

Article

Study on Earthquake Failure Mechanism and Failure Mode of Cable-Stayed Pipeline Bridge Considering Fluid–Structure Coupling

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Abstract: To investigate the failure mode of the cable-stayed pipeline bridge under seismic loading, this study focuses on an oil and gas cable-stayed pipeline bridge as the research subject. A full-scale finite element calculation model of the structural system is established using ANSYS Workbench 14.0 software, considering the stress characteristics and structural properties of the oil and gas pipeline. Additionally, a fluid–structure coupling effect finite element model is developed to account for the influence of medium within the pipeline. The analysis includes evaluating deformation, stress, strain, and other responses of the oil and gas pipeline subjected to seismic waves from different directions. The results indicate that the overall damage in the pipeline is consistent with maximum deformation, stress, and strain, concentrated at both the inlet/outlet ends and side spans; however, variations exist in terms of seismic damage depending on wave directionality. Furthermore, by considering interactions between various components within the oil and gas cable-stayed pipeline bridge's structural system during strong earthquakes, this study analyzes failure mechanisms caused by the support–pipeline interaction as well as excessive displacement-induced failure patterns in bridge towers. Finally, a proposed failure mode for pipe bridge systems resulting from longitudinal slip between supports and pipelines, along with excessive displacement of bridge towers, is presented.

Keywords: oil and gas cable-stayed pipeline bridge; fluid–structure coupling; failure mechanism; failure mode



Citation: Zhu, X.; Weng, G. Study on Earthquake Failure Mechanism and Failure Mode of Cable-Stayed Pipeline Bridge Considering Fluid–Structure Coupling. *Appl. Sci.* **2023**, *13*, 9583. <https://doi.org/10.3390/app13179583>

Academic Editor: Laurent Daudeville

Received: 27 July 2023

Revised: 16 August 2023

Accepted: 22 August 2023

Published: 24 August 2023



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1. Introduction

The structural integrity of straddling oil and gas pipelines is a critical aspect for ensuring the safety of long-distance transportation, with seismic activity posing one of the most significant threats. Extensive engineering practice highlights the importance of studying the failure mechanisms caused by earthquakes in these pipeline structures. When investigating damage mechanisms, it is essential to consider the influence of oil and gas mediums on pipeline behavior. In the case of cable-stayed pipeline bridges used for oil and gas transportation, the load within the pipes consists of various materials, such as oil and natural gas, which can affect the pipeline's performance during transport operations. While this effect may not be prominent under normal circumstances, strong earthquakes can induce vibrations in both the pipeline structure and its contents, leading to mutual interactions that impact the overall system stability. Therefore, theoretical analysis and numerical simulations analyzing earthquake failure mechanisms in straddling oil and gas pipelines must incorporate considerations for medium–pipeline interactions [1,2].

Fluid–structure coupling (FSC) is a multi-physical field coupling problem that involves the interaction between fluid dynamics and structural mechanics. Since the 1970s, foreign scholars have been extensively studying fluid–structure coupling vibration. Mueller [3] conducted a comparative analysis of the dynamic characteristics of an experimental structural

system under both coupled and uncoupled conditions to investigate the effect of fluid–structure coupling. Lavooij et al. [4] analyzed the phenomenon of pressure attenuation in three-dimensional pipeline systems and attributed it to the influence of fluid–structure coupling, which was further supported by theoretical verification. The establishment of a nonlinear dynamic model for pipeline vibration considering fluid–structure coupling requires assumptions such as non-viscous fluids, incompressible pipelines, neglecting shear deformation and moment of inertia in section vibrations, etc. Building upon these assumptions, numerous scholars have focused on investigating other influencing factors. Paidoussis et al. [5] examined gravity effects, damping properties of pipe materials, and viscous damping while proposing a general equation to describe nonlinear dynamics in structures. Based on this work, Lee et al. [6] developed a nonlinear model capturing the impact of fluid–structure coupling by disregarding Poisson’s ratio effects. In China, research on the seismic response considering fluid–structure coupling vibrations in pipelines emerged relatively late. Fei et al. [7] proposed a comprehensive mathematical model for fluid–structure coupling in pipeline systems with complex boundary conditions, employing two distinct modeling methods. Xu et al. [8] developed a mathematical model based on an actual suspended oil pipeline, considering the fluid–structure coupling effect during earthquakes. They established the vibration equation of the pipeline using the finite element method and the Hamilton principle and solved it directly to obtain the seismic dynamic response under various flow rates and boundary conditions using the Newmark step-by-step integration method. Liang et al. [9] constructed a finite element model incorporating fluid–structure coupling to analyze the seismic performance of pipelines. By varying parameters such as the medium density and velocity within the pipeline, they identified their close relationship with pipeline failure. Xu et al. [10] employed a fourteen-equation model along with the transfer matrix method (TMM) to describe fluid–structure coupling in liquid-filled pipelines, presenting a general solution applicable to multi-branch pipelines, while also providing a means for predicting the frequency response in complex pipeline systems. Xu et al. [11] proposed a precise and efficient method for transferring coupling data interfaces to describe the vibration response model caused by the fluid–solid coupling effect of oil and gas pipeline structures, thereby achieving a comprehensive calculation model for fluid–solid coupling vibrations in oil and gas pipelines. Dos et al. [12] utilized a reduced order model to analyze the fluid–structure coupling in pipelines, employing the Bernoulli–Euler beam to represent the pipeline and a nonlinear oscillator to represent the fluid dynamics. The reduced order model successfully simulated the pipeline response spectrum while considering variations in flow rate parameters and random fluctuations. Wang et al. [13] investigated the dynamic characteristics of buried water supply pipelines under earthquake actions, establishing a tube–fluid–solid coupling model for such scenarios and exploring stress responses of pipelines subjected to seismic dynamic actions.

The current analysis of seismic failure mechanisms in cable-stayed straddling oil and gas pipelines, both domestically and internationally, is still imperfect as it only remains at the stage of finite element simulation analysis. Furthermore, there is a lack of experimental research conducted thus far. Wu et al. [14] compared the seismic response results of long-span cable-stayed tube bridges considering linear and nonlinear problems, emphasizing the necessity to consider the nonlinear effects when analyzing the seismic response of such structures. Extensive research has been carried out on earthquake failure mechanisms in suspension pipeline span structures and highway cable-stayed bridges worldwide. In order to investigate the seismic failure and damage of a suspended cable pipeline span structure specifically, Wu et al. [15] designed an experimental scale model for this purpose. They measured vibration and displacement under different pigging speeds and liquid deposition volumes using this scale model, subsequently establishing an empirical formula for the displacement–time curve based on their experimental data. Gao et al. [16] utilized ANSYS software to simulate the seismic damage of a suspended-cable bridge in Changqing Oil Field and obtained the seismic performance of the structure in different directions of seismic propagation through nonlinear time-history analysis. Nie et al. [17] investigated the

failure mode of a long-span suspension bridge based on its design scheme and determined that the seismic failure mode of the tower is characterized by simultaneous double-plastic hinge failures, with plastic failure occurring simultaneously at both the tower body and bottom under longitudinal earthquake action. Dusseau et al. [18] conducted modal and response spectrum seismic analyses on finite element models of four existing pipeline suspension bridges, revealing that locations near the end of suspension pipes experience higher stress levels under earthquake excitation, while support towers for some pipe bridges are prone to damage during high-intensity earthquakes. Zhong et al. [19] simulated the failure mechanism of pipeline joints under earthquake actions, analyzing deformation, stress, and strain characteristics of these joints while summarizing key causes leading to pipeline failures. Guo et al. [20] developed a nonlinear numerical model to investigate the interaction between a large-diameter cylinder structure and soil mass and examined the dynamic response of the structure under recorded seismic waves. Liu et al. [21] analyzed the dynamic response of underground pipelines during earthquakes, conducting numerical simulations of underground pipelines subjected to uniform 3D seismic activation using the mass method, ultimately capturing pipeline displacement, acceleration, and stress responses under such activation.

Currently, there is limited research on the seismic failure modes of cable-stayed pipeline bridge structures, primarily in comparison to other types of span structures. Chen et al. [22] confirmed that under abnormal near-fault earthquakes, the deck of a cable-stayed bridge may vertically disengage from the shear key at the beam pier connection, and they observed that significant lateral displacement at the deck end can lead to damage near the intersection with tower decks. Zhong et al. [23] investigated the combined effects of vertical ground motion (VGM) and horizontal ground motion (HGM) on damage modes and sequences in long-span cable-stayed bridges. VGM had minimal impact on the bearing damage probability but adversely affected the tower and pier damage probability, shifting vulnerability from bearings to piers and towers. Xie et al. [24] designed and constructed a 70/1400 scale model of a 1 m span, cable-stayed bridge to study its seismic response and potential failure mode under lateral seismic excitation. Xie et al. [25,26] conducted an elastoplastic analysis on an actual long-span cable-stayed bridge to investigate the damage and failure modes of the structural system when subjected to seismic waves along both longitudinal and transverse directions. The evaluation index used was the Park damage index. Wang et al. [27] investigated the macroscopic manifestations and microscopic failure phenomena of earthquake-induced damage in buried pipelines, categorizing them into three categories and nine typical failure modes. They also summarized the causes and failure mechanisms associated with each mode. Hu et al. [28] utilized ANSYS software to simulate the entire process of a model under earthquake loading, from stress analysis of concrete units to gradual failure of tower feet leading to instability of the bridge tower. Li et al. [29] discussed control strategies for preventing collapse in cable-stayed bridges, including high-damping rubber bearings, fluid viscous dampers, and locking clutch control methods, and they demonstrated that these three collapse control methods can enhance the anti-collapse ability of bridge specimens while achieving a delayed collapse time, as desired. Ceravolo et al. [30] successfully employed the Wiener entropy of strain measurements as a reliable tool to detect and assess multiple damages of varying sizes and severities in a buried steel pipeline model, demonstrating its viability.

