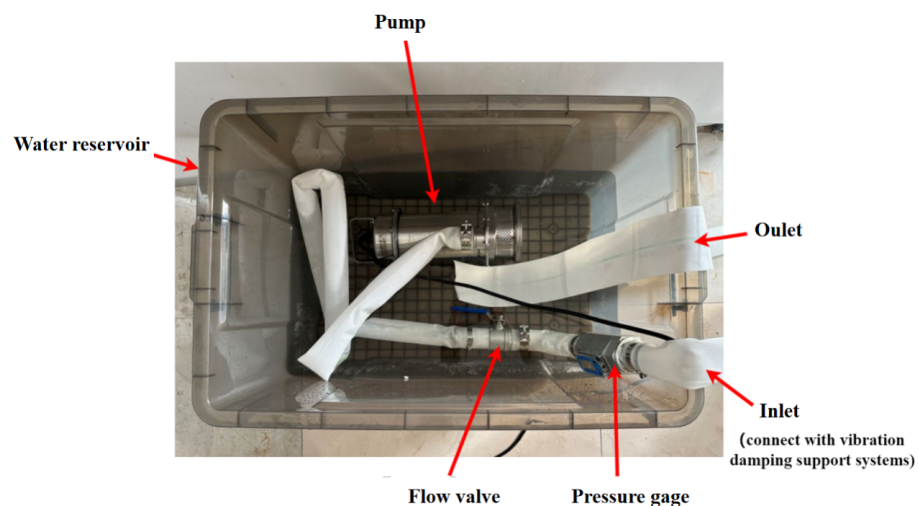


Figure 20. Experimental platform for observation of crack propagation of damaged liquid-filled cylindrical shell—fluid delivery subsystem.

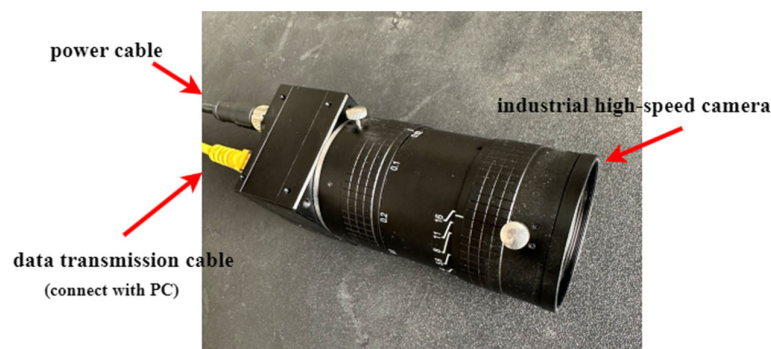


Figure 21. Experimental platform for observation of crack propagation of damaged liquid-filled cylindrical shell—image acquisition subsystem.

The isolation support subsystem in the crack propagation observation experimental platform for damaged liquid-filled cylindrical shells is shown in Figure 19. The isolation support subsystem consisted of isolation platform brackets, isolation platforms, clamps, and pipe racks. The isolation platform bracket was used to support the isolation platform, and its supporting platform foot and base both contained a damping isolation system, which had an excellent vibration reduction effect. The bracket body was made of carbon steel, which had a large weight and high hardness, and maintained stability even under large impacts. The isolation platform was installed above the isolation platform bracket for fixing experimental equipment. The platform was equipped with 10×10 array M6 threaded holes with a spacing of 25 mm, which accurately installed experimental components. The bottom of the platform also included a damping isolation system, which had a certain vibration reduction effect. The pipe rack was used to fix the test tube component, with an M6 threaded column at the bottom, which was conveniently fixed on the isolation platform. The top was a circular clamp, which was fastened to the pipe rack by screws; the clamp was used to connect the inlet and outlet pipes to the test tube components, forming a fluid circulation circuit. The isolation support subsystem was connected to the fluid transport subsystem through the inlet and outlet pipelines.

The fluid transport subsystem in the experimental platform for observing crack propagation in damaged liquid-filled cylindrical shells is shown in Figure 20. The fluid conveying system consisted of a submersible pump, a reservoir, a flow valve, a pressure gauge, an inlet pipeline, and an outlet pipeline. The submersible pump was used to provide fluid pressure, allowing the experimental fluid to circulate in the fluid circuit of the experimental platform. The reservoir was used to store experimental fluids and ensure the normal operation of the submersible pump. The flow valve was used to control the flow rate in the fluid circuit of the experimental platform, in order to achieve the function of adjusting the pressure of the experimental fluid. The pressure gauge was used to read the real-time pressure of the experimental fluid. The inlet pipeline was used to transport the experimental fluid from the fluid transport subsystem to the test tube component. The reflux pipeline was transported back to the reservoir by the fluid in the test tube, forming a complete experimental platform fluid circuit.

