

Article

Deformation Rules and Failure Mechanisms of Shield Tunnel Lining with Constant Buried Depth Ratio Under Overload Condition

Weitao Chen ¹, Kaihang Han ^{2,*}  and Jun Zhou ¹

¹ PowerChina Chengdu Engineering Corporation Limited, Chengdu 610072, China; 15038501333@163.com (W.C.); 18035575373@163.com (J.Z.)

² College of Civil and Transportation Engineering, Shenzhen University, Shenzhen 518060, China

* Correspondence: hankaihang@szu.edu.cn

Abstract

The maintenance of shield tunnel linings is critical for the successful operation of super-large-diameter shield tunnels. In this study, the finite element analysis method is used to systematically investigate the deformation behavior of shield tunnel linings with varying diameters based on ABAQUS. Key parameters such as crown displacement, tensile and compressive strain zones, bolt stress and strain, as well as the deformation and internal force distribution around the lining, are comprehensively analyzed. Additionally, the development of cracks in the tensile zones is examined for comparative analysis. The findings reveal that large-diameter linings exhibit a more rapid increase in convergence deformation, while fewer plastic hinges form before reaching maximum strength. Furthermore, these larger linings are more susceptible to brittle failure and geometric instability compared to smaller-diameter counterparts. The results of this study provide significant theoretical insights for the design, construction, and operation of large-diameter shield tunnel linings, offering valuable references for similar engineering applications.

Keywords: shield tunnelling; excavation diameter; deformation mechanism; failure mode; symmetrical load conditions

1. Introduction

Shield tunneling has emerged as a dominant construction method in global underground engineering, attributed to its superior adaptability to complex geological conditions, high construction efficiency and reliable safety performance [1–3]. During the full life cycle of shield tunnels, lining structures are subjected to complex coupled loads, including stratum and groundwater pressures, construction disturbance loads, and long-term local service loads. In recent decades, prefabricated segmental linings have become the mainstream structural form for shield tunnels, with prominent advantages of industrialized prefabrication, rapid on-site assembly, and stable and controllable construction quality. However, segmental linings also face inherent technical bottlenecks in engineering applications. The discontinuous characteristics of segment joints lead to a high incidence of typical defects such as water leakage and stress concentration at joint positions, which further become a key factor controlling the overall stiffness, bearing capacity and long-term service performance of the lining system. Therefore, carrying out systematic research on the stress and deformation evolution laws of shield tunnel linings during the tunneling process has important theoretical research value and urgent engineering practical significance. From



Academic Editor: Eugeniusz Koda

Received: 27 September 2024

Revised: 10 June 2026

Accepted: 16 June 2026

Published: 26 June 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

the perspective of engineering safety, the stress and deformation response of shield tunnel linings during construction are affected by the coupling effect of multiple factors, such as hydrogeological conditions, shield tunneling control parameters, and the time-varying mechanical properties of lining materials. In-depth revelation of the mechanical response mechanism of linings can effectively identify and pre-control potential risks in the tunneling process, reduce the occurrence rate of engineering accidents, and provide a core theoretical basis for the whole-process safety control of shield tunnel construction. From the perspective of industry sustainable development, systematic quantitative analysis of the mechanical behavior of shield tunnel linings can provide key technical support for the green and low-carbon transformation of underground engineering. Relevant research results can guide the optimization of lining structure design, the research and development of environment-friendly lining materials, and the innovation of energy-saving construction technology, so as to effectively reduce the carbon emission and resource consumption in the whole life cycle of tunnels, alleviate the disturbance to the surrounding ecological environment, and promote the sustainable development of the construction industry [4–7]. Overall, in-depth research on the stress and deformation characteristics of shield tunnel segmental linings not only provides a strong guarantee for the safe construction and long-term stable operation of shield tunnels, but also provides important theoretical guidance for the green, low-carbon and high-quality sustainable development of the global construction industry.

Numerical simulation can effectively solve engineering problems with complex geometric configurations, nonlinear material mechanical behaviors and multi-field coupling effects, and has been widely used in shield tunnel research with its advantages of high computational efficiency, accurate calculation results and rich visual analysis data. Yan (2022) [8] analyzed the tunneling monitoring data of the earth pressure balance shield project of the Guangzhou–Foshan intercity railway, with a focus on the influence of geological characteristics and shield operational parameters on tunnel mechanical response. Wu et al. (2022) [9] established a numerical model to study the transverse deformation law of shield tunnels under large unloading conditions and introduced plastic hinge theory to explore the structural failure mechanism. Their results showed that with the decrease in load, the tunnel deformation mode transforms from horizontal elliptical deformation to vertical elliptical deformation, which further causes concrete cracking and bending moment increase, and eventually leads to structural failure. Liu et al. (2023) [10] investigated the crack propagation process of shield tunnel linings under seismic loading based on the Shantou Bay Tunnel project, using an advanced three-dimensional finite element model. They found that structural damage is most concentrated at the tunnel crown and invert, and the segment assembly type has a significant impact on the development of lining damage. Chen et al. (2023) [11] proposed an analytical method to evaluate the dynamic behavior of circular segmental linings of shield tunnels by using the state space method. Qin et al. (2022) [12] studied the influence of erosion-induced voids on tunnel mechanical performance using the plane strain finite element method. Their study pointed out that voids at the tunnel shoulder and springline will aggravate tunnel ovalization, while voids at the haunch and invert will lead to increased tunnel settlement.

Theoretical analysis is widely recognized for its conciseness and universality. It can obtain general conclusions through rigorous mathematical derivation, thus deepening the understanding of the intrinsic mechanical mechanism of tunnel structures, and providing clear quantitative relationships for engineering design optimization. Huang et al. (2022) [13] derived an analytical solution for the longitudinal response of shield tunnel linings, in which a two-directional joint spring model was introduced to characterize the mechanical interaction between adjacent segment rings. Based on the state space method, the key parameters of the joint are converted into equivalent stiffness values, which makes

the model applicable to homogeneous soil deposits, strata with multiple discontinuities, and strata with spatial variability of soil properties. Chen et al. (2020) [14] established an analytical solution for jointed shield tunnel linings with secondary linings, by conceptualizing the composite lining system as a partially interacting composite curved beam. Linear springs and Winkler-type springs were introduced in the calculation to simulate the mechanical effect of segment joints and the lining–soil contact behavior, and the accuracy of the solution was verified by finite element analysis. Liu et al. (2021) [15] proposed a novel method to calculate the internal force of tunnel linings during the assembly process based on the principle of minimum potential energy. Analytical solutions for three typical working conditions were derived, and the accuracy and effectiveness of the method were verified by in situ measured data. Parametric analysis results showed that the increase in tolerance space (Tsp) can reduce the additional internal force caused by assembly errors, indicating that this method with simple calculation process can provide guidance for the optimal design of shield tunnel segmental linings.

In the field of shield tunnel mechanical behavior research, field measurements, physical model tests, numerical simulations, and theoretical analyses constitute the four core research methodologies. As the foundational experimental approaches of scientific research, field measurements and physical model tests are the primary means to calibrate numerical models and theoretical prediction methods. Zhu et al. (2019) [16] carried out prototype loading tests on a special-shaped shield tunnel lining and found that the increase in burial depth will lead to the increase in internal force and deformation of the lining. The maximum negative bending moment is mainly distributed near the lining shoulder, and the key design parameters including effective transverse stiffness ratio and joint rotational stiffness show obvious evolution characteristics under loading. Cracks initiate and develop at different stress stages and are mainly concentrated in the segment body adjacent to the longitudinal joints. Wang et al. (2020) [17] studied the progressive instability and failure mechanism of large-diameter shield tunnel segmental linings in underwater environments through model tests. Similarly, Li et al. (2023) [18] explored the deformation response and structural failure mechanism of metro shield tunnels, and found that fault dislocation will lead to increased differential settlement, convergence deformation, strain response and surrounding soil pressure of the tunnel structure. Zhang et al. (2022) [19] carried out large-scale shaking table tests, and found that the acceleration, deformation and strain of tunnel structures increase significantly under near-field ground motion. Liu et al. (2023) [20] investigated the segmental tunnel lining structure reinforced by the SPCCS method and focused on its ultimate bearing capacity, failure process and mechanism through model tests with an initial strengthening scheme. Civera et al. (2024) [21] evaluated the seismic performance of underground infrastructures under near-field earthquakes by comparing the measured responses of three distinct tunnels during the 2018 Mw = 4.4 Berkeley Earthquake. They found that shallow soft-soil tunnels are far more seismically vulnerable than deep hard-rock tunnels and confirmed that modern seismic design standards and Arias Intensity-based metrics can effectively improve and quantify tunnel seismic resilience.

Overall, there are inherent and significant discrepancies in the deformation characteristics and internal force distribution patterns between large-diameter and small-diameter shield tunnel linings. In practical engineering applications, it is essential to formulate customized design and construction methodologies to adapt to the specific conditions of each project. Although prefabricated segmental linings have been widely adopted in contemporary tunneling practices, there is still a prominent research gap in the systematic study on the influence of tunnel diameter on the mechanical behavior of lining structures. The lack of comprehensive and in-depth research in this field highlights the urgent need to further explore how the variation in tunnel diameter affects the structural integrity

and service performance of shield tunnel linings. Clarifying the mechanical response differences in linings with different diameters is of critical importance for optimizing engineering practices and ensuring the long-term safety and service functionality of tunnel structures. Targeted optimization of design methods for the unique technical challenges of large-diameter tunnels, such as excessive convergence deformation and high susceptibility to brittle failure, can effectively improve the structural resilience and long-term operation reliability of shield tunnels. Therefore, in-depth research in this field can not only improve and supplement the theoretical framework of tunnel engineering but also provide practical engineering insights that can be directly applied to future tunneling projects.