Building upon this, we apply the fluid–solid coupling method to analyze the seismic response of oil and gas pipelines straddling a cable-stayed pipe bridge in this study. The ANSYS software, along with other finite element tools, is utilized to establish a fluid–structure coupling model for the oil and gas pipeline, cable-stayed pipe bridge system. We conduct an analysis on the total deformation and equivalent stress experienced by the oil and gas pipeline under both calculation methods, revealing insights into how fluid–structure coupling affects its failure mechanism. Furthermore, we delve into discussing the failure mode of the cable-stayed pipe bridge oil and gas pipeline structure system resulting from interactions among various components, while also defining different types of damage

inflicted upon the oil and gas pipeline due to these interactions. These findings provide valuable references for seismic design, construction methodologies, and mechanical model analyses pertaining to straddle-type oil and gas pipelines.

2. Theory and Simulation

2.1. Straddling Oil and Gas Pipeline Dynamics Theory

In the process of pressure flow in oil and gas pipelines, when the fluid contacts solid surfaces, it exerts forces that cause structural deformation. Generally, this deformation is small and gradually changes over time, making it relatively stable. However, during an earthquake event, intense pipeline vibrations can result in significant deformations that impact the distribution of fluid loads within the pipeline. This leads to alterations in fluid velocity and pressure fields, ultimately affecting the motion state of the medium within the pipeline. Consequently, these interactions between the fluid medium and solid structure are referred to as fluid–solid coupling effects.

According to the fluid–structure coupling mechanism, it can be categorized into two manifestations. The first manifestation involves a blending of the solid and fluid domains, making it challenging to distinguish between them. This is observed in phenomena such as turbulence and seepage. The second manifestation occurs at the interface between the solid and fluid domains. In this paper, we focus on the latter type of coupling exhibited by oil and gas pipelines.

The fluid–solid coupling problem can be classified into unidirectional and bidirectional coupling based on the need for data transmission between the fluid and solid interfaces. Unidirectional coupling assumes that the influence of the solid on the fluid is insufficient to alter the flow field's shape, disregarding deformation and displacement transfer from solid to fluid. It only calculates one-way data transfer results from fluid to solid. However, this method yields inaccurate results as it is only suitable when the fluid significantly affects the solid structure, while neglecting any substantial impact of the solid on the fluid. In contrast, bidirectional coupling considers two-way data transfer at their interface, accounting for interactions between both phases. This approach aligns with real-world behavior and provides more realistic calculation outcomes. Therefore, this study adopts bidirectional fluid–solid coupling to simulate interactions between the oil–gas medium and the pipeline.

The numerical simulation of convection–solid coupling should adhere to the fundamental equations of fluid mechanics and solid mechanics, specifically the fluid control equation, solid control equation, and coupling control equation.

2.1.1. Fluid Control Equation

When the fluid flows in the pipe, it needs to follow the basic conservation laws, namely the law of conservation of mass, the law of conservation of momentum, and the law of conservation of energy.

(1) Mass conservation equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_x)}{\partial x} + \frac{\partial(\rho u_y)}{\partial y} + \frac{\partial(\rho u_z)}{\partial z} = 0 \quad (1)$$

where: ρ is the density, t is the time, and u_x , u_y , and u_z are the velocity components in the x , y , and z directions, respectively.

(2) Momentum conservation equation

$$\begin{cases} \frac{\partial(\rho u_x)}{\partial t} + \nabla \cdot (\rho u_x \vec{u}) = -\frac{\partial P}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} + \rho f_x \\ \frac{\partial(\rho u_y)}{\partial t} + \nabla \cdot (\rho u_y \vec{u}) = -\frac{\partial P}{\partial y} + \frac{\partial \tau_{yx}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} + \rho f_y \\ \frac{\partial(\rho u_z)}{\partial t} + \nabla \cdot (\rho u_z \vec{u}) = -\frac{\partial P}{\partial z} + \frac{\partial \tau_{zx}}{\partial x} + \frac{\partial \tau_{zy}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + \rho f_z \end{cases} \quad (2)$$

where: $\nabla = i(\partial/\partial x) + j(\partial/\partial y) + k(\partial/\partial z)$, ∇ is the Hamiltonian differential operator, P is the pressure on the surface of the fluid element, f_x , f_y , and f_z are the unit mass forces in the three directions, respectively, and τ_{xx} , τ_{xy} , and τ_{zx} are the components of the viscous stress, τ , on the surface of the element.

(3) Energy conservation equation

$$\frac{\partial(\rho E)}{\partial t} + \nabla \cdot [\vec{u}(\rho E + P)] = \nabla \cdot \left[k_{eff} \nabla T - \sum_j h_j J_j + (\tau_{eff} \cdot \vec{u}) \right] + S_h \quad (3)$$

where: E is the total energy of the fluid, k_{eff} is the effective heat conduction coefficient, h is the enthalpy, h_j is the enthalpy of the component j , J_j is the diffusion flux of the component j , and S_h is the volume heat source term, including the chemical reaction heat and other user-defined terms.

2.1.2. Governing Equation for Solids

The governing equations for solids can be derived from Newton's second law, as follows:

$$\rho_s \ddot{d}_s = \nabla \cdot \sigma_s + f_s \quad (4)$$

where: ρ_s is the solid density, $\ddot{d}_s$ is the solid acceleration, σ_s is the Cauchy stress tensor, and f_s is the volume force vector.

2.1.3. The Governing Equation of Fluid–Structure Coupling

The reasonable planning of the fluid and solid domains is a fundamental calculation prerequisite for pipeline fluid–solid coupling problems. Therefore, it is essential to accurately select the coupling surface for the fluid and solid interaction. At the interface of fluid and solid coupling, both the kinematic balance equation and the dynamic balance equation of the fluid and solid domains must be simultaneously satisfied.

$$\begin{cases} d_f = d_s \\ \tau_f \cdot n_f = \tau_s \cdot n_s \end{cases} \quad (5)$$

where, d_f and d_s are the boundary displacements of the fluid and solid, respectively, τ_f and τ_s are the shear force vectors of the fluid and solid, respectively, while n_f and n_s are the numbers of nodes of the fluid and solid, respectively.

2.2. Straddling Oil and Gas Pipeline Model and Parameters

The prototype used in this paper is a real oil and gas pipeline, constructed as a single-tower and double-cable-plane cable-stayed pipe bridge. A cable oil and gas pipe bridge system was established, and the three-dimensional finite element model of the entire bridge was created using ANSYS Workbench. The model represents a single-tower cable-stayed bridge with a vase-shaped structure, featuring a tower height of 72 m. The truss beam has a width of 0.284 m, consisting of vertical rods, chord rods, and oblique belly rods. Each truss beam measures 2 m in length, with every two trusses supported by an arrangement. For oil and gas transmission purposes, two pipes were installed in parallel on the support of each truss beam. The oil and gas transmission adopted two pipes, set up on the support of the truss beam in parallel. The pipe specification is: $\Phi 711 \text{ mm} \times 12.7 \text{ mm}$, the total length is 284 m, and the bridge span arrangement is 142 m + 142 m. The cable-stayed cables were arranged in a fan shape, and 6×37 galvanized steel wire rope was used. The basic cable distance is 10 m and the cable distance on the bridge tower is 1.5 m. The specifications are: $\Phi 25.5$, $\Phi 36$, $\Phi 42$, and $\Phi 45$. The span structure model of the cable-stayed pipe bridge is shown in Figure 1. The model has 77,582 nodes and 14,414 units.

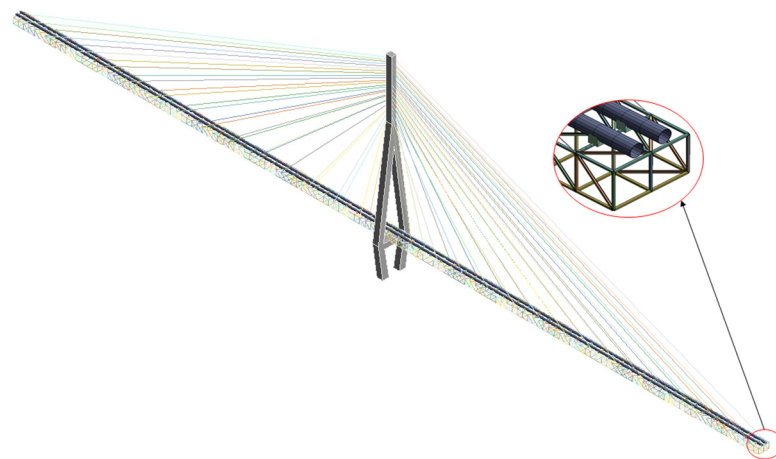


Figure 1. Overall finite element model of the cable-stayed tube bridge span structure.

The material types and mechanical properties of each component in the cable-stayed tube bridge span structure are shown in Table 1.

Table 1. Parameters of the cable-stayed tube bridge.

Parts	Materials	Density (kg/m ³)	Poisson's Ratio	Modulus of Elasticity (MPa)	Yield Strength (MPa)
Bridge tower	Q345 steel	7850	0.3	2.06×10^5	378
Truss beams	Q345 steel	7850	0.3	2.06×10^5	378
Bearings	Cast iron	7850	0.3	1.5×10^5	400
Pipes	X60	7850	0.3	2.06×10^5	425
Dragline	Galvanized steel rope	5200	0.3	2.0×10^5	1670

2.3. Seismic Wave Selection and Working Condition Setting

2.3.1. Seismic Wave Selection

The cable-stayed pipe bridge structure system discussed in this paper is situated in the 8-degree area, classified as a class II site, with a characteristic period of 0.35 s. Therefore, the EI-Centro seismic wave-recorded data were selected as the input seismic wave for analysis. This study primarily focuses on investigating the structural damage mechanism under strong earthquake events; hence, the peak acceleration of the seismic wave was adjusted to 10.0 m/s^2 , and an earthquake duration of 50 s with a time interval of 0.02 s was considered for analysis purposes. It should be noted that this paper solely examines consistent excitation inputs of seismic waves for the pipe bridge structure.