The image acquisition subsystem in the experimental platform for observing crack propagation in damaged liquid-filled cylindrical shells is shown in Figure 14. The image acquisition system consisted of a high-speed industrial camera and a personal computer. High-speed industrial cameras were used to capture data images during crack propagation experiments, and the images were sent to personal computers through data cables; personal computers were used to receive and store experimental image data sent by high-speed industrial cameras, and perform postprocessing to make the experimental images more intuitive and clear.

5.3. Experimental Results of Crack Propagation in Damaged Liquid-Filled Cylindrical Shells

Figure 22 shows the results of crack extension paths for the crack extension experiment of a liquid-filled damaged cylindrical shell. The left side of the figure shows the state of the test tube before the experiment, the middle part of the figure shows the test tube after the completion of the liquid-filled crack extension experiment, while the right side of the figure shows the simulation results of the damaged cylindrical shell model with the same dimensional parameters obtained through numerical calculations. From the experimental results, it can be seen that the cracks in the test tubes grew from the crack tip and continued to expand along the axial direction under the internal liquid pressure, regardless of the initial angle of the prefabricated cracks. Compared with the simulation results obtained through numerical calculations, the crack expansion paths of the damaged liquid-filled cylindrical shells under internal liquid pressure were essentially the same, showing a high degree of consistency. This observation provides a profound physical understanding of the crack extension behavior. First, the experiments clearly showed that crack extension tended to proceed along the axial direction of the material even when the initial crack angle

was different. This emphasizes the dominant role of axial stresses in the crack extension process, which is less related to the initial crack direction.

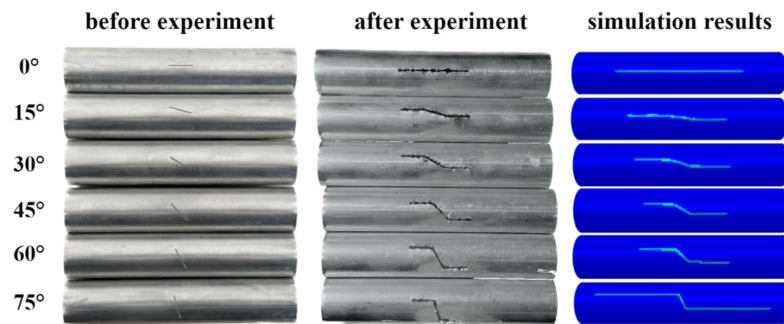


Figure 22. Experimental results of crack propagation of damaged liquid-filled cylindrical shell.

Figure 23 illustrates the analysis of the fluid flow dynamics after crack extension compared to the simulation results in an experimentally damaged, fluid-filled, axially cracked cylindrical shell. A detailed analysis of the experimental data resulted in a sequence of events after crack penetration. Initially, the experiment produced an eruption of fluid from the center of the crack in a fluid-filled test tube. This initial eruption marked the instant of crack penetration, which is a critical stage in the fluid–shell interaction. Subsequently, crack extension occurred, a critical moment that affected the structural integrity of the shell. As the crack expanded, fluid was sequentially ejected from the advancing crack front along the crack’s expansion path. This sequential fluid ejection is important because it shows the fluid response to dynamic changes in the shell microstructure. Notably, the fluid flow reached a distinct peak at the initial penetration location. The experimental peak height was shown to be slightly higher than that predicted by the original kinetic model. Despite the slight difference in peak heights, the overall change in flow state was closely related to the simulation results. The consistency of the fluid outflow process validates the effectiveness of the theoretical model in capturing the fundamental aspects of the flow–shell interaction during crack extension. The consistency of experimental and simulation results emphasizes the important validation of the theoretical framework.

