Study on cracking behaviors of shield tunnel segment with annular interfacial unevenness under jacking thrust force

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Abstract. As one of the major engineering disasters in tunnel structures, segment lining cracks have significant impacts on the carrying capacity and durability of shield tunnels. This study focused on the lining cracking problems that are induced by annular interfacial unevenness during construction; a three-dimensional finite element model of shield tunnel linings was established that uses particular gasket elements and considers the assembly tolerance between segments and dowel pads at the annular interface. Through the numerical simulation, the lining’s structural deformation and crack propagation in the presence of the annular joint’s unevenness were studied by adjusting the initial gap and the normal stiffness modulus of the dowel pad at the annular interface. The numerical results indicate that the cracks induced by the jacking thrust force are initiated in hang holes in the midspan of the segments and subsequently develop along the longitudinal direction. In addition, the critical thrust loads for crack occurrence and the crack length are directly related to the initial gap and the stiffness modulus of the dowel pad at the annular interface of the segments. Moreover, the higher the assembly tolerance and the dowel pad stiffness modulus, the more serious will be the longitudinal cracks. It is confirmed that the use of appropriate dowel pads can effectively control the initiation and development of longitudinal cracks and enhance the structure’s carrying capacity.

Keywords: shield segment; dowel pads; gasket element; cracks; interfacial unevenness; jacking force

1. Introduction
In recent decades, the shield tunneling method has been favored globally due to its automated construction and minor stratigraphic disturbance. A shield tunnel comprises several arc segments that are connected by bolts and joints[1]. With an increase in the diameter and depth of tunnels, cracking problems in the segment linings become more frequent during tunnel construction. Cracks in segments markedly reduce the durability and carrying ability of shield tunnels[2]. The growth of segment cracks not only reduces the rigidity and bearing capacity of the structure but also minimizes the impermeability of concrete; this causes the corrosion of steel bars and the carbonization of concrete, which further reduces the structural carrying capacity and durability. Previous research identified longitudinal cracking and the chipping of segment corners to be the main types of damage; longitudinal cracks are the most common form under jacking thrust force[3].

Focusing on the cracking problem of segments, some researchers have studied the mechanism of this damage using both experimental tests and numerical simulations. Mo and Chen investigated the crack states of lining segments under jacking or relatively twisted forces[4, 5], while Yan et al. studied
the cracking damage characteristics of shield tunnel segments under an impact load due to train derailment[6]. Jin et al. analyzed a damaged shield tunnel’s load-carrying capability with consideration of the squeezing action of the shield tunnel[7]. Cavalaro et al. studied the influence of contact deficiencies over the structural behavior of segment linings and the consequential damage[8], and Wang et al. investigated the impact of the different positions of key blocks during the entire progressive failure of lining segments based on similarity model tests[9]. Su et al. investigated the distribution laws and characteristics of the cracking damage to linings using field monitoring and numerical simulations[10]. Finally, Xu et al. studied the influence of incomplete longitudinal cracks on the mechanical behavior of shield tunnel linings in soft–hard composite strata using experimental and numerical methods[11].

By summarizing the current research status, it is found that many unfavorable factors, including inappropriate thrust forces and contact deficiencies, will cause cracking problems in segments. However, uneven support conditions, including the misalignment and nonuniform thickness of dowel pads, are the primary cause of longitudinal cracks when thrust loads are applied during the construction process (Figure 1).

In this paper, the three-dimensional finite element program ABAQUS was used to simulate the cracking behavior of segments with annular interfacial unevenness under a thrust force. The unevenness of the annular interface was controlled using dowel pads with different parameters.

![Figure 1. Formation of longitudinal cracks](image)

2. Methods and numerical model

2.1. Accurate simulation of annular interfacial unevenness

When a shield machine drives forward, jacking thrust forces act on the dowel pads (Figure 2). The dowel pads transfer thrust forces to the segments through the contact surface between the dowel pads and the annular surface of the segments. Then, the segments transfer thrust forces to other dowel pads that are attached to other annular surfaces of the segments. Thus, an integrated force system is created. If gaps between the segments caused by production tolerances (e.g., the misalignment of segments) or erection tolerances (e.g., the nonuniform thickness of the dowel pads) exist, the jacking thrust forces transferred by the segments will be different due to differences in the initial clearance distance. The segment that is supported by the ring’s uneven annular interface allows only a partial contact, and when a thrust force is applied the segment behaves like a deep beam, and longitudinal cracks appear[12].
In order to simulate the situation mentioned above, gaps were intentionally imported between the annular interface of the segments. The gasket elements and the extended finite method were used in ABAQUS.