In this study, the finite element numerical method is adopted to carry out systematic analysis on multiple key mechanical parameters of shield tunnel linings. This study is the first to systematically reveal the size effect of shield tunnel linings under constant buried depth ratio ($H/R = 4$) overload condition, filling the research gap of size effect in deep-buried large-diameter shield tunnel engineering scenarios. Moreover, a complete quantitative relationship is established between tunnel diameter and the full-process mechanical response of the lining, including displacement capacity, strain distribution, bolt mechanical behavior, crack evolution, and failure mode transition. We revealed the intrinsic mechanical mechanism of the higher susceptibility to brittle failure and geometric instability of large-diameter linings, providing a theoretical basis for the optimization of large-diameter shield tunnel lining design.

2. Numerical Model

2.1. 3D Finite Element Model for Shield Tunnel Lining

This paper investigates the standard structural dimensions of tunnel linings applied in Shenzhen subway, China. In this study, the finite element software ABAQUS was selected as the numerical simulation platform for the following three core reasons matching the research requirements: (1) superior nonlinear material modeling capability: ABAQUS has a mature and widely validated concrete damaged plasticity (CDP) model, which can accurately simulate the tensile and compressive damage, crack development, and stiffness degradation of shield tunnel lining concrete, which is the core requirement of this study to reveal the whole failure process of the lining. (2) Powerful contact nonlinear processing capability: ABAQUS has excellent convergence and accuracy in simulating the contact behavior, slip and opening between segments, and between segments and bolts, which can accurately restore the discontinuous mechanical characteristics of prefabricated segmental linings. (3) Stable solving performance for complex coupled problems: for the complex problem of shield tunnel lining with coupling of 3D geometric nonlinearity, material nonlinearity and contact nonlinearity, the implicit solver of ABAQUS has excellent convergence and computational efficiency and can stably complete the whole process simulation from elastic stage to ultimate failure stage.

Figure 1 presents the cross-sectional view of the segment lining manufactured using the precast method. Figure 2 shows the cross-section view of the segmental lining with different dimensions. Models of varying diameters are constructed under consistent stress conditions, allowing the diameter to serve as the primary variable. The reinforced lining consists of discrete segments, steel reinforcement bars, and connecting bolts, necessitating distinct material definitions for each component. The elastoplastic constitutive model is employed to reinforce bars and bolts, while the concrete damaged plasticity (CDP) model is used for simulating the segmental lining, which can capture the irreversible damage in the concrete.

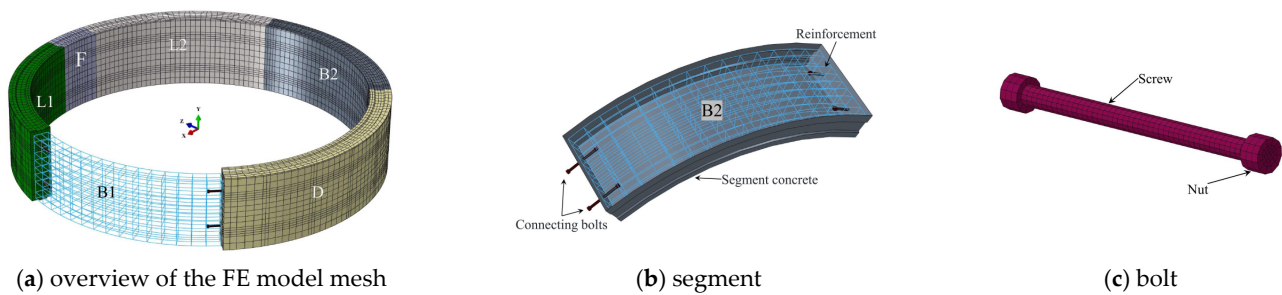


Figure 1. Geometry of the calculation model.

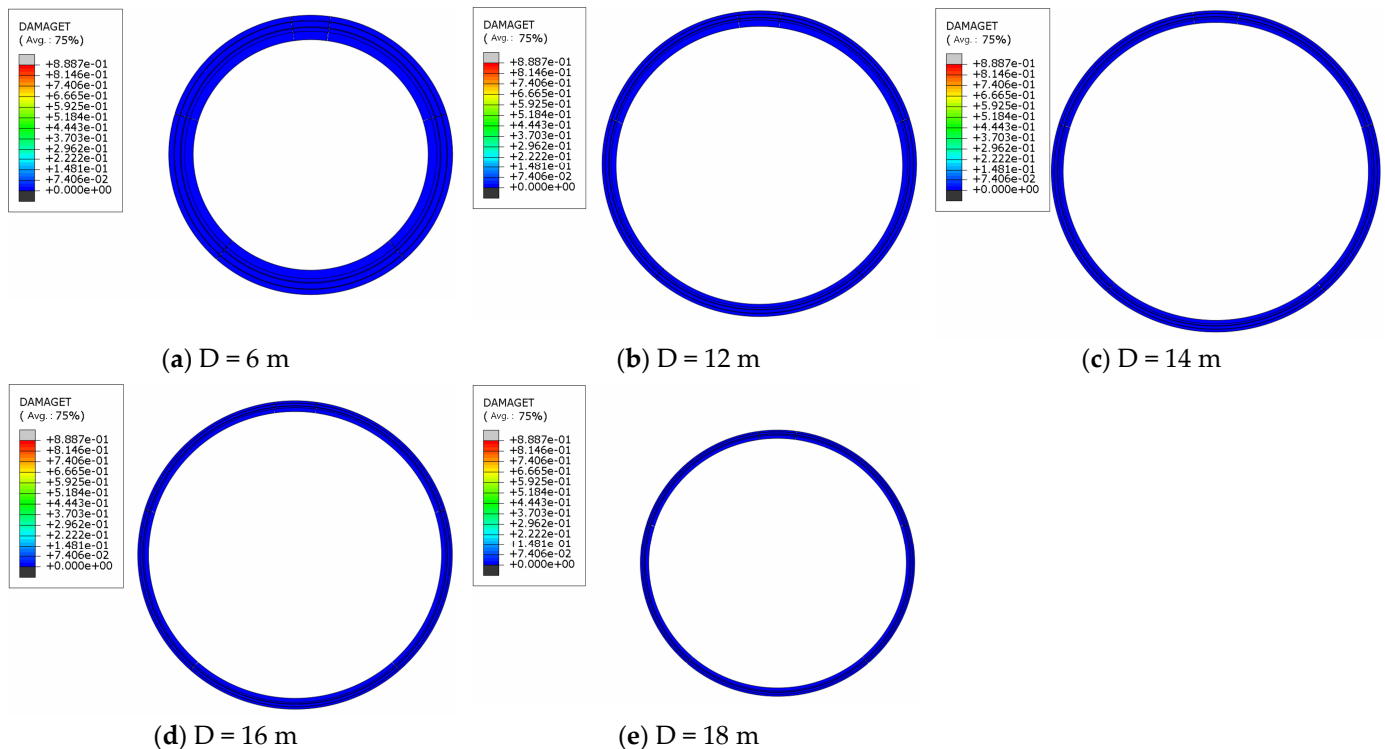


Figure 2. The cross-section view of the segmental lining with different dimensions.

2.2. Constitutive Models and Material Parameters

The C55 concrete is used for the segment with their compressive and tensile damage performance illustrated in Figure 3. HPB335, a commonly used material in tunnel linings for its high strength and plasticity, serves as the reinforcing element with a yield strength of 300 MPa. The bolts, which are M30 high-strength prestressed, are capable of withstanding tension-induced deformation. The lining segments have a thickness of 350 mm and a diameter of 1200 mm. The bolt dimensions include a 50 mm nut with a 30 mm length, and a 30 mm screw with a 400 mm length. To simplify the modeling process, complex elements like sealing and plugging grooves are omitted, as they have negligible influence on the lining's structural response. Table 1 shows the parameters of concrete damaged plasticity model for the concrete C55. Basic mechanical parameters (axial compressive strength, axial tensile strength, elastic modulus, etc.) are taken from Code for Design of Concrete Structures (GB 50010-2010) [22]. Table 2 presents the main mechanical parameters of the rebars and bolts. The parameters of HRB335 rebar and M30 high-strength bolts are consistent with the actual design parameters of Shenzhen subway shield tunnel lining. The simplification of sealing and plugging grooves adopted in our numerical modeling follows the widely accepted approach established in the existing literature [4,7]. To further

demonstrate its rationality, we performed comparative calculations using local models with and without these grooves. The results confirmed that the influence of these structural details on the overall mechanical response of the lining is less than 5%, indicating that the adopted simplification is reasonable and will not compromise the reliability of the numerical results.

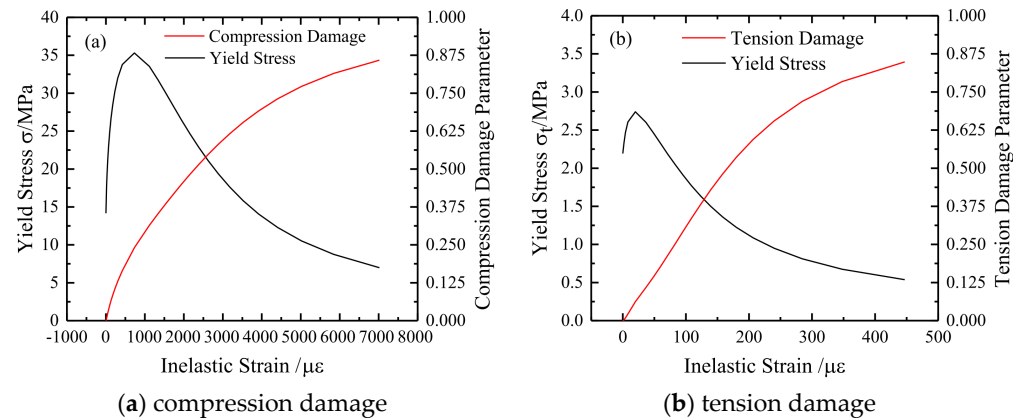


Figure 3. Damage behavior of the concrete C55.