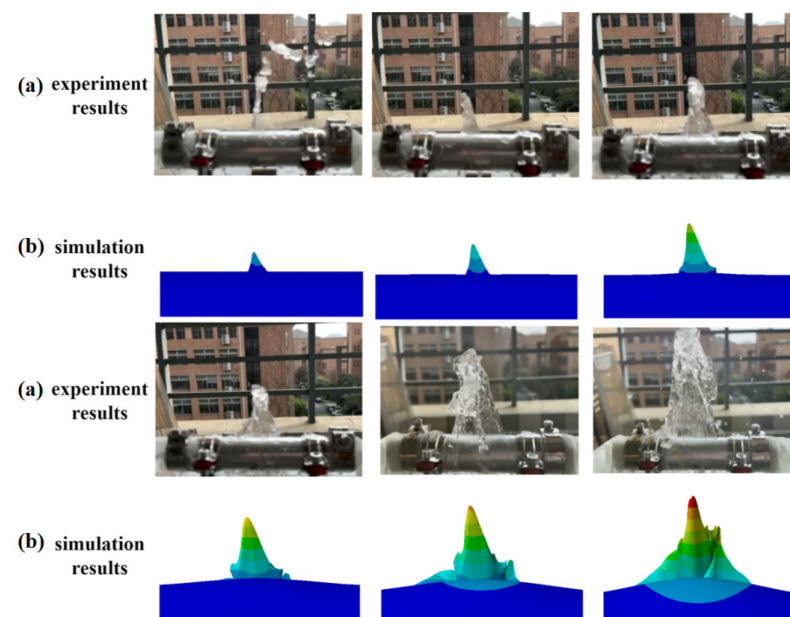


Figure 23. Experimental results on the flow pattern of damaged liquid-filled cylindrical shells containing axial crack.

6. Conclusions

This paper presents a static modeling method for damaged fluid-filled cylindrical shells based on the extended finite element method (XFEM), exploring the impact of different initial crack angles on the crack propagation paths and failure processes of the shells. Additionally, based on fluid-structure interaction theory, a dynamic model of the damaged fluid-filled cylindrical shell was established to capture the crack propagation process under fluid influence. This study also analyzed changes in pressure and flow state during the shell's failure process and verified these findings experimentally. The main conclusions are summarized as follows:

(1) The initial crack angle influences the direction of crack propagation in the damaged fluid-filled cylindrical shell. Initially, the crack gradually deviates from its original direction towards the axial direction and then extends along the axis. After the crack penetrates the outer wall, it rapidly expands along the path of the inner wall crack and eventually propagates in conjunction with it. The inner wall, subjected to direct pressure, causes the crack path to progress several mesh elements faster than that of the outer wall.

(2) As the initial crack angle increases, the plastic deformation and the speed of crack penetration in the damaged fluid-filled cylindrical shell model gradually decrease. When the initial crack angle is 0° , the crack penetrates the cylindrical shell model the fastest. However, when the initial crack angle is 75° , the difference between the initial and expansion directions of the crack is significant, resulting in a slower penetration speed of the crack through the damaged fluid-filled cylindrical shell.

(3) Cracks typically extend along the axis of the damaged fluid-filled cylindrical shell towards both ends. When the initial direction of the crack aligns with its expansion path, the crack is more likely to extend and penetrate through the shell. In this scenario, the maximum fluid pressure that the damaged fluid-filled cylindrical shell can withstand drops to its lowest value.

(4) Based on fluid-structure interaction theory, a dynamic model of the damaged fluid-filled cylindrical shell was established, studying the changes in internal fluid pressure and the flow state during crack penetration. When the initial crack was an axial crack with a depth of 2.25 mm and a width of 10 mm, the maximum internal fluid pressure in the damaged fluid-filled cylindrical shell was 102.22 MPa. The maximum internal pressure that the shell could withstand, calculated using XFEM under the same conditions, was 99.17 MPa, with an error of 3.07%.

Author Contributions: Conceptualization, H.Z. and L.L.; article identification, screening, retrieval, selection, and analysis, H.Z., H.Q. and D.T.; formal analysis and investigation, D.T. writing—original draft preparation, H.Z. and T.H.; tables and figures generation, H.Z. review and editing, S.X. supervision, L.L., H.Q. and D.T.; funding acquisition, L.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported in part by the Natural Science Foundation of China (NSFC) under Grant No. 52305139; Zhejiang Provincial Natural Science Foundation under Grant No. LQ23E050017; Zhejiang Provincial Natural Science Foundation under Grant No. LR22E050005; Zhejiang Province Postdoctoral Scientific Research Preferred Funding Project under Grant No. ZJ2022068.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare that they have no conflict of interest.

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