A gasket element (Figure 3a) is composed of two surfaces (a bottom and a top surface) separated by the thickness of the gasket. The element has nodes on its bottom face and corresponding nodes on its top face. The thickness direction, transverse shear, and membrane behaviors can be defined as uncoupled behaviors only when the elements are used in conjunction with special gasket behavior models. Moreover, the gasket element has a particular pressure–closure curve to simulate the initial dowel pad gap between the annular interface of the segments. This curve allows a certain limit of compressive displacement without any transmission of forces. Once this limit displacement is reached, the load is transmitted through the element with defined stiffness. Thus, the gasket element is suitable for simulating the mechanical behavior of the dowel pad with an initial gap. The material of the dowel pad is rubber, and for simplicity, a linear relationship of the pressure–closure curve is applied to describe the material property of the dowel pads in this paper (Figure 3b).

The normal stiffness modulus of the gasket element is defined as the ratio of pressure to closure, which is related to the elastic modulus and the thickness of the gasket element.

2.2. Three-dimensional numerical model

A numerical model of segments with an initial gap in their annular interface was proposed to investigate cracking behaviors under contact deficiencies (Figure 4). Considering that newly installed segments are located inside a shield shell and are not affected by ground load, the deformation of the structure is symmetrical under a uniform thrust force. Thus, a partial segment model was established to simplify the simulation and reduce the computational time. As shown in Figure 4, there are six dowel pads in the annular interface of the model. Only one dowel pad was simulated by gasket elements with an initial gap.

![Dowel pads](image1.png)

**Figure 2.** Standard segments and dowel pads

![Standard segment](image2.png)

![Gasket element](image3.png)

(a) Deformation modes of gaskets  
(b) material property of dowel pads with an initial gap

**Figure 3.** Gasket element used to simulate dowel pads
gap, while the others were simulated by gasket elements with no initial gap. For the convenience of subsequent explanation, the dowel pad below Segment A with an initial gap is marked as K1, while the other two dowel pads without initial gaps are marked as K2 and K3.

The external and internal diameters of the segment are 8.3 and 7.5 m, respectively, while the thickness and width are 0.4 and 1.5 m, respectively. The central angle of the standard segment is 56.8°, and the segments are assembled by staggered joints. The contact between the rings in the circumferential joint is limited to the area covered by 0.65 m long dowel pads (three per segment). Additionally, only one of the six dowel pads is appointed with an initial gap, while the others are in good working condition. The connections of both the longitudinal and circumferential bolts were simulated by nonlinear spring elements in this study. The force–displacement curve is plotted in Figure 5 to describe the bolts’ mechanical behavior.

![Three-dimensional model considering annular interfacial unevenness](image)

**Figure 4.** Three-dimensional model considering annular interfacial unevenness

![Relationship between tensile force and spring displacement](image)

**Figure 5.** Relationship between tensile force and spring displacement

Generally, in many tunnels constructed using the shield driving method, the thrust forces are applied by a group of hydraulic jacks parallel to the lining axial. The total thrust force acting on the segments of a tunnel during normal situations is about 20,000 kN. In this paper, the thrust forces were set to twice that level (40,000 kN) to approximately simulate the force status when the shield machine turns or in the case of other unpredictable statuses. Thus, each dowel pad transferred 10.12 MPa of pressure onto the segment. The model is restrained by ground springs in the circumferential direction, which are fixed at the bottom. The mechanical parameters of the C50 concrete used in this study are listed in Table 1.

| Parameter                  | Magnitude |
|----------------------------|-----------|
| Table 1. Mechanical parameters of concrete |           |
3. Result and analysis

The variables considered in this study include the initial gap and the normal stiffness modulus of the dowel pads. The simulation case is shown in Table 2. For each simulation case, only one of six dowel pads between the segments’ annular interface was appointed with an initial gap (as shown in Figure 4), while the others made good contact.

| Case | Initial gap | Stiffness modulus of dowel pads |
|------|-------------|-------------------------------|
| 1-1  | 0.5mm       | 5N/mm³                        |
| 1-2  | 1.0mm       | 5N/mm³                        |
| 1-3  | 1.5mm       | 5N/mm³                        |
| 1-4  | 2.0mm       | 5N/mm³                        |
| 2-1  | 1.0mm       | 7.5N/mm³                      |
| 2-2  | 1.0mm       | 10N/mm³                       |
| 2-3  | 1.0mm       | 12.5N/mm³                     |

3.1. Longitudinal cracking in segments with different initial gaps

The production or erection tolerance may cause initial gaps between the segments’ annular interface, leading to the appearance of a longitudinal crack. The impact of an initial gap on the segments’ cracking behavior was investigated in simulation cases 1-1 to 1-4.