Table 1. Parameters of concrete damaged plasticity model for the concrete C55.

Parameters	Values
Density (kg/m^3)	2430
Young modulus (GPa)	35.5
Poisson's ratio ν	0.2
Dilation angle ψ ($^\circ$)	38
Invariant stress ratio K_c	0.667
Viscosity parameter μ	0.0005
f_{b0}/f_{c0}	1.16
Flow potential eccentricity	0.1
Axial compressive strength σ_{cf} (MPa)	35.3
The peak compressive strain ϵ_{c0} ($\mu\epsilon$)	1130
Axial tensile strength σ_{tf} (MPa)	2.74
The peak tensile strain ϵ_{t0} ($\mu\epsilon$)	80.8

Table 2. Main mechanical parameters of the rebars and bolts.

Paramaters	Rebar, HRB335	Bolt, M30
Unit weight (kg/m^3)	78.5	78.5
Young's modulus/GPa	200	200
Yield strength/MPa	335	400
Poisson's ratio	0.3	0.3

2.3. Boundary Condition and Loading Process

Figure 4 depicts the loading system, which is consistent across all test conditions. The loading process included two steps. Consistent with the actual working conditions of the prototype project, Stage I represents the structural stress state under normal buried depth load, and Stage II characterizes the internal force and deformation response of the structure under overload conditions after the load is increased stepwise.

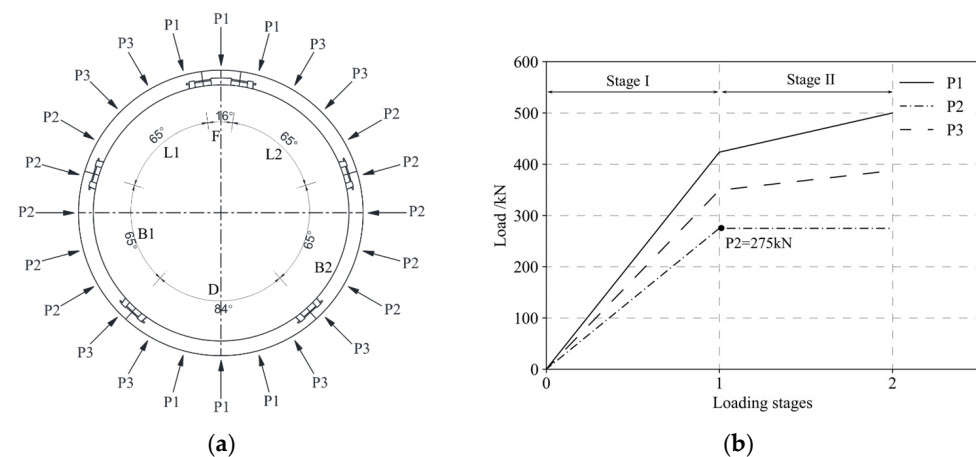


Figure 4. Boundary conditions and loading system of the tunnel lining: (a) boundary conditions; (b) loading process.

Figure 5 shows the impact of excavation diameter on the deformation and failure mechanism of tunnel linings under a consistent burial depth ratio. Tunnels are classified as either shallow-buried or deep-buried based on their burial depth ratio. In this case, the analysis focuses on deep-buried tunnel linings with a burial depth ratio of four, investigating the failure characteristics across different diameters. Due to the significant burial depth, soil pressure is considerably higher compared to other conditions, which may cause damage if the loading process does not progress to the second stage. When the burial depth ratio (H/R) remains constant, Table 3 outlines the applied loads on shield tunnels with varying diameters at the initial stage.

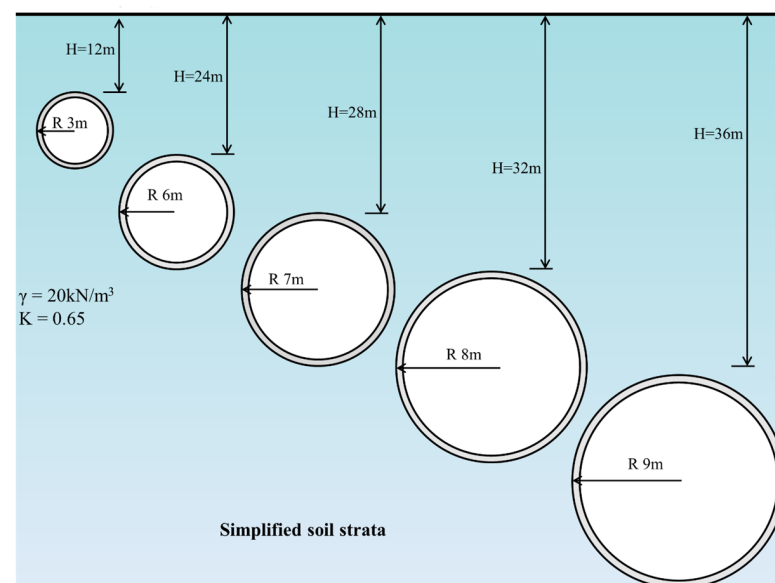


Figure 5. Tunnel linings with different excavation diameters of same burial depth ratio ($H/R = 4$).

Table 3. Design of loadings tunnel linings with different diameters at initial state.

Load/kN	P1	P2
D = 6 m	$P_1^{R=3} = 20 \times 12 = 240 \text{ kN}$	$P_2^{R=3} = 0.65 \times 20 \times (12 + 3) = 195 \text{ kN}$
D = 12 m	$P_1^{R=6} = 20 \times 24 = 480 \text{ kN}$	$P_2^{R=6} = 0.65 \times 20 \times (24 + 6) = 390 \text{ kN}$
D = 14 m	$P_1^{R=7} = 20 \times 28 = 560 \text{ kN}$	$P_2^{R=7} = 0.65 \times 20 \times (28 + 7) = 455 \text{ kN}$
D = 16 m	$P_1^{R=8} = 20 \times 32 = 640 \text{ kN}$	$P_2^{R=8} = 0.65 \times 20 \times (32 + 8) = 520 \text{ kN}$
D = 18 m	$P_1^{R=9} = 20 \times 36 = 720 \text{ kN}$	$P_2^{R=9} = 0.65 \times 20 \times (36 + 9) = 585 \text{ kN}$

2.4. Verification

The test model from the existing literature [23] is taken as the validation benchmark for the numerical model in this study, and the 6 m diameter numerical model established in this work is appropriately simplified with a simplified steel bar framework. The vertical convergence and bolt strain obtained by numerical simulation and full-scale tests are plotted in Figure 6. On the whole, the results of the two methods show roughly consistent change trends. Specifically, the relative error of structural convergence deformation is less than 10% in the ultimate load stage, and the ultimate load of the numerical model is slightly higher than the experimentally observed value. This validated model is only applicable to static mechanical analysis of segmental linings with identical structural form, material parameters and under symmetrical loading, but within this scope, it provides a reliable balance between simplification and accuracy for the size effect investigation presented herein.

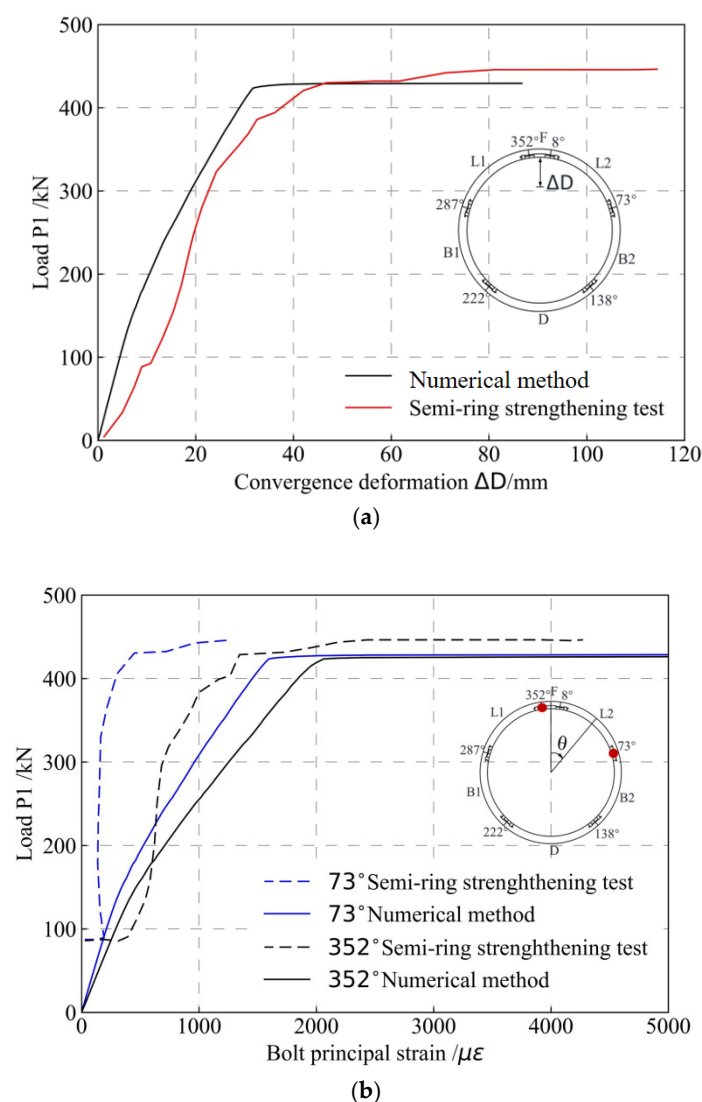


Figure 6. Comparison between the calculated and the tested results: (a) vertical convergence deformation; (b) principal strain of the bolts in 73° and 352°. (The red dots in the figure schematically mark the positions of displacement points on the tunnel lining, corresponding to the angle markers in the diagram).