2.3.2. Working Condition Setting

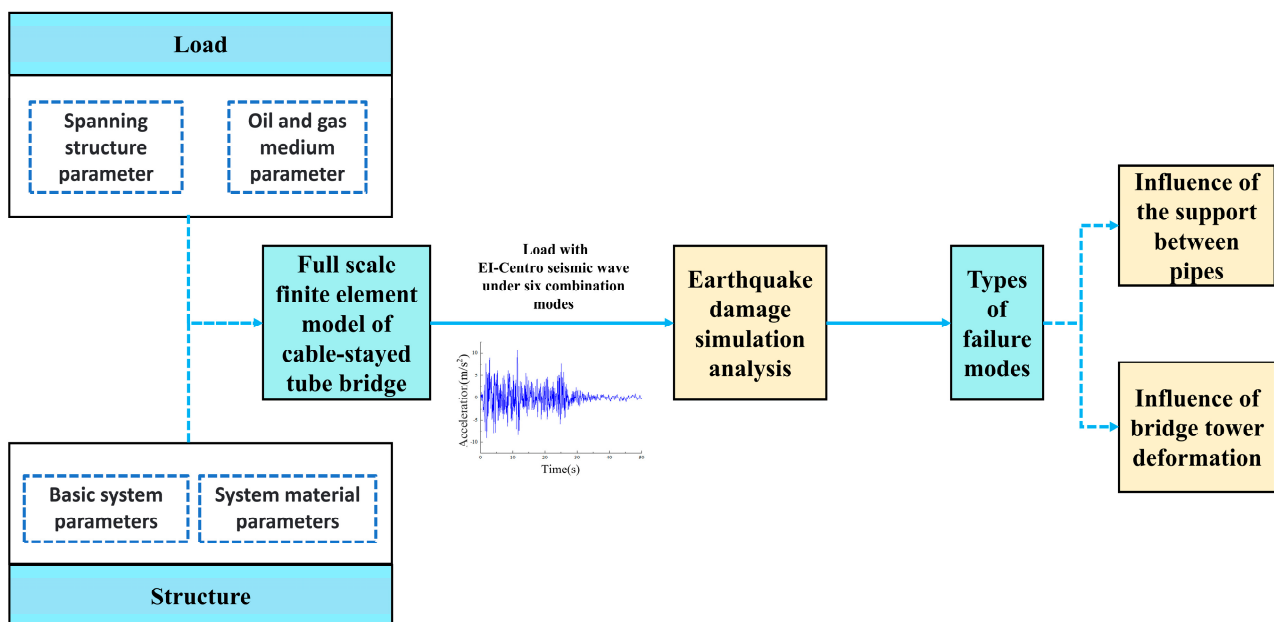
According to the “Seismic Technical Code for Oil and Gas Transmission Pipeline Engineering” (GB/T50407-2017) [31], the consideration of vertical and horizontal seismic waves is omitted when the seismic wave amplitude is less than 0.2 g. Considering the significant magnitude of the seismic wave amplitude employed in this study, it was necessary to separately calculate the three-dimensional seismic waves. Moreover, in cases where local seismic waves are bidirectional or tri-directional, the ratio of ground motion along the longitudinal bridge, transverse bridge, and vertical bridge should be 1:0.85:0.65, respectively. Consequently, a total of six working conditions were established by considering both the independent and joint actions of each vibration component, as presented in Table 2.

Table 2. Working condition setting.

Working Condition	Combination Mode of Seismic Action Direction
1	X
2	Y
3	Z
4	X + Y
5	X + Z
6	X + Y + Z

Note: X, Y, and Z represent the three translational components of seismic wave propagation along longitudinal, transverse, and vertical bridges.

The specific simulation analysis process is shown in Figure 2 below.

**Figure 2.** Simulation analysis process.

3. Results

3.1. Simulation Analysis of Earthquake Damage of Oil and Gas Pipeline Structure

In the process of oil and gas transmission, the medium in the pipeline exerts a significant influence on its structural behavior, particularly during seismic events when fluid-induced vibrations can significantly impact the overall integrity of the pipeline. Therefore, this study employed a fluid–structure coupling approach to investigate the failure mechanism of pipelines under earthquake conditions.

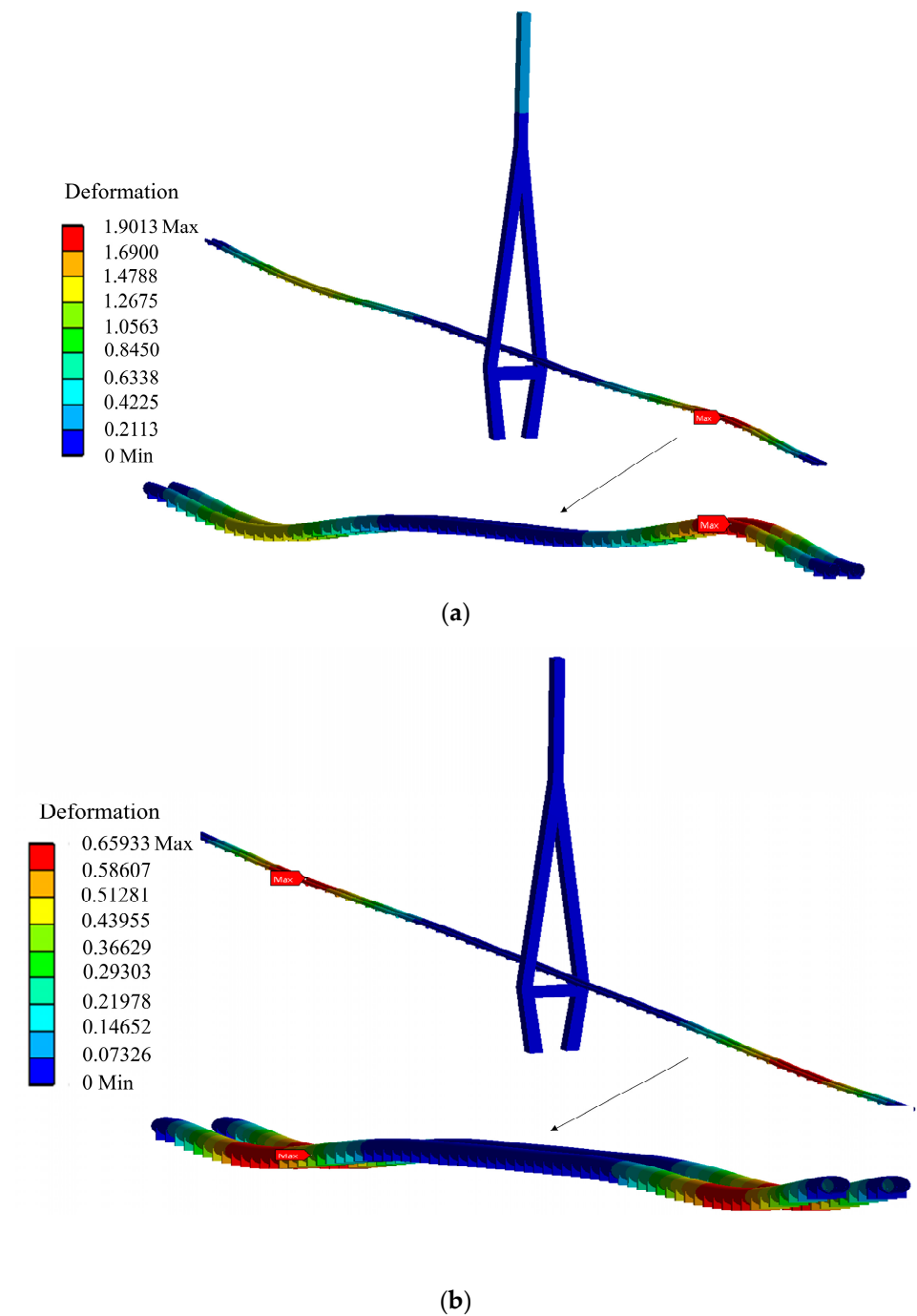
3.1.1. Analysis of Pipeline Structure Deformation

The present study primarily investigated the fluid–structure coupling-induced deformation of the pipe bridge system under six distinct operational conditions. Figure 3 illustrates the maximum deformation observed in the pipe bridge system across various working scenarios.

The maximum deformation of the oil and gas pipeline structure under different seismic waves was determined by extracting the highest deformation value from Figure 3, as presented in Table 3.

The results presented in Figure 3 and Table 3 demonstrate that, across the six operational conditions, the pipeline experienced maximum deformation at 11 s under seismic wave action. Notably, the midspan positions of both the left- and right-side spans exhibited the most significant deformation, displaying an antisymmetric pattern. Comparative anal-

ysis of deformation and damage caused by three unidirectional seismic waves revealed that longitudinal waves exerted the greatest influence on pipeline deformation, followed by vertical waves. Transverse waves primarily affected deformations in the pipe bridge system atop the bridge tower through transverse bending.