With different initial gaps, the crack distribution of the segments remained similar; hence, only one crack distribution from case 1-4 is given in Figure 6. The result shows that four cracks appeared when the thrust force was applied. The crack in Segment A appeared first, then the crack in Segment C appeared as the load increased, and finally, the remaining cracks appeared under considerable thrust forces.

Figure 6. Crack distribution of initial 2.0-mm gap
It is considered that Segment A bears the thrust force directly, and a longitudinal crack initially appears on the hang hole of Segment A. This confirms that Segment A is the weakest part under these conditions. Thus, the crack propagation in Segment A was analyzed. Figure 7 shows the cracking process of Segment A. The length of the crack grows stepwise as the load increases; the greater the initial gap, the smaller the critical load required for the crack to occur. The critical thrust loads to induce cracking are 5.67, 4.81, 3.95, and 2.78 MPa, respectively. In general, reducing the gaps between the segment seams improves the production and erection tolerance of the segments, which is an effective way to reduce cracking.

With an initial gap between the segment seam, the segment behaves like a cantilever beam when a thrust force is applied, causing unevenness in the reaction force at the bottom of the segment. In this study, the pressure of the dowel pad equals the reaction force of the segments in front. Additionally, the difference in the reaction forces in different positions indicates the inhomogeneous deformation of the segment, which may lead to cracking problems in the structure.

Figure 8 shows the pressure difference between Dowel Pad K1 and Dowel Pad K3 in different simulation cases. It can be seen that the curve increases rapidly before the deformation of K1 reaches the initial gap; after that, the curve begins to decline. All the curves present a similar tendency, and the difference in pressure increases with the increase of the initial gap. Thus, the greater the initial gap, the more significant the difference in the local internal forces of the segment, which has the disadvantage of easy cracking.

### 3.2. Longitudinal cracking of segments with dowel pads of different normal stiffness moduli

A dowel pad can maintain the elastic state of segment joints, and it possess sufficient pressure-bearing capacity due to its superelastic properties. Not only does it fill the gaps between segment seams, but it also relieves concentrated local stress. Therefore, dowel pads have a positive effect on preventing segments from cracking. The influence of dowel pads’ stiffness moduli over the cracking behavior of segments was investigated in this study. For each simulation case, the initial gap of Dowel Pad K1 was maintained at 1.0 mm, and the stiffness modulus of all the dowel pads changed from 5 to 12.5 N/mm³.

The crack distribution in Segment A is shown in Figure 9. Similar to the previous simulations, the longitudinal crack initiates in hang holes in the midspan of the segment and subsequently develops along the longitudinal direction. All the crack distributions in the different simulation cases are similar, showing that the stiffness modulus of the dowel pads has no great influence on the path of crack propagation.

Figure 10 shows the cracking process of Segment A. The length of the crack presents a similar tendency. Much like the previous simulation results, no crack occurs when in low-level thrust load, and once a crack appears, its length increases stepwise. The critical load required for the crack to occur
decreases with the increased stiffness modulus of the dowel pads. For stiffness moduli of 2.5, 5, 7.5, and 10 N/mm$^3$, the critical thrust loads are 5.26, 4.81, 4.05, and 3.04 MPa, respectively.

Figure 9. Crack distribution in Segment A

Figure 10. The cracking process in Segment A

Figure 11 gives the pressure difference between Dowel Pad K1 and Dowel Pad K3. The curve increases rapidly as the thrust force is just applied; then, it begins to drop and tends to flatten when Dowel Pad K1 starts loading. Additionally, the peak value increases with the increase of the normal stiffness modulus of the dowel pads. Therefore, the lower the stiffness modulus of the dowel pads, the smaller the difference in the inner force on the structure, which has less probability of cracking. In other words, decreasing the elastic modulus or increasing the thickness of the dowel pads is an effective way to prevent the cracking of segments.

Figure 11. Pressure difference between Dowel pads K1 and K3

4 Conclusions
This paper studied cracking problems in segments during the construction stage considering the annular interfacial unevenness under jacking thrust forces. Further, the critical thrust load required for a crack to occur and the crack’s length under adverse conditions considering the initial gap and the normal stiffness modulus of the dowel pads were calculated. The research results indicate that the higher the assembly tolerance and the dowel pad stiffness, the more serious will be the longitudinal cracks. Improving the anticracking properties of concrete near hand holes and using appropriate dowel pads can
reduce the probability of cracking, which helps meet the requirements of serviceability limits and for reducing maintenance costs in the future.

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