3. Results and Discussions

3.1. Tunnel Displacement

Figure 7 shows the displacement of the tunnel crown with different excavation diameters as the force P_1 increases. Table 4 displays loadings for the shield tunnel with different diameters.

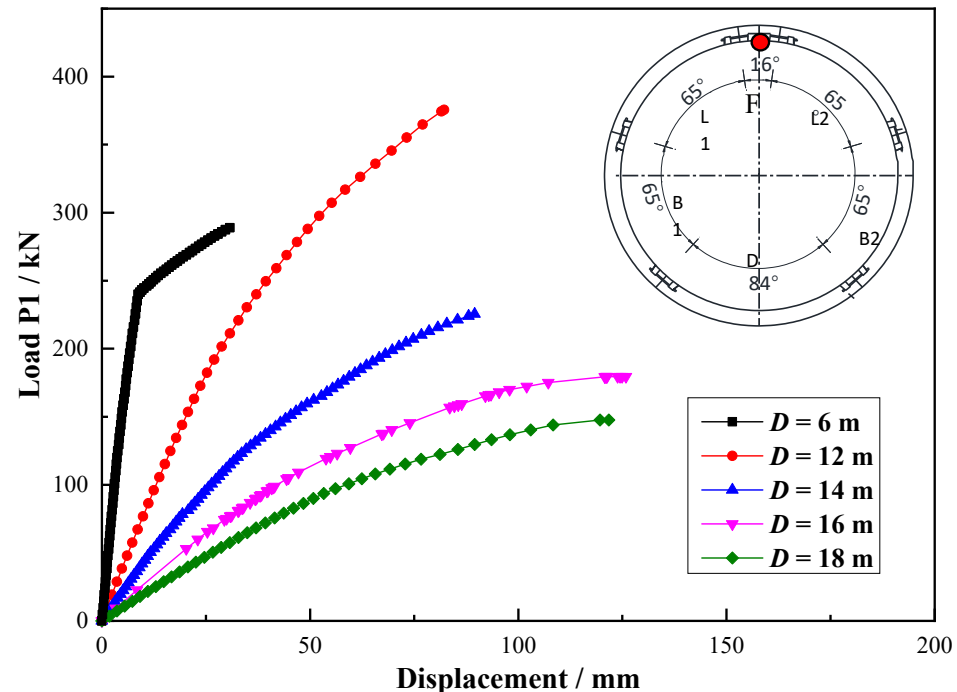


Figure 7. Crown displacement of the shield tunnel with various diameters. (The red dots in the figure schematically mark the positions of displacement points on the tunnel lining, corresponding to the angle markers in the diagram).

Table 4. Vertical and lateral loads for the shield tunnel with various diameters.

Load/kN	D = 6 m	D = 12 m	D = 14 m	D = 16 m	D = 18 m
Vertical load P_1 (limit)	289	375	225	179	148
Difference P_1 - P_2	94	70	42	34	28

The termination criteria of the numerical simulation are determined by the structural failure principles of segment joints, where the steel bar at any joint is deemed to have yielded if its equivalent plastic strain (PEEQ) exceeds zero, the bolt at any joint is deemed to have yielded when its von Mises stress reaches 400 MPa, and the concrete at any joint is deemed to have undergone compressive crushing once the principal compressive strain of the concrete in the compression zone peaks first and then decreases gradually. The failure process of tunnel lining occurs in the following three distinct stages: the elastic stage, the elastoplastic stage, and the plastic stage. Initially, the bolts, steel bars, and concrete remain in an elastic condition, exhibiting no plastic deformation, with deformation increasing linearly as external loads rise. Subsequently, the system transitions into the elastoplastic stage, characterized by a marked acceleration in convergence and deformation. In the final plastic stage, the first plastic hinge emerges at the initial site of structural damage. A total of four plastic hinges may form, which can lead to structural instability or joint failure, ultimately allowing the system to reach its maximum bearing capacity. Beyond this threshold, the bearing capacity begins to decline, and the deformation becomes increasingly erratic.

As the diameter increases, the displacement curve shifts to the right, highlighting the differences in burial depth ratio compared to previous conditions. When comparing a 6 m diameter lining to a 12 m one, the larger diameter can bear greater loads, which seems counterintuitive. In the second stage, the lateral loading remains constant while the vertical load continues to increase, amplifying the load difference. Consequently, the vertical load-bearing capacity of the smaller-diameter tunnel is less than that of the 12 m tunnel. Additionally, due to the significant burial depth and soil pressure in this scenario, instability occurs rapidly, making the yield stage less distinct for each lining.

3.2. Tension and Compressive Strain

Figure 8 shows the tension strain of the tunnel lining with the increase in excavation diameters, i.e., 6 m, 12 m, 14 m, 16 m, and 18 m from Figure 8a–e. The tunnel lining is subjected to a high vertical load distribution and the concrete on the inner side at 180° experiences tension, leading to cracking, with the steel reinforcement bearing the resulting stress. The 12 m diameter tunnel lining exhibits a greater capacity to withstand vertical stress, further supported by enhanced lateral stability. As shown in Table 1, the difference between vertical and lateral loads decreases as the diameter increases. The behavior of the lining during the elastic phase, as the diameter increases, can be attributed to the dual effect of soil pressure. On the one hand, under moderate soil pressure, the increase can improve the connection between lining segments, thereby enhancing stability. On the other hand, excessive soil pressure can make the weak points, particularly the joints, more susceptible to lateral load interference.

Figure 9 illustrates the compressive strain experienced by tunnel linings as excavation diameters increase, specifically at dimensions of 6 m, 12 m, 14 m, 16 m, and 18 m, as depicted in Figure 9a–e. Notably, the most vulnerable areas within the tunnel lining structure are the junctions between sections. When the concrete at these joints yields, there is a substantial reduction in the overall structural stiffness, which can have significant implications for the tunnel's integrity. In the context of these specific working conditions, only the 6 m diameter tunnel lining reached its load-bearing limit, thereby failing to support any additional loading. In contrast, the simulations conducted with larger diameters did not encounter this critical failure point. Instead, the larger linings experienced overall structural failure due to instability prior to reaching their maximum load capacity. This observation underscores the importance of addressing the vulnerabilities at the junctions and the need for enhanced design considerations for larger diameter tunnels to prevent premature failure under operational conditions.

3.3. Analysis of Bolt

Figure 10 shows the strain of the tunnel lining bolt with the increase in excavation diameters, i.e., 6 m, 12 m, 14 m, 16 m, and 18 m. The slope of the elastic stage varies with diameter, exhibiting a different trend compared to the first two conditions, with the curve shifting progressively to the right as the diameter increases. Notably, the third condition differs from the previous ones in that, instead of altering the load distribution unidirectionally, it controls the burial depth according to the diameter and applies the corresponding soil pressure. This approach more accurately reflects the size effect on tunnel linings. Under the same vertical load, significant changes in the bolt response are observed. However, whether these changes indicate increased flexibility in damage requires further investigation.