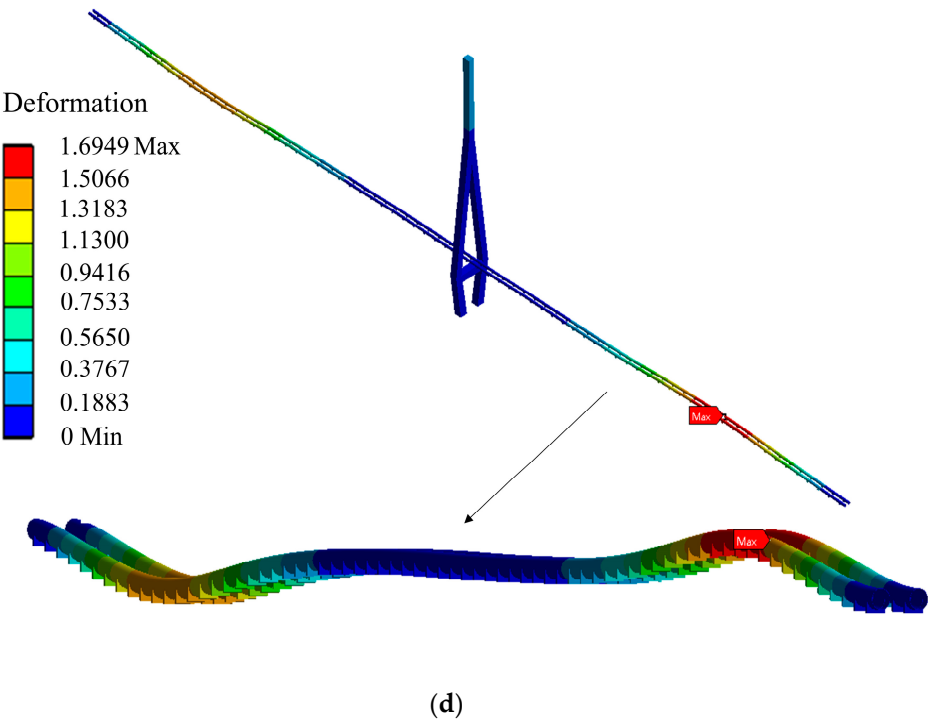
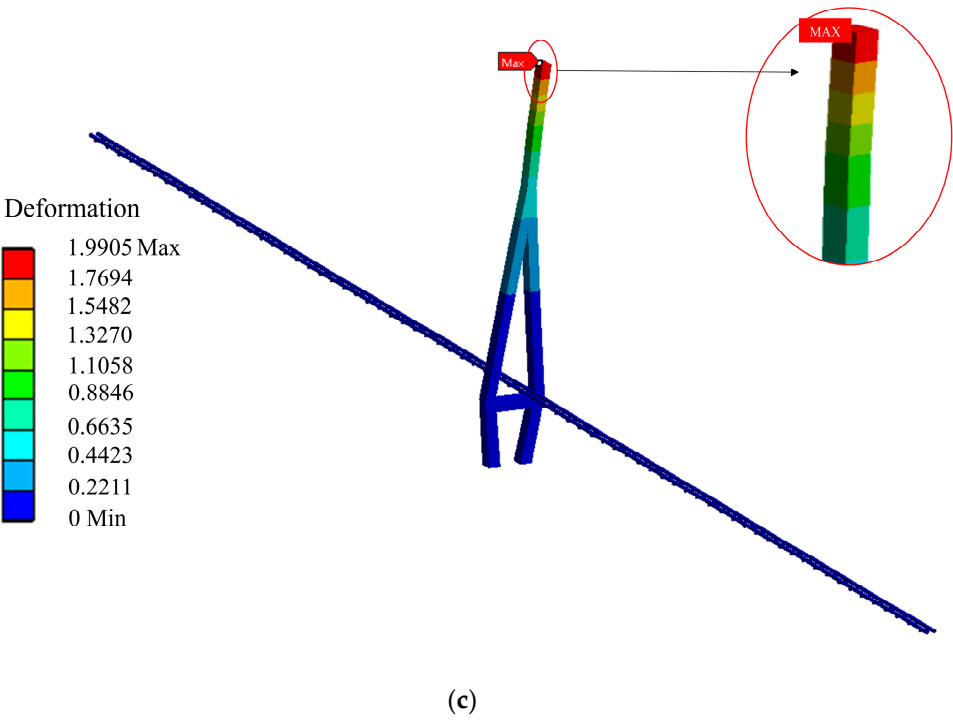
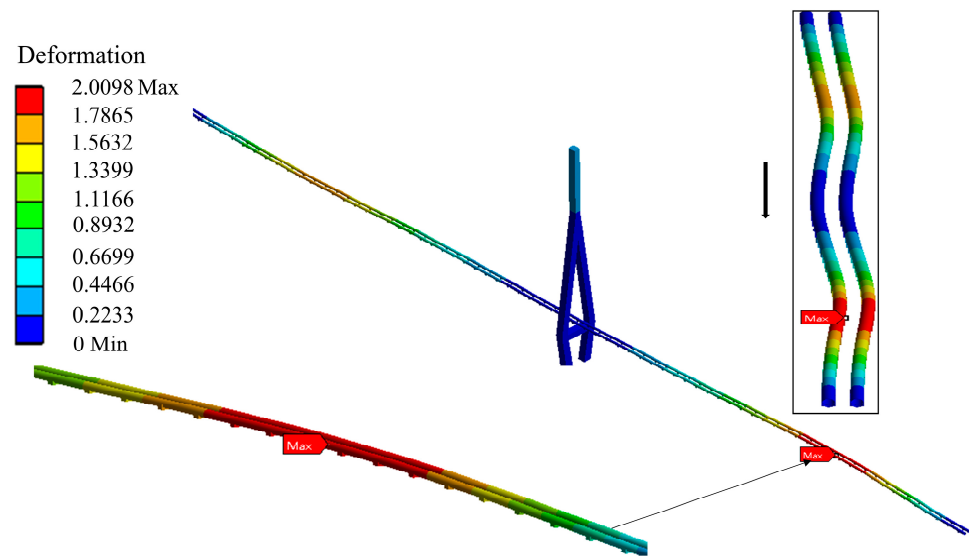
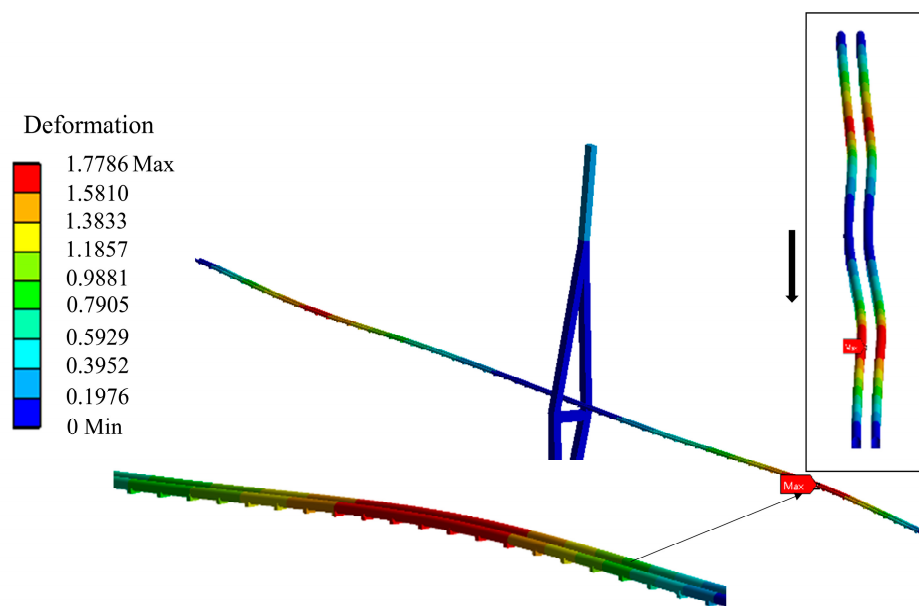


Figure 3. Cont.



(e)



(f)

Figure 3. Maximum deformation of the pipeline structure under different working conditions. (a) Deformation under the X-direction earthquake, (b) deformation under the Y-direction earthquake, (c) deformation under the Z-direction earthquake, (d) deformation under the X + Y direction, (e) deformation under the X + Z direction, and (f) deformation under the X + Y + Z direction.

The influence of multi-directional seismic waves was primarily observed in the alteration of unidirectional seismic waves following their respective combination, resulting in varying deformation conditions. When longitudinal and vertical seismic waves acted together, the maximum pipeline deformation was 1.69 m, which is smaller than the maximum deformation of 1.90 m when longitudinal seismic waves acted alone, indicating a weakened pipeline deformation. Conversely, when longitudinal and transverse seismic waves coexisted, the bridge tower's top experienced intensified deformation. Furthermore,

under the influence of three-way seismic waves, the pipe bridge system exhibited further reduced deformations. Consequently, it can be inferred that multi-directional ground motion leads to more reasonable deformations in the pipe bridge system.

Table 3. Preview of the maximum deformation of the pipeline structure under different working conditions.

Working Conditions	Maximum Deformation Time (s)	Maximum Deformation (m)	Maximum Deformation Characteristics
X	11.94	1.901	Right straddle mid-upper bend
Y	11.66	0.659	Bend the left and right midspan under
Z	25.76	1.991	Lateral side bend at the top of the tower
X + Y	11.98	1.695	Right straddle mid-upper bend
X + Z	11.96	2.010	Lateral side bend at the top of the tower
X + Y + Z	11.96	1.779	Lateral and vertical bending of the left- and right-side span, midspan

In conclusion, when considering the fluid–structure coupling effect of oil and gas pipelines, the deformation of the pipeline is similar to that of a pipeline considering the additional mass effect. The maximum displacement response occurs in the middle span between the left and right sides. Therefore, under strong earthquake action, excessive deformation of the side spans may lead to structural damage in the pipeline system. When analyzing seismic effects on bridges, particular attention should be paid to deformations occurring in these side spans. Among different seismic wave directions, longitudinal waves have the greatest influence on pipeline deformation, followed by vertical waves, while transverse waves primarily affect displacements at the top of bridge towers within pipe bridge systems. Furthermore, under combined multi-directional ground motion, pipeline deformations are smaller compared to those resulting from single earthquake events, thus indicating a weakening effect on pipeline deformations due to multi-directional seismic wave actions.

3.1.2. Stress and Strain Analysis of Pipeline Structure

In order to further elucidate the failure mechanism of pipe bridge systems during earthquakes, we obtained the strain at multiple maximum stress points in oil and gas pipeline structures. The resulting equivalent strain cloud map, depicting the maximum stress conditions under six different operational scenarios, is presented in Figure 4.

The stress–strain conditions of the pipeline structure under various seismic waves were derived from the strain cloud map depicting the maximum stress in Figure 4, as presented in Table 4.

Table 4. Strain at the maximum stress of the pipeline structure under various working conditions.

