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Full-Ring Experimental Study of the Lining Structure of Shanghai Changjiang Tunnel

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Abstract: Shanghai Changjiang Tunnel, 15 m in diameter, is one of the world's largest shield-driven tunnels in diameter. Tongji University has recently carried out a test on the full-scale three-ring lining structure of Changjiang Tunnel. This paper introduces the testing processes, including loading apparatuses, test contents, test cases, etc., and makes comparison with other shield lining structure tests conducted before, and finally gives some evaluations on the design of the tunnel.

Key words: Shield-driven tunnel, lining structure, full-scale test, load apparatus.

1. Introduction

Shield driven tunnel construction has played an important role in tunnel construction since its debut 100 years ago. It experienced great development in recent years with the appearance of various cross-section shield machines, and the shield diameter becomes increasingly larger. The design of the lining segments has close connection with the structure safety, construction quality, engineering investment, etc.. Therefore full-scale or other appropriate scale tests are often conducted before the construction of large tunnels, so as to verify the rationality and feasibility of the design, to control the construction quality, to make proposal of optimization, and thus to get better techniques and greater benefits.

The experimental study of tunnel lining structures has been conducted many times in China and other countries. In 1999, Tongji University and Shanghai Tunnel Engineering & Rail Transit Design and Research Institute (STEDI) carried out a joint test of full-scale single-