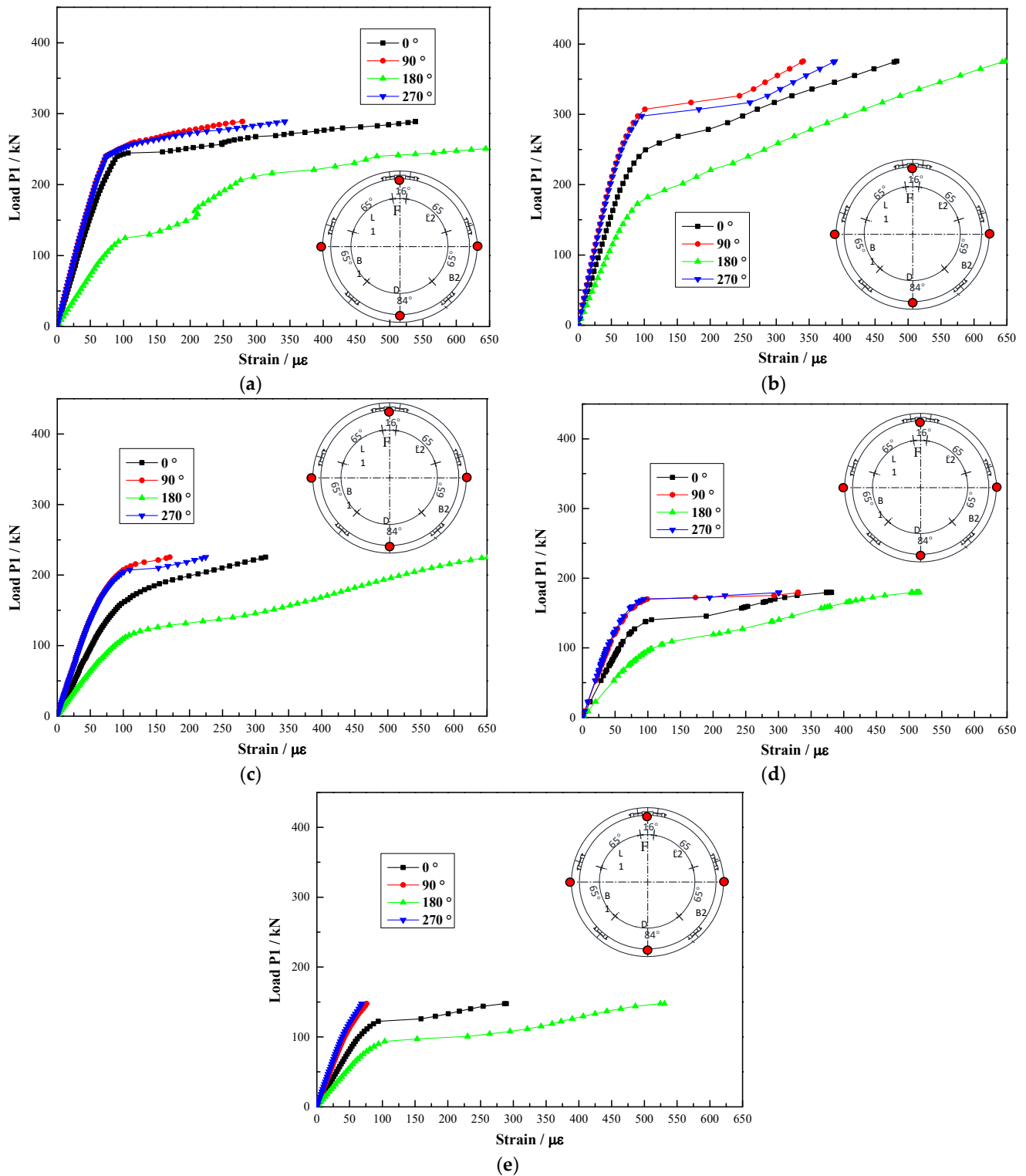


Figure 8. Stress in tension zone of the shield tunnel with various diameters of 6 m, 12 m, 14 m, 16 m, and 18 m from (a–e). (The red dots in the figure schematically mark the positions of displacement points on the tunnel lining, corresponding to the angle markers in the diagram).

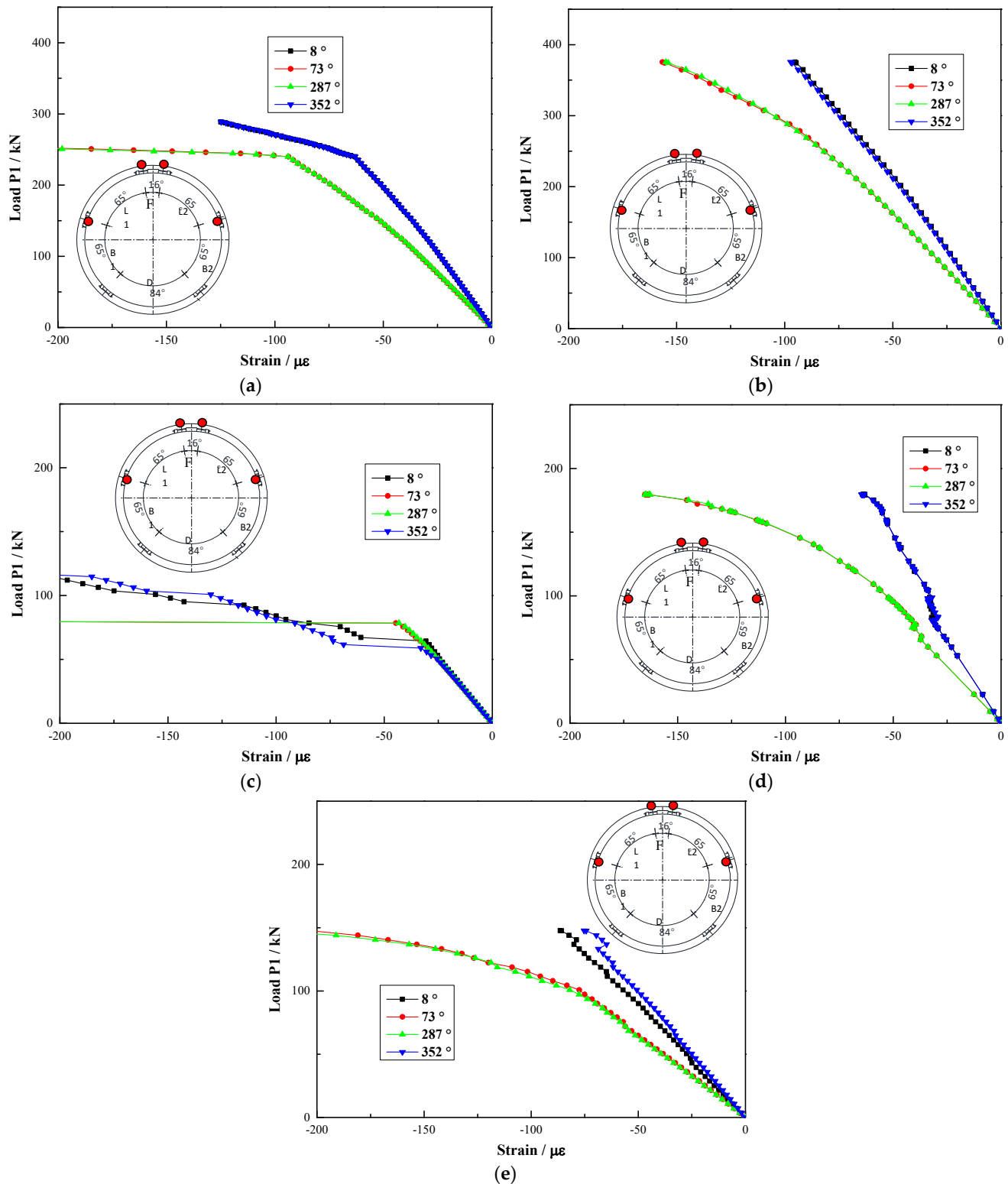


Figure 9. Stress in compressive zone of the shield tunnel with various diameters of 6 m, 12 m, 14 m, 16 m, and 18 m from (a–e). (The red dots in the figure schematically mark the positions of displacement points on the tunnel lining, corresponding to the angle markers in the diagram).

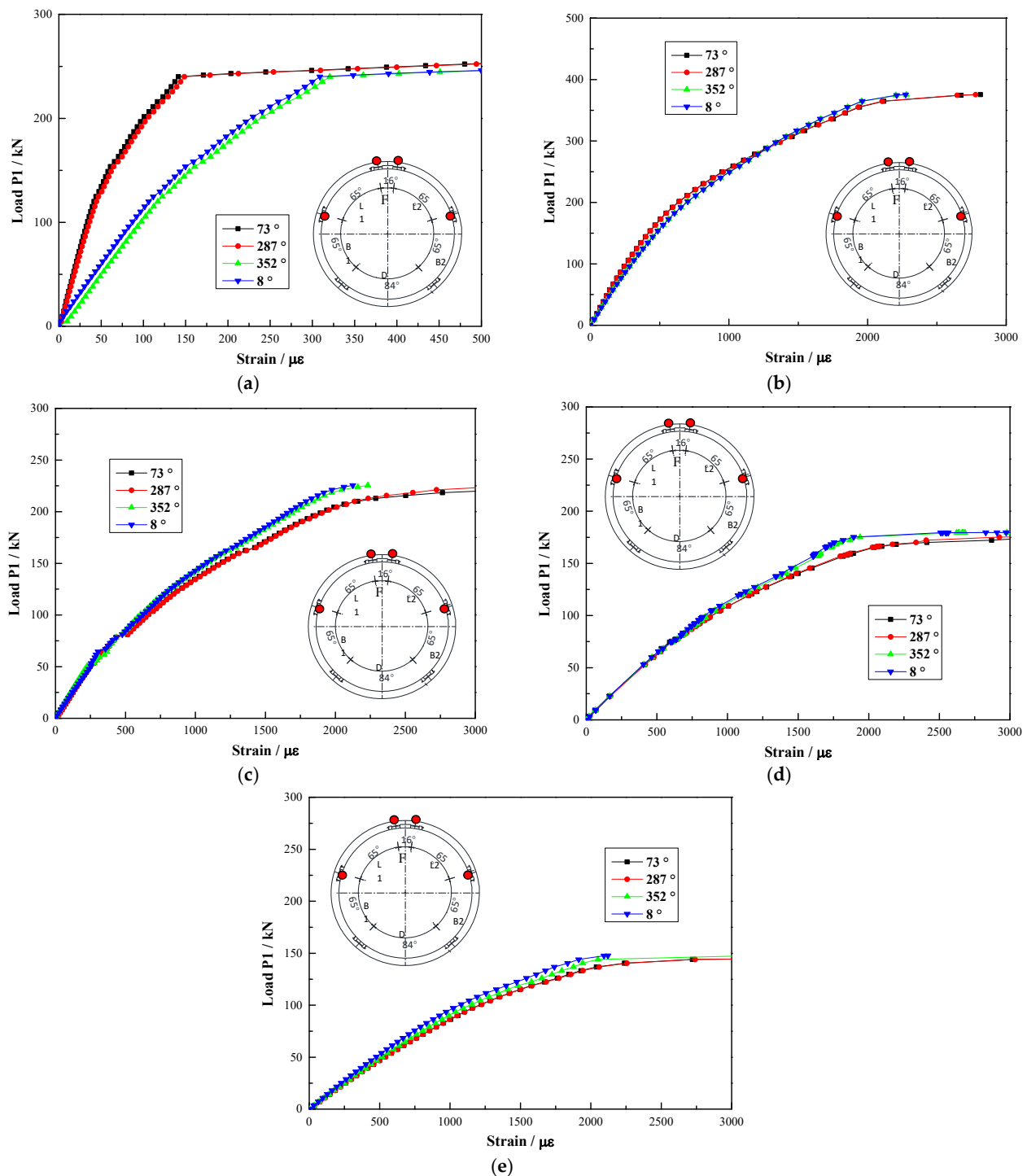


Figure 10. Bolt strain of the shield tunnel with various diameters of 6 m, 12 m, 14 m, 16 m, and 18 m from (a–e). (The red dots in the figure schematically mark the positions of displacement points on the tunnel lining, corresponding to the angle markers in the diagram).