Working Conditions	Maximum Stress Moment (s)	Maximum Stress (MPa)	Maximum Strain (10^{-3})	Maximum Stress Position
X	27.6	458.79	2.279	Pipe inlet end, upper side
Y	11.7	404.22	1.964	Pipe inlet end, upper side
Z	25.5	663.02	4.420	Bottom sides of tower
X + Y	27.6	462.09	2.244	Pipe inlet end, upper side
X + Z	25.2	516.36	3.442	Bottom sides of tower
X + Y + Z	27.6	467.84	2.731	Pipe inlet end, upper side

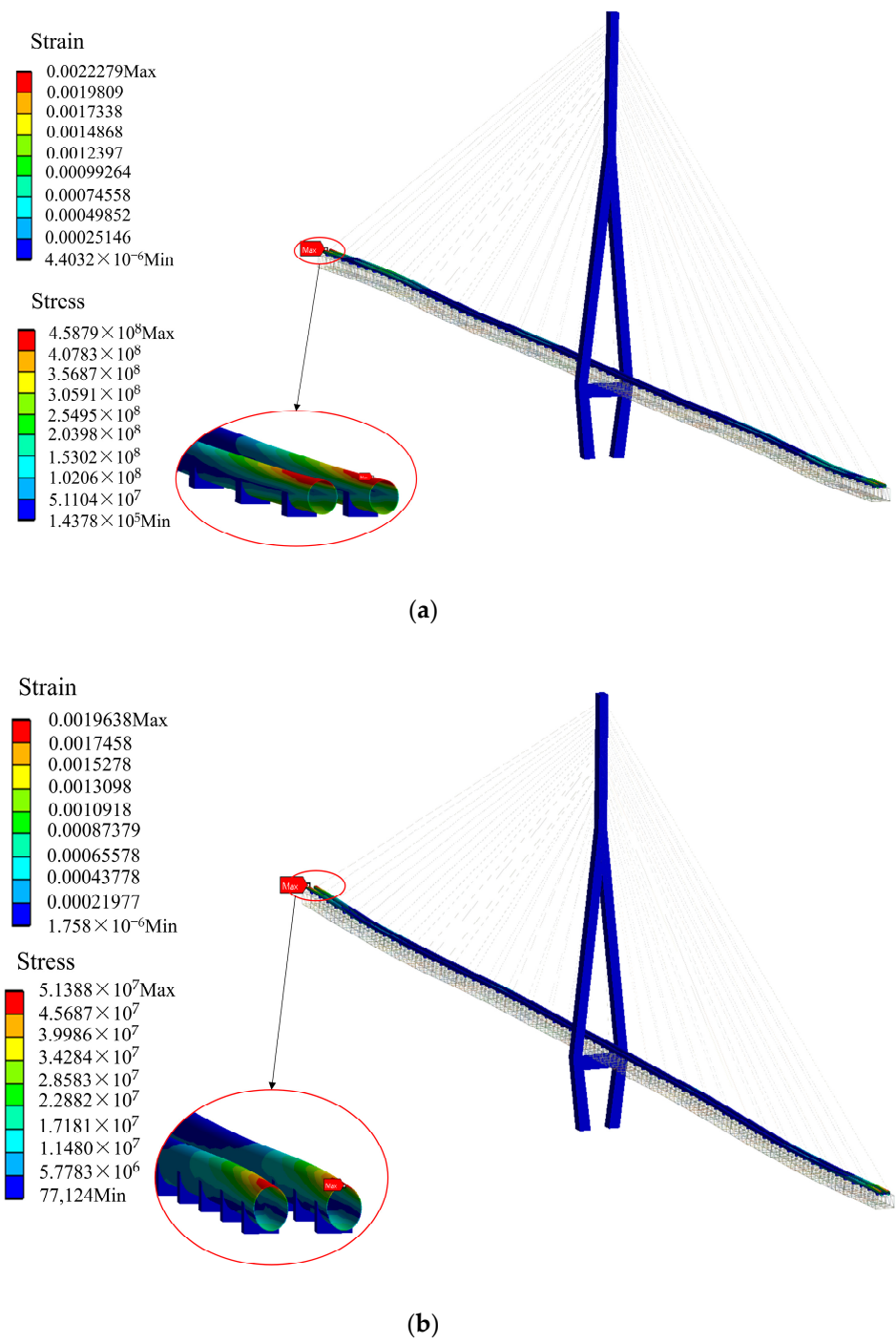
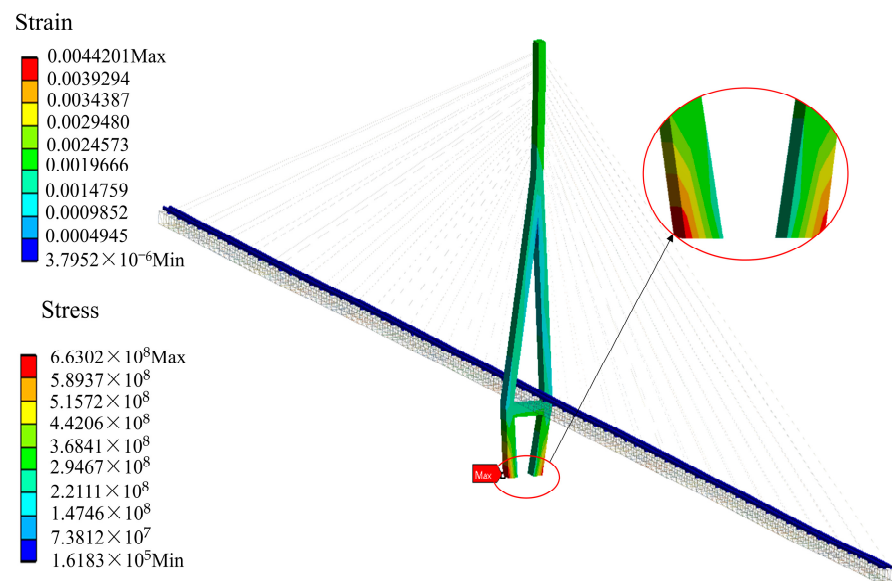
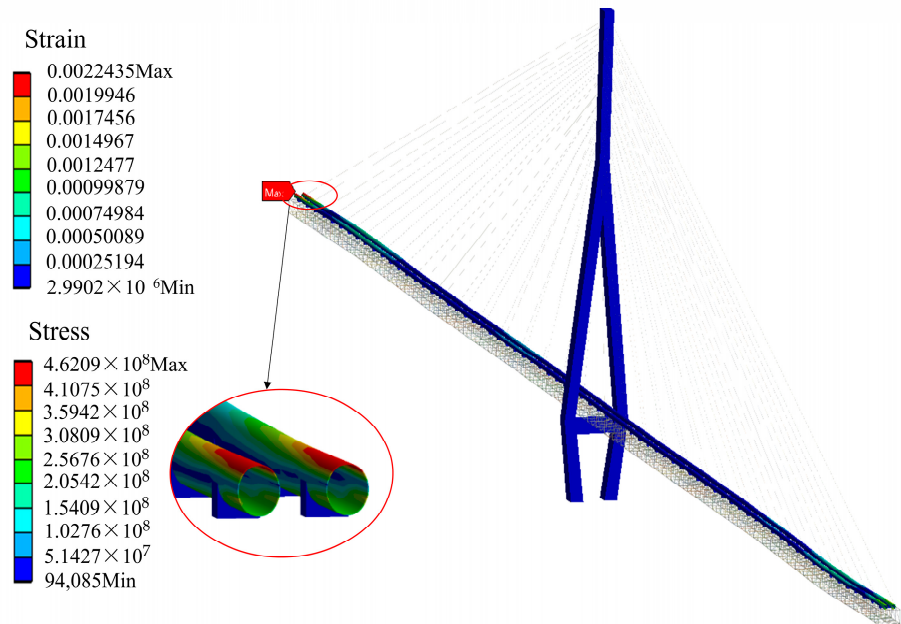


Figure 4. Cont.



(c)



(d)

Figure 4. Cont.