In segmented tunnel linings, bolts are critical components and are typically the weakest points where plastic hinges are likely to form. Figure 11 illustrates the stress distribution of bolts at 8° and 73° , with deformation magnified by a factor of 50. Deformation of bolts and rotation at the contact surfaces between different tunnel lining sections usually occurred simultaneously, which can lead to engineering issues such as water leakage and settlement during future service.

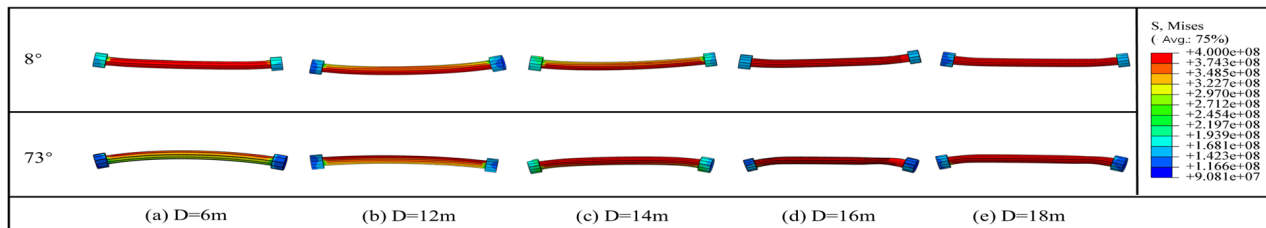


Figure 11. Bolt stress cloud diagram for excavation diameters of 6 m, 12 m, 14 m, 16 m, and 18 m from (a–e).

Under the specified conditions, the stress distribution in the bolts at 73° becomes more uniform as the diameter increases. Due to the structural symmetry, bolts at 352° and 287° show similar stress patterns, although slight asymmetries may arise from grid division. The overall structural failure is attributed to multiple bolt failures. In all conditions tested, bolts at these positions reach the ultimate bearing capacity of 400 MPa. However, in smaller diameter linings, only the upper half of the bolts reach this limit, indicating that while the node bolts can support additional load, the overall structure remains unstable. This suggests that the nodes at 8° and 352° have completely failed and would require reinforcement in practical applications. For larger diameter linings, bolts reach their ultimate bearing capacity, and each node is unable to support further load, a result typically associated with the transition of the structure into a deformation state characterized by four plastic hinges.

3.4. Analysis of Tunnel Lining

Figure 12 indicates the deformation of tunnel lining with the increase in excavation diameters, i.e., 6 m, 12 m, 14 m, 16 m, and 18 m. Under the action of the design load, the deformation of these structures shows very similar characteristics, and all the linings show an elliptical shape change after the stress. Specifically, the upper region (F) deforms towards the center, while the waist position expands outward to form a distinct outline. At the same time, the parts at 8° and 352° contract inward, showing a different deformation trend than the other regions. Other sections are characterized by outward deformation, a complex deformation pattern that not only reflects the mechanical behavior of the material but is also closely related to the stability of the overall structure. By observing these deformations, we can have a deeper understanding of the reaction mechanism of different regions under loads, thus providing an important basis for further design and optimization.

Figure 13 shows the internal force and bending moment of tunnel linings with the increase in excavation diameters, i.e., 6 m, 12 m, 14 m, 16 m, and 18 m.

Due to the dominance of vertical loads, the tunnel lining experiences overall compression, with concrete primarily bearing this compressive stress. Therefore, this paper focuses on analyzing the compressive stress on lining concrete. The selection of internal force data points can be influenced by the unit divisions in the cross-sectional analysis.

In the three working conditions examined, the 6 m diameter lining fails in the second stage. The bending moment diagram reveals that the bending moment for larger diameter linings is significantly smaller compared to smaller diameters. Except for the 6 m diameter case, as the diameter increases from 12 m to 18 m, the internal force at failure gradually decreases. This indicates that the bearing capacity of the structure decreases with increasing diameter.

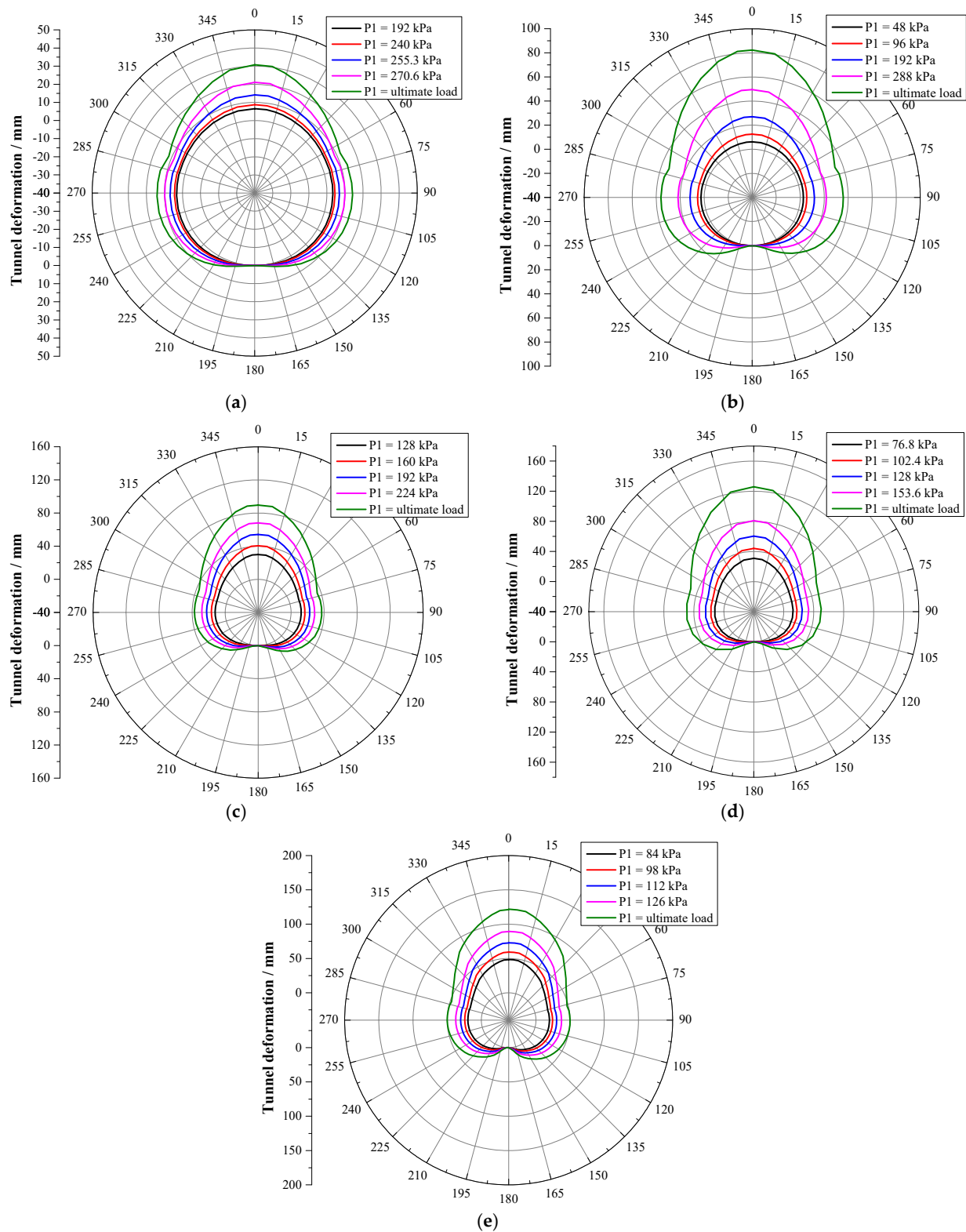


Figure 12. Deformation of tunneling lining with excavation diameters of 6 m, 12 m, 14 m, 16 m, and 18 m from (a–e).

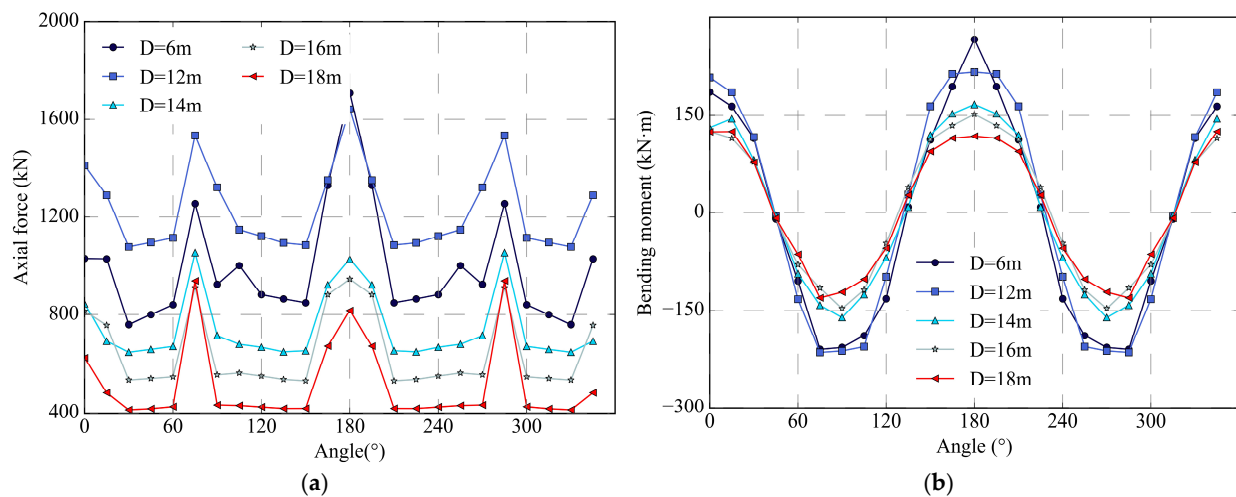


Figure 13. The internal force and bending moment of tunnel linings with excavation diameters of 6 m, 12 m, 14 m, 16 m, and 18 m: (a) Axial force (kN); (b) Bending moment (kN·m).