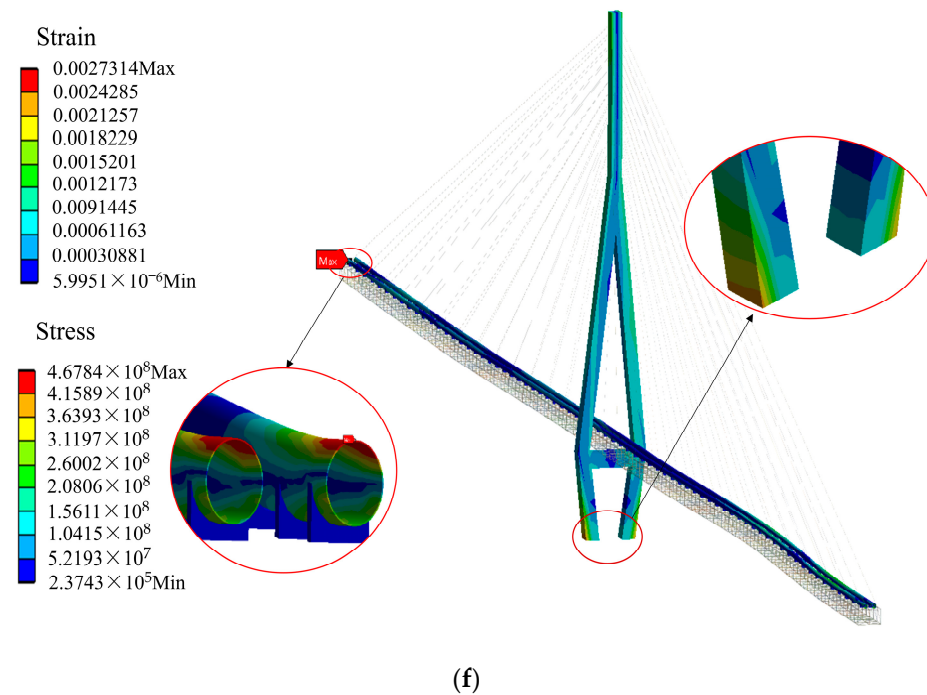
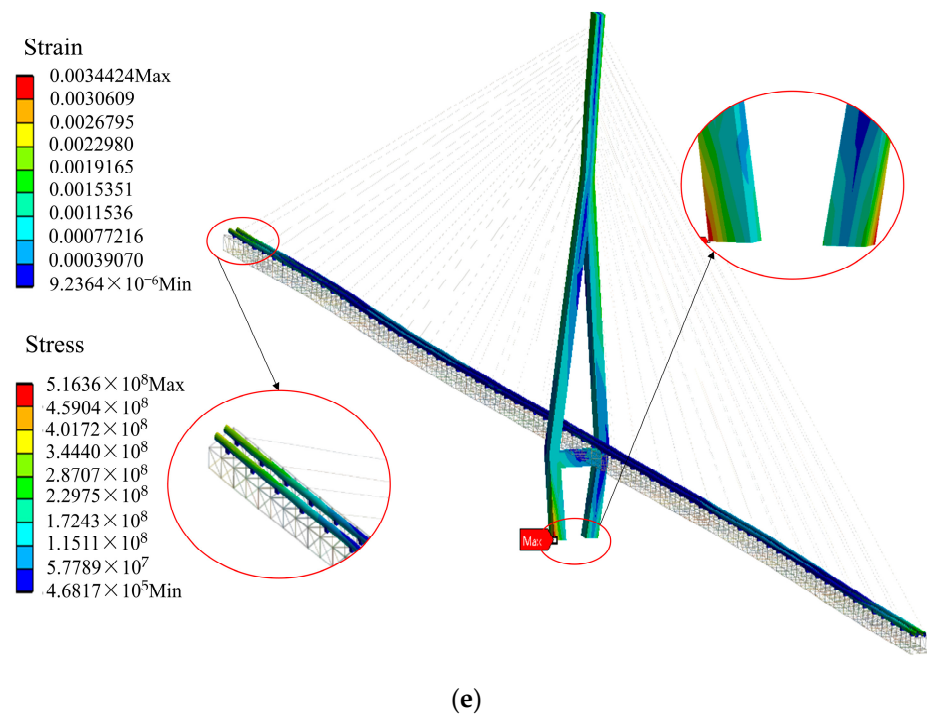


Figure 4. Strain at the maximum stress of the pipeline structure under different working conditions. Maximum deformation of the pipeline structure under different working conditions. (a) Strain under the X-direction earthquake, (b) strain under the Y-direction earthquake, (c) strain under the Z-direction earthquake, (d) strain under the X + Y direction earthquake, (e) strain under the X + Z direction earthquake, and (f) strain under the X + Y + Z direction earthquake.

It can be observed from Figure 4 and Table 4 that, under the six operational conditions, the strain duration at the pipeline's maximum stress induced by seismic waves was concentrated around 27 s. By comparing and analyzing the strains at maximum stress caused by three unidirectional seismic waves on the pipeline, it became evident that vertical and horizontal seismic waves primarily generated maximum strains at the inlet and outlet

of the pipeline. The maximum strain generated by vertical seismic waves was 1.4 times greater than that of horizontal seismic waves, resulting in a peak stress of 458.79 MPa on the pipeline, which exceeds its material yield limit, causing plastic deformation to occur. Additionally, under transverse seismic wave action, the structural system experienced its highest strain at both ends of the bridge tower's bottom section. Consequently, when subjected to these three directional seismic waves, buckling failure is prone to occur at both ends of the pipeline due to excessive stress and strain. Furthermore, due to excessive vertical displacement of the pipeline's left and right sides in the middle span, there was also a significant increase in stress at the lower end of the pipeline. Simultaneously, as the bridge tower underwent substantial displacement and deformation in both spans, there was a corresponding amplification of stress and strain at the upper end of the pipeline in the middle span.

The combined effect of multi-directional seismic waves resulted in a more intricate maximum strain pattern for the pipe bridge structure. When subjected to bidirectional seismic waves, both ends of the pipe and bottom of the bridge tower experienced smaller maximum stresses compared to those induced by unidirectional seismic waves since joint earthquake action weakens the overall strain within the pipe bridge system. However, under three-way ground motion, strains intensified at both ends of the pipeline, with an increase 1.2 times greater than that observed under unidirectional ground motion.

In summary, when considering the fluid–structure coupling effect of oil and gas pipelines, the maximum stress and strain occur at the inlet and outlet ends under earthquake loading. The pipeline is susceptible to buckling and failure at both ends. Under unidirectional seismic waves, longitudinal waves induce a greater strain response compared to vertical waves. Transverse seismic waves have the most significant influence on the stress–strain behavior of the structural system, with the maximum strain observed at the bottom of the bridge towers. The combined action of bidirectional seismic waves reduces stress and strain at critical points along the pipeline, while three-directional seismic wave combinations exacerbate failure and damage in oil and gas pipelines.

3.2. Study on Seismic Failure Modes of Cable-Stayed Pipe Bridge Oil and Gas Pipeline Structure

In general, the seismic damage of large-scale, complex oil and gas pipeline engineering structures often neglects the interaction between the oil and gas pipelines and cable-stayed pipe bridge structures. The oil and gas pipeline serves as a critical structural component within the cable-stayed pipe bridge system. To ensure its safety, this study analyzed the failure mechanisms of oil and gas pipelines under strong earthquakes in such systems, revealing their vulnerable points. However, compared to highway or railway bridges, cable-stayed pipe bridges with integrated oil and gas pipelines exhibit lower lateral stiffness and more intricate vibration characteristics. This complex structural system comprises various components, including bridge towers, cables, truss beams, supports, and pipelines, that interact during earthquake events, resulting in coupled, random, and multifaceted forms of seismic damage. Failure in one component may trigger failures in others due to interdependencies among them, leading to diverse failure modes within the pipe bridge system when subjected to strong earthquakes.

3.2.1. Cable-Stayed Pipeline Bridge: Types of Failure Modes of Oil and Gas Pipelines

According to the seismic failure types of highway cable-stayed bridges, although the entire structure does not completely collapse and become destroyed under strong earthquakes, localized components within the structural system often experience failures, leading to overall structural failure. The tower, support, and cable anchor pier are frequently damaged components in highway cable-stayed bridges. Drawing an analogy from the damage observed in local components of highway cable-stayed bridges and based on the damage mechanism of pipe bridge structures mentioned earlier, in this study, we further analyzed the localized components of a cable-stayed pipe bridge oil and gas pipeline system. Specifically, we investigated the interaction between the support and the pipeline

as a potential cause for pipeline damage and explored additional failure modes resulting from bridge tower deformation in order to gain insights into the failure mechanisms specific to cable-stayed pipe bridge oil and gas pipeline structures.

- (1) The influence of the interaction between the support and the pipeline on the structural system

The analysis of the overall deformation of the pipeline also considers the support located beneath it as a force component. According to seismic technical specifications for oil and gas transmission pipelines, if a span structure is utilized as a support element, longitudinal earthquake effects necessitate considering the longitudinal slip of the pipeline on the support. Therefore, further refinement of the model enables analyzing the interaction between the support and the pipeline in pipe bridge systems under longitudinal seismic waves, leading to potential failure modes of oil and gas pipelines.

- (2) The influence of tower deformation on the structural system

The bridge tower is the crucial load-bearing component of the cable-stayed pipe bridge, responsible for supporting the truss beam, pipeline, and other structural elements. A failure in the bridge tower would result in a significant reduction in the overall bearing capacity of the structure and may even render the entire pipe bridge system non-functional. Previous studies have indicated that excessive displacement at the top of the bridge tower can lead to structural overturning; however, there is currently no clear criterion for tower collapse. Based on existing research, when the displacement at the top of a cable-stayed pipe bridge's tower exceeds 1/100th of its height, it is considered to have lost its carrying capacity. The structural system fails to function effectively when the bridge tower exceeds the serviceability limit state (SLS). The height of the bridge tower in this paper is 72 m; that is, when the displacement of the top of the bridge tower exceeds 0.72 m, the structure is deemed to pose a hazardous undertaking.

3.2.2. Influence of Support on the Interaction between Pipelines

Based on the investigation of the additional mass of the pipe bridge system, the relationship between the pipe and the support was transformed into a weak constraint. The friction coefficient was adjusted to 0.2, while considering the peak acceleration of the EI-Centro wave as an intensity index. The seismic wave was inputted longitudinally along the bridge, with gradually increasing peak accelerations ranging from 0.2 g to 1.0 g, in increments of 0.2 g. Nonlinear time-history analysis was conducted on the pipe bridge structure under various peak seismic accelerations to investigate damage outcomes resulting from the interaction between the support and the pipeline.

- Displacement response of the support

Under seismic activity, excessive longitudinal displacement between the support and the pipeline can result in localized damage, and ultimately, lead to pipeline failure. Therefore, we numerically analyzed the relative displacements of supports under different peak accelerations. Figure 5 illustrates the distribution of supports with the highest equivalent deformation. It is evident from the figure that due to the structural system's complexity, the position of maximum equivalent deformation varied; however, it predominantly occurred near both ends of the import and export sections at approximately one-fourth of the span length from either side.

Therefore, the bearing experiencing the most significant equivalent deformation during the seismic process within the initial 30 s was selected. Subsequently, an analysis of the longitudinal displacement time-history curve for this particular bearing was conducted, as depicted in Figure 6. The maximum relative longitudinal displacement value is presented in Table 5.

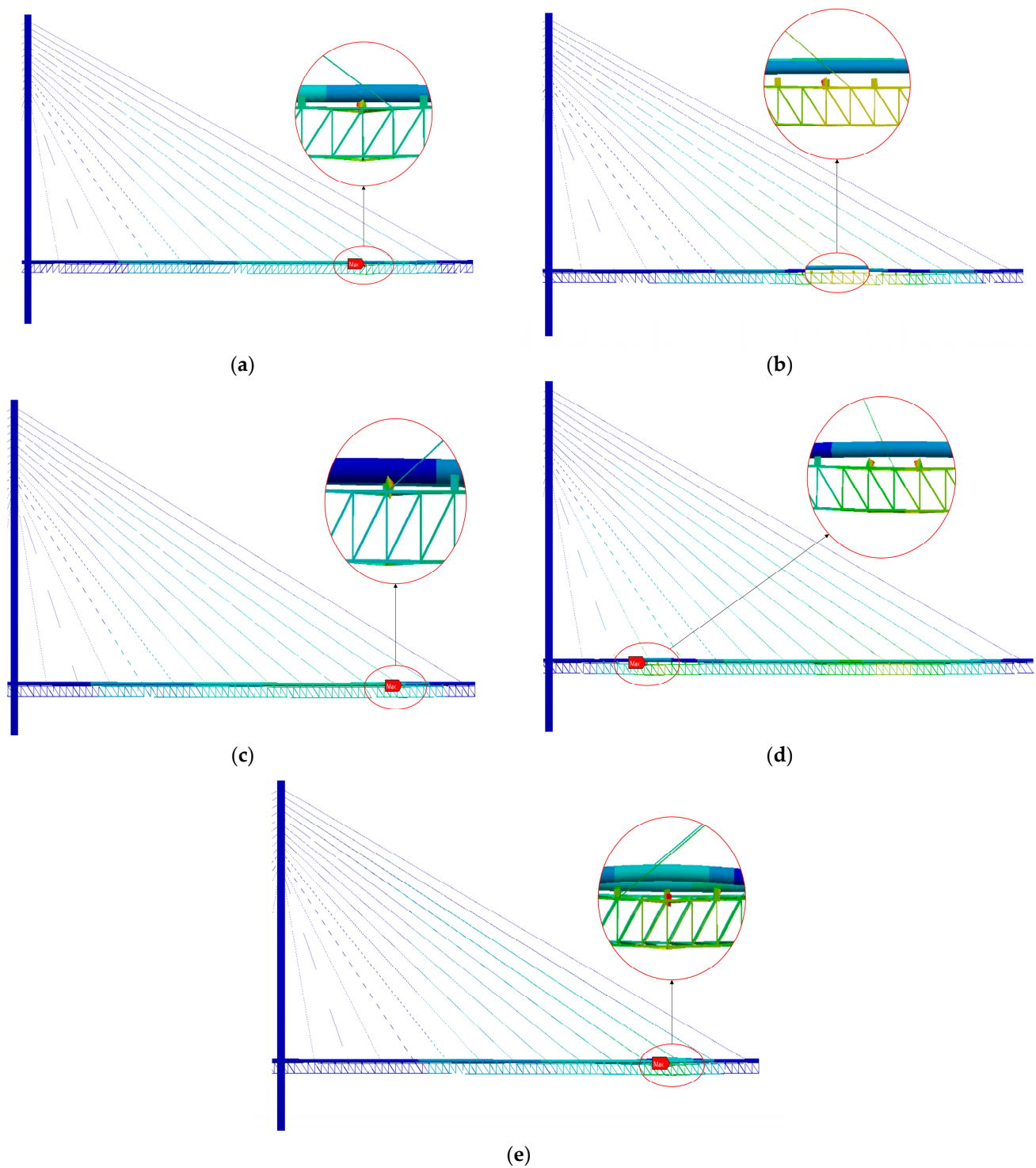


Figure 5. Distribution of supports with the largest equivalent deformation. Maximum deformation of the pipeline structure under different working conditions: (a) 0.2 g maximum equivalent deformation support, (b) 0.4 g maximum equivalent deformation support, (c) 0.6 g maximum equivalent deformation support, (d) 0.8 g maximum equivalent deformation support, and (e) 1.0 g maximum equivalent deformation support.

The longitudinal displacement of the support gradually increased with the increase in peak acceleration, as evident from Figure 6. At a peak acceleration of 0.2 g, the longitudinal displacement of the support was measured at 0.134 m, while it reached 0.325 m at a peak acceleration of 1.0 g. Consequently, an increasing tilt angle was observed in the support

until separation occurred between the pipeline and the support, resulting in a noticeable gap forming between them. This indicates that under longitudinal seismic waves, slippage occurs longitudinally between the pipe and its supporting structure, which intensifies with higher peak seismic accelerations. It should be noted that collision between the support and the pipeline can cause localized damage to the latter, hence highlighting the significance of considering their interaction.

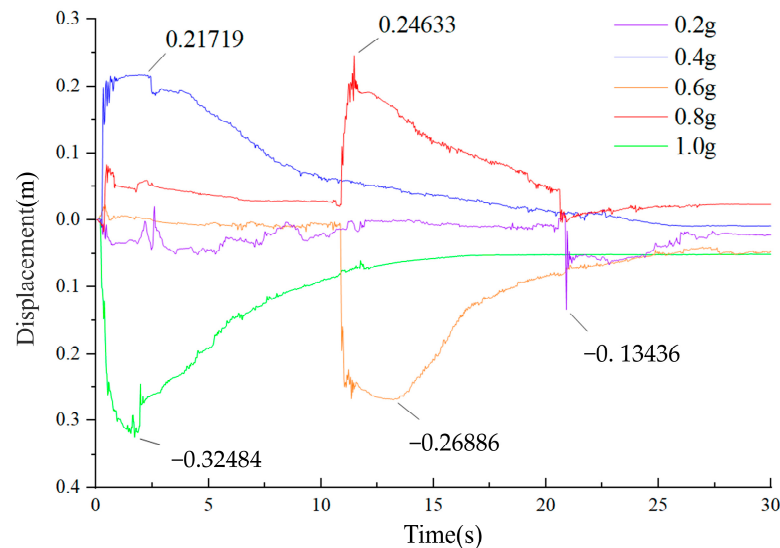


Figure 6. Longitudinal displacement of the maximum displacement support.

Table 5. Maximum longitudinal relative displacement of the pipeline.

Peak Acceleration	Maximum Longitudinal Relative Displacement (m)
0.2 g	0.134
0.4 g	0.217
0.6 g	0.269
0.8 g	0.246
1.0 g	0.325

- Pipeline stress distribution

It is evident from the aforementioned analysis that the interaction between the support and the pipeline induced localized failure in the pipeline. We further elucidated the occurrence of local failure in the pipeline due to stress concentration by examining its maximum longitudinal position. Figure 7 depicts a stress cloud map illustrating equivalent stresses experienced by the pipeline at this critical longitudinal displacement.

The increase in the peak seismic acceleration resulted in a gradual increase of the equivalent stress at the local location of the pipeline, leading to stress concentration phenomena, as depicted in Figure 7. When the peak seismic acceleration ranged from 0.2 to 0.4 g, the equivalent stress experienced by the pipeline remained below its yield strength of 425 MPa. However, when the peak seismic acceleration reached 0.6–1.0 g, deflection caused by the longitudinal slip of the supports induced higher stresses at the contact surface between the pipeline and the support system, surpassing material yield limits and resulting in stress concentration within the pipeline itself. This localized increase in stress ultimately led to buckling failure.

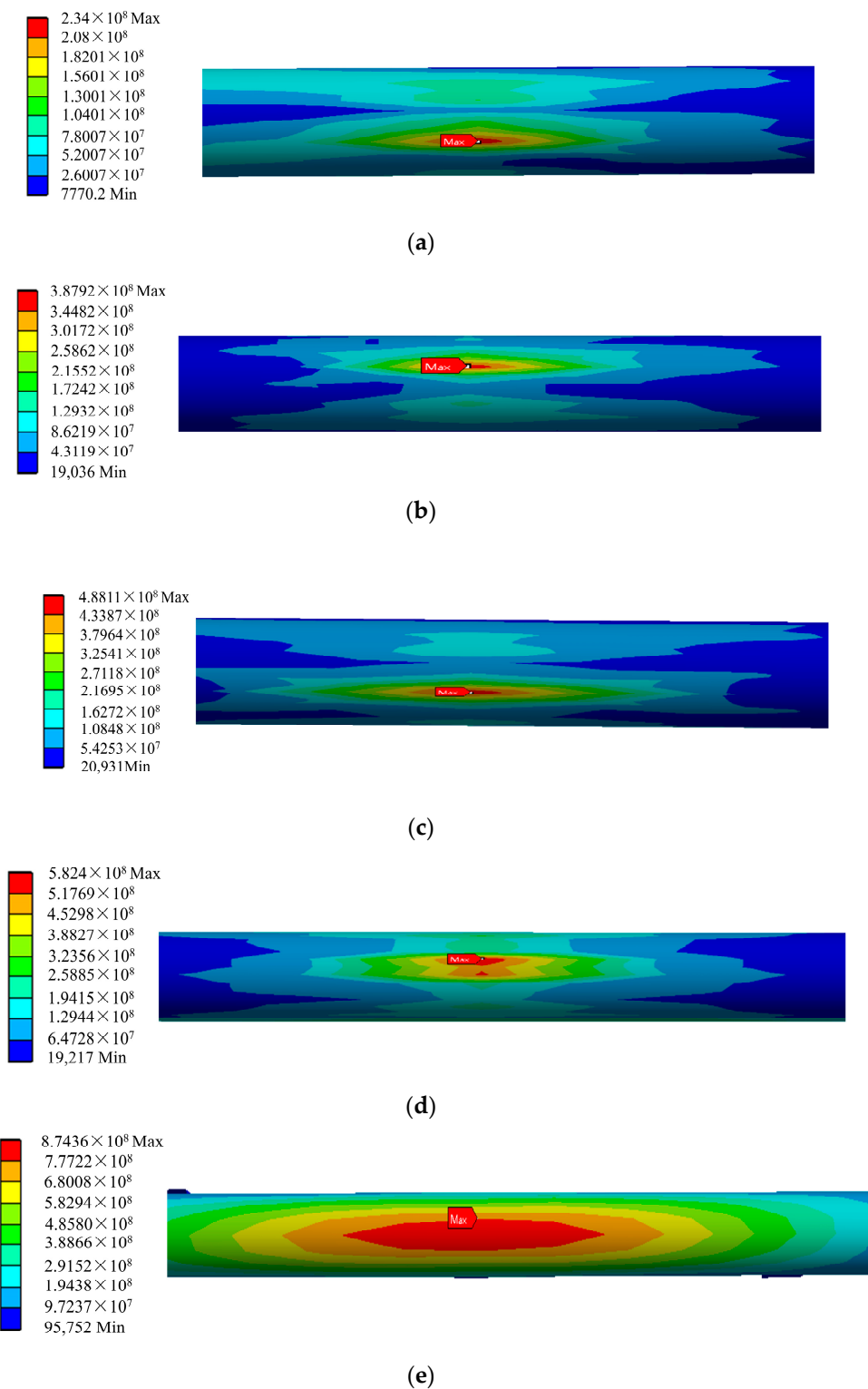


Figure 7. Equivalent stress nephogram of the pipe at maximum longitudinal displacement. Maximum deformation of the pipeline structure under different working conditions: (a) 0.2 g equivalent stress cloud map, (b) 0.4 g equivalent stress cloud map, (c) 0.6 g equivalent stress cloud map, (d) 0.8 g equivalent stress cloud map, and (e) 1.0 g equivalent stress cloud map.