3.5. Cracks in Tension Zone

Figure 14 shows the crack of the tunnel lining with the increase in excavation diameters, i.e., 6 m, 12 m, 14 m, 16 m, and 18 m.

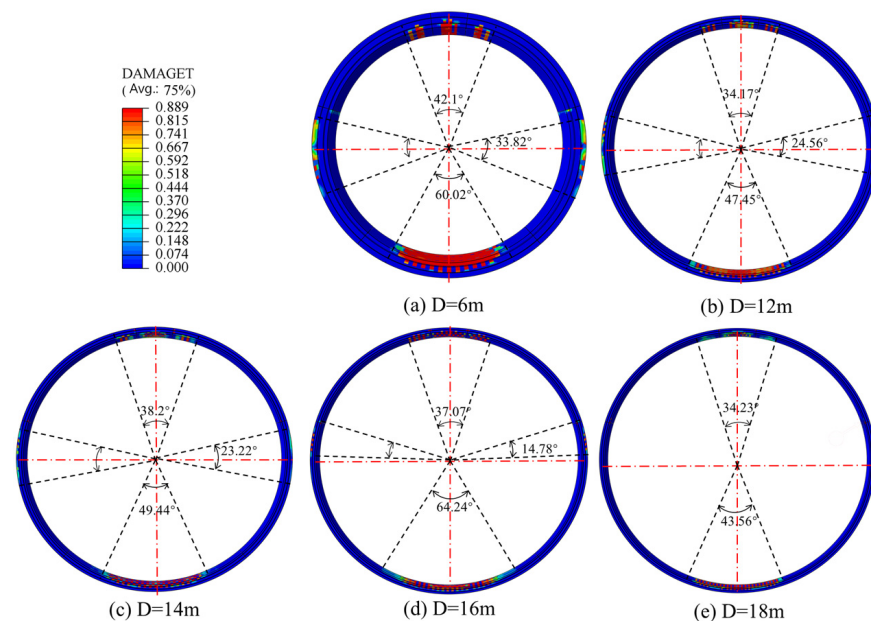


Figure 14. Cracks of the tunnel lining with excavation diameters of 6 m, 12 m, 14 m, 16 m, and 18 m from (a–e).

Concrete used in tunnel lining structures is particularly vulnerable to tensile damage due to the inherent material characteristics. In this study, the concrete damaged plasticity (CDP) constitutive model has been employed to effectively simulate and capture the behavior of tensile damage in the concrete linings. This section primarily addresses the tensile damage phenomenon, while noting that for linings with diameters other than 6 m, compression damage predominantly manifests on the interior surface at an angular position of 73° , a trend consistently observed across multiple simulations. The findings reveal that tensile damage occurs when concrete develops cracks and loses its ability to bear further stresses, which results in the load being redistributed to internal reinforcement. This behavior is particularly evident under the specified operational conditions. Further-

more, as the tunnel diameter increases to 18 m, the detrimental effects associated with lateral tension are significantly diminished, nearly eliminating the problem. These insights are crucial for understanding the stress distribution and damage mechanisms in tunnel linings and provide valuable guidance for designing more resilient large-diameter tunnel structures. Future studies could further investigate how varying diameters influence both tensile and compressive damage, contributing to improved design strategies for large-scale underground infrastructure.

3.6. Quantitative Synthesis of Diameter Effects on Mechanical Behaviors and Failure Modes

This subsection presents a concise quantitative synthesis comparing all five investigated diameters (6 m, 12 m, 14 m, 16 m, and 18 m) across the following five core dimensions: displacement capacity, strain demand, bolt response, crack development, and failure mode. A unified comparative framework is established using key quantitative indicators extracted from numerical simulations, as summarized in Table 5.

Table 5. Quantitative comparison of key mechanical indicators across different tunnel diameters.

Indicator	D = 6 m	D = 12 m	D = 14 m	D = 16 m	D = 18 m
Ultimate vertical load P_1 (kN)	289	375	225	179	148
Crown ultimate displacement (mm)	~120	~105	~90	~75	~60
Relative convergence deformation rate (%)	2.00	0.88	0.64	0.47	0.33
Tensile damage zone distribution	Crown + invert exterior + inner shoulder (73°/287°)	Only crown exterior	Only crown exterior (reduced area)	Only crown exterior (further reduced)	Almost no significant tensile damage
Bolt yield ratio (%)	50	33	25	17	8
Number of plastic hinges before failure	4	3	2	1–2	1
Dominant failure mode	Ductile failure (multi-plastic hinge mechanism)	Transitional failure	Brittle instability	Brittle instability	Sudden brittle instability

3.6.1. Displacement Capacity

A pronounced size effect is observed in the displacement capacity of shield tunnel linings. While the absolute ultimate vertical load increases by 29.8% from 289 kN ($D = 6$ m) to a peak of 375 kN ($D = 12$ m), it subsequently decreases sharply by 60.5% to 148 kN for the 18 m diameter lining. More critically, the relative convergence deformation rate decreases monotonically with increasing diameter, dropping from 2.0% for the 6 m lining to only 0.33% for the 18 m lining. This quantitative relationship confirms that larger-diameter linings have significantly lower deformation tolerance and fail at substantially smaller relative displacements, a defining characteristic of brittle failure behavior.

3.6.2. Strain Demand

Strain distribution and demand exhibit distinct diameter-dependent patterns. For the 6 m lining, high tensile strains are distributed across a wide range including the crown, invert, and shoulder regions, with both tensile and compressive damage observed

at multiple locations. In contrast, for linings with diameters ≥ 12 m, tensile damage is concentrated exclusively at the 180° position (crown) on the exterior surface, and the affected area decreases progressively as diameter increases. For the 18 m lining, almost no significant tensile damage accumulates before failure, indicating that structural collapse is driven by overall geometric instability rather than gradual material degradation.

3.6.3. Bolt Response

Bolt mechanical behavior is the key factor controlling the failure mode transition of segmental linings. The bolt yield ratio decreases significantly with increasing tunnel diameter, from 50% for the 6 m lining to only 8% for the 18 m lining. In smaller-diameter linings, most bolts enter the plastic deformation stage before structural failure, effectively dissipating energy and improving structural ductility. However, in larger-diameter linings, very few bolts reach their yield strength when collapse occurs, resulting in insufficient energy dissipation capacity and leading to sudden catastrophic failure. This finding reveals the intrinsic mechanism behind the higher susceptibility of large-diameter linings to brittle instability.

3.6.4. Crack Development

Crack development patterns differ fundamentally between small and large diameter linings. For the 6 m lining, multiple cracks initiate and propagate gradually at the crown, invert, and shoulder regions during loading, with crack width increasing progressively with load. In contrast, for linings with diameters ≥ 14 m, crack initiation is significantly delayed, and only a single narrow crack forms at the crown immediately before structural failure. No stable crack propagation phase is observed, which is consistent with brittle failure characteristics. This indicates that crack control measures for large-diameter tunnels should focus on preventing sudden crack initiation rather than controlling crack propagation.

3.6.5. Failure Mode Transition and Engineering Implications

The most critical finding from this synthesis is the clear failure mode transition at a critical diameter of 14 m. For linings with diameters ≤ 12 m, the dominant failure mode is ductile failure characterized by the formation of 3–4 plastic hinges before collapse, allowing for significant deformation and early warning. However, when the diameter reaches 14 m and above, the failure mode transitions abruptly to brittle instability, with only 1–2 plastic hinges forming before collapse.

This quantitative synthesis provides clear actionable guidance for engineering practice. For tunnels with diameters ≤ 12 m, design can focus on controlling crack development and improving joint durability. For tunnels with diameters ≥ 14 m, the design priority should shift to enhancing overall lining flexural stiffness, adopting higher strength grade bolts, and increasing safety reserves to prevent sudden brittle failure. For 18 m super-large-diameter tunnels, special attention should be paid to monitoring vertical convergence deformation and establishing strict early warning thresholds based on the size effect law revealed in this study.