3.3. Influence of Bridge Tower Deformation

Based on the calculation and analysis of the previous six working conditions, under the influence of transverse seismic waves, the pipe bridge system experienced maximum

deformation at the top of the bridge tower. At this juncture, the displacement of the bridge tower measured 1.99 m, significantly surpassing the recognized collapse limits for towers in general practice. Consequently, we aimed to analyze the acceleration and displacement responses at different peak levels experienced by the top of the bridge tower during transverse earthquakes, thereby establishing a comprehensive understanding of the failure mechanisms leading to structural failure in pipe bridges.

3.3.1. Shift Response of the Top Part of the Bridge Tower

Through comparative analysis of the displacement response of the bridge's top under different peak accelerations of transverse seismic waves, Figure 8 presents the time-history curve for the bridge's top, while Table 6 displays both maximum and residual displacements.

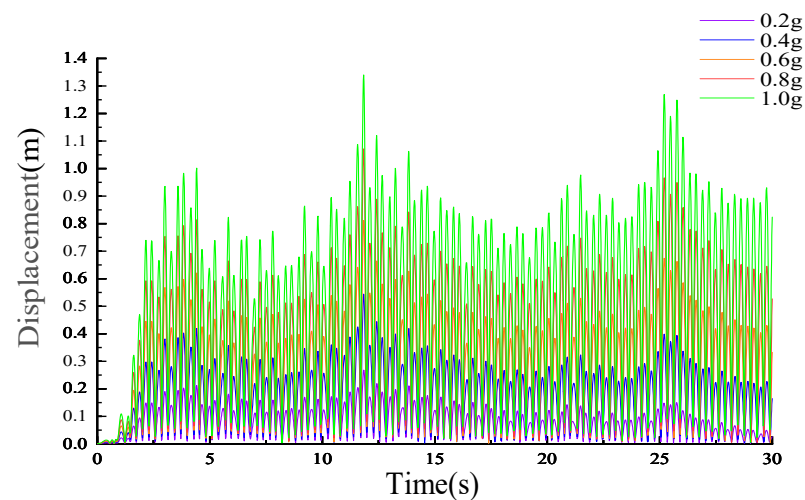


Figure 8. Time-history curve of the top part of the bridge tower.

Table 6. Maximum and residual displacement at the top of the bridge tower.

Peak Acceleration	Maximum Displacement (m)	Residual Displacement (m)
0.2 g	0.268	0.026
0.4 g	0.544	0.165
0.6 g	0.811	0.333
0.8 g	1.071	0.527
1.0 g	1.340	0.824

The displacement response of the top of the bridge tower under different peak accelerations exhibited overall consistency, as evident from Figure 8 and Table 6. Moreover, the displacement gradually increased with an increase in the peak earthquake acceleration. Notably, when the peak seismic acceleration was below 0.4 g, the displacement remained within acceptable limits for tower collapse. However, at a peak seismic acceleration of 0.6 g, the maximum displacement at the top of the bridge tower measured 0.811 m, surpassing the prescribed limit of 0.72 m for tower collapse. Subsequently, as peak acceleration continued to rise, so did the displacement at the top of the tower. At a peak acceleration of 1.0 g, this led to a maximum displacement at the top of the tower reaching 1.34 m—significantly exceeding specified limits. When subjected to a complete seismic wave, the bridge tower underwent plastic deformation, as evidenced by a certain displacement of its top relative to the initial position. At a peak acceleration of 0.2 g, the residual displacement at the top of the tower was minimal. However, as the peak acceleration increased, there was an augmented distance between the tower top and its original position, leading to residual displacement once plastic deformation set in.

3.3.2. Acceleration Response of the Top of the Bridge Tower

Through comparative analysis of the acceleration response of the bridge tower's top under transverse seismic waves with varying peak accelerations, we obtained the transverse acceleration time-history curve for the top of the bridge tower, as depicted in Figure 9.

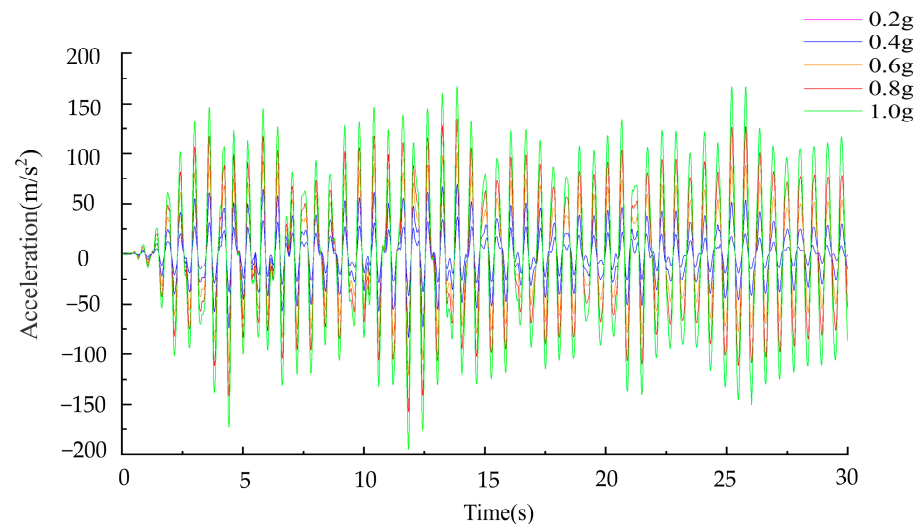


Figure 9. Time-history curve of lateral acceleration at the top of the bridge tower.

The transverse acceleration at the top of the bridge tower exhibited consistent overall changes under different peak seismic accelerations, as depicted in Figure 9. As the peak seismic acceleration increased, so did the transverse acceleration at the top of the bridge tower. Excessive transverse acceleration can compromise the stability of the bridge tower when subjected to transverse seismic waves, thereby escalating its failure potential. Simultaneously, this deterioration in stability also impacted the pipeline stability and exacerbated pipeline failures and destruction.

The increase in the earthquake peak acceleration was observed to result in a gradual escalation of deformation and acceleration at the top of the bridge tower, thereby highlighting its significant impact on the pipeline. The collapse of the bridge tower can lead to failure in crucial supporting functional components of the pipe bridge structure, consequently causing a loss of support for the oil and gas pipeline at the middle span. This ultimately leads to substantial deformation and subsequent failure of the oil and gas pipeline.

4. Conclusions

In this paper, we systematically investigated the nonlinear failure mechanism of trans-type oil and gas pipelines under strong earthquake conditions using ANSYS Workbench finite element analysis software and a fluid–solid coupling method. Additionally, we considered the potential failure modes of oil and gas pipelines resulting from the interaction between cable-stayed pipe bridges and the structural components of the pipeline. The following conclusions were drawn from this study:

- (1) By employing ANSYS Workbench finite element software, we analyzed the failure mode of long-span oil and gas pipelines subjected to strong earthquakes. The failure mode remained consistent for both unidirectional and multi-directional ground motion input. The maximum deformation occurred at the midpoint between the left and right spans, while maximum stress was observed at the inlet and outlet ends of the pipeline.
- (2) Under unidirectional seismic waves, longitudinal seismic waves (X direction) had a greater influence on pipeline deformation compared to vertical seismic waves (Y direction), with maximum deformation concentrated in the left and right spans,

while transverse seismic waves (Z direction) exerted a stronger impact on the top of bridge towers.

- (3) The deformation of the pipe bridge system is influenced by the pipeline medium in a complex manner: when longitudinal and vertical seismic waves had a significant impact, the pipeline deformation was mitigated, when longitudinal and transverse seismic waves acted together, the top of the bridge tower experienced intensified deformation, and when three-directional seismic waves occurred, a further reduction in the pipe bridge system deformation was observed.
- (4) Strong earthquakes can cause failure and damage to pipelines due to interactions among various components within the pipe bridge system. The interaction between the support and the pipeline led to a longitudinal slip, resulting in stress concentration and buckling failure of the pipeline. Additionally, large displacements of the bridge tower during strong earthquakes can lead to its collapse. As the primary support for the entire cable-stayed tube bridge system, such collapse damage will ultimately result in pipeline failure.

Author Contributions: X.Z., formal analysis, methodology, validation, visualization, and conceptualization; G.W., formal analysis, methodology, software, and editing. All authors have read and agreed to the published version of the manuscript.

Funding: The financial support for this work was provided by the National Natural Science Foundation of China (No. 52174061), the Natural Science Foundation of Shaanxi Province, China (2022JM-279), the Yulin Science and Technology Plan Project (CXY-2020-095), the Xi'an Shiyou University Youth Science and Technology Innovation Fund Project (2015BS55), and the Key Research and Development Program of Shaanxi (Program No. 2022GY-431).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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