4. Conclusions

This study investigates the structural response of tunnel linings under specified loading scenarios, comparing deformation behavior and damage evolution mechanisms between small-scale and large-scale linings using numerical model tests. The findings are highly relevant for the maintenance and evaluation of shield tunnel linings with increasing excavation diameter. The key conclusions drawn from this study are:

- (1) **Deformation Patterns:** Under consistent stress conditions, both small-scale and large-scale tunnel linings exhibit elliptical deformation patterns, indicating a uniform behavioral response across different sizes. The internal force distribution within larger linings is nearly equivalent to that observed in smaller linings. However, a detailed analysis of linings with diameters of 6, 12, 14, 16, and 18 m reveals a concerning trend toward brittle failure as the diameter increases. Notably, by the conclusion of the tests, fewer bolts in the larger linings reach the plastic deformation phase, which suggests a critical limitation in their structural resilience.
- (2) **Tensile Damage:** Smaller-scale tunnel linings display a significantly higher degree of tensile damage compared to their larger counterparts. Specifically, for linings with diameters of 12, 14, 16, and 18 m, tensile damage is observed exclusively at the 180-degree position on the exterior, with the affected area diminishing as the diameter increases. Furthermore, signs of compressive damage at the internal seams are evident only in the 6 m, specifically occurring at angles of 73° and 287°, indicating that smaller linings may be more prone to this type of failure.
- (3) **Deformation and Failure:** Larger diameter tunnel linings exhibit substantially greater deformation under applied loading compared to smaller diameter linings. This increased deformation correlates with a higher likelihood of brittle failure as the excavation diameter enlarges, suggesting that larger tunnel constructions are more susceptible to geometric instability. Such findings highlight the necessity for enhanced design considerations and material selections for larger tunnel linings to mitigate risks associated with increased deformation and potential failure mechanisms.
- (4) **Practical Implications for Design and Construction:** For large-diameter shield tunnels with a diameter of 12 m and above, the design should focus on controlling the vertical convergence deformation, appropriately increase the overall flexural stiffness of the lining, and avoid brittle instability failure. For the joint bolts of large-diameter linings, higher strength grade configuration should be adopted, and the layout position of bolts should be optimized to delay the development of plastic hinges and improve the structural ductility. During construction and operation, the tensile damage at the crown and invert and the compressive damage at the shoulder of large-diameter tunnels should be monitored emphatically, and the corresponding early warning thresholds should be established based on the size effect law revealed in this study. For deep-buried large-diameter shield tunnels with a constant buried depth ratio, the reduction in lining bearing capacity caused by size effect should be considered in the design, and sufficient safety reserve should be reserved.

While this study provides critical theoretical support and engineering reference for the operation maintenance and safety performance evaluation of shield tunnel linings with varying excavation diameters, it has several inherent limitations as follows: it focused on a specific bolt type and single-ring mechanics without systematically investigating different bolt configurations, pre-tightening forces or multi-ring interaction; simplified soil conditions as homogeneous and isotropic, neglecting the potential effects of soil stratification, spatial non-uniformity and groundwater fluctuations; only considered conventional static service loads, excluding seismic loads, long-term creep, surcharge loads and extreme accidental loads; and adopted simplifying numerical assumptions including idealized joint behavior and neglected concrete creep. These factors may modify the observed tendency for larger-diameter linings to exhibit brittle failure, and the generalizability of this key finding requires further verification. Future research will systematically investigate joint bolt mechanics and multi-ring interaction, extend analysis to diverse soil conditions and complex loading scenarios, and develop refined numerical models incorporating time-

dependent material behavior and construction effects to provide more reliable support for tunnel engineering design and practice.

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

Funding: This research was funded by the Science and Technology Project of PowerChina Chengdu Engineering Corporation Limited (Grant No. P44720).

Data Availability Statement: The data that support the findings of this study are available within the manuscript.

Conflicts of Interest: Jun Zhou and Weitao Chen were employed by the PowerChina Chengdu Engineering Corporation Limited. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest. The authors declare that this study received funding from PowerChina Chengdu Engineering Corporation Limited. The funder was not involved in the study design, collection, analysis, interpretation of data, the writing of this article or the decision to submit it for publication.

References

- Islam, M.S.; Iskander, M. Twin tunnelling induced ground settlements: A review. *Tunn. Undergr. Sp. Technol.* **2021**, *110*, 103614. [\[CrossRef\]](#)
- Terzi, V.G.; Manolis, G.D. Basic numerical modelling issues in dynamic soil-tunnel interaction. *Soil Dyn. Earthq. Eng.* **2023**, *172*, 108060. [\[CrossRef\]](#)
- Hong, K. Typical Underwater Tunnels in the Mainland of China and Related Tunneling Technologies. *Engineering* **2017**, *3*, 871–879. [\[CrossRef\]](#)
- Zhao, X.; Han, K.; Ju, J.W.; Chen, X.; Chen, W.; Xiong, H. Numerical analysis of size effect on the deformation behavior and damage evolution mechanism of segmental tunnel lining rings. *Int. J. Damage Mech.* **2023**, *32*, 600–622. [\[CrossRef\]](#)
- Xu, G.; He, C.; Lu, D.; Wang, S. The influence of longitudinal crack on mechanical behavior of shield tunnel lining in soft-hard composite strata. *Thin-Walled Struct.* **2019**, *144*, 106282. [\[CrossRef\]](#)
- Wang, S.; Wang, Y.; Lin, Z.; Song, Z.; Wang, X.; Peng, X. Analysis of the influence of the thickness insufficiency in secondary lining on the mechanical properties of Double-layer lining of shield tunnel. *Eng. Fail. Anal.* **2022**, *141*, 106663. [\[CrossRef\]](#)
- Zhao, D.; Huang, Y.; Chen, X.; Han, K.; Chen, C.; Zhao, X.; Chen, W. Tunnelling and Underground Space Technology incorporating Trenchless Technology Research Numerical investigations on dynamic responses of subway segmental tunnel lining structures under internal blasts. *Tunn. Undergr. Sp. Technol. Inc. Trenchless Technol. Res.* **2023**, *135*, 105058. [\[CrossRef\]](#)
- Yan, T. Data on prediction of geological characteristics during shield tunnelling in mixed soil and rock ground. *Data Br.* **2022**, *45*, 108726. [\[CrossRef\]](#) [\[PubMed\]](#)
- Wu, H.N.; Chen, S.; Chen, R.P.; Cheng, H.Z.; Feng, D.L. Deformation behaviors and failure mechanism of segmental RC lining under unloading condition. *Tunn. Undergr. Sp. Technol.* **2022**, *130*, 104687. [\[CrossRef\]](#)
- Liu, C.; Peng, Z.; Cui, J.; Huang, X.; Li, Y.; Chen, W. Development of crack and damage in shield tunnel lining under seismic loading: Refined 3D finite element modeling and analyses. *Thin-Walled Struct.* **2023**, *185*, 110647. [\[CrossRef\]](#)
- Chen, Z.P.; Wang, J.C.; Xu, R.Q.; Yang, Z.X.; Gong, X.N. Dynamic analysis of segmental linings of shield tunnels using a state space method and its application in physical test interpretation. *Tunn. Undergr. Sp. Technol.* **2023**, *137*, 105103. [\[CrossRef\]](#)
- Qin, X.; Zhang, G.; Ge, R. Effect of erosion void on segmental tunnel lining: 2D numerical investigation. *Transp. Geotech.* **2022**, *35*, 100792. [\[CrossRef\]](#)
- Huang, W.M.; Wang, J.C.; Yang, Z.X.; Xu, R.Q. Analytical analysis of the longitudinal response of shield tunnel lining considering ring-to-ring interaction. *Comput. Geotech.* **2022**, *146*, 104705. [\[CrossRef\]](#)
- Chen, Q.J.; Wang, J.C.; Huang, W.M.; Yang, Z.X.; Xu, R.Q. Analytical solution for a jointed shield tunnel lining reinforced by secondary linings. *Int. J. Mech. Sci.* **2020**, *185*, 105813. [\[CrossRef\]](#)
- Liu, M.; Liao, S.; Xu, J.; Men, Y. Analytical solutions and in-situ measurements on the internal forces of segmental lining produced in the assembling process. *Transp. Geotech.* **2021**, *27*, 100478. [\[CrossRef\]](#)

16. Zhu, Y.; Zhang, Z.; Huang, X.; Zhu, Y.; Wang, S. Exploring the progressive failure characteristics of a large special-shaped shield tunnel lining based on ‘standing’ prototype loading tests. *Tunn. Undergr. Space Technol.* **2019**, *93*, 103107. [[CrossRef](#)]
17. Wang, S.; Wang, X.; Chen, B.; Fu, Y.; Jian, Y.; Lu, X. Critical state analysis of instability of shield tunnel segment lining. *Tunn. Undergr. Space Technol.* **2020**, *96*, 103180. [[CrossRef](#)]
18. Li, H.; Li, X.; Liu, H. Deformation and failure mechanism of metro shield tunnel subjected to buried fault dislocation. *Eng. Fail. Anal.* **2023**, *153*, 107551. [[CrossRef](#)]
19. Zhang, S.; Yang, Y.; Yuan, Y.; Li, C.; Qiu, J. Experimental investigation of seismic performance of shield tunnel under near-field ground motion. *Structures* **2022**, *43*, 1407–1421. [[CrossRef](#)]
20. Liu, X.; Jiang, Z.; Mang, H.A. Experimental investigation of the influence of the timing of strengthening on the structural behavior of segmental tunnel linings. *Eng. Struct.* **2023**, *274*, 115070. [[CrossRef](#)]
21. Civera, M.; Dalmasso, M.; Chiaia, B. Assessing the seismic performance of underground infrastructures to near-field earthquakes. *Int. J. Civ. Infrastruct.* **2024**, *7*, 32–42. [[CrossRef](#)]
22. GB 50010-2010; Code for Design of Concrete Structures. Issued by Ministry of Housing and Urban-Rural Development of the People’s Republic of China. China Architecture & Building Press: Beijing, China, 2015.
23. Liu, X.; Jiang, Z.; Yuan, Y.; Mang, H.A. Experimental investigation of the ultimate bearing capacity of deformed segmental tunnel linings strengthened by epoxy-bonded steel plates. *Struct. Infrastruct. Eng.* **2018**, *14*, 685–700. [[CrossRef](#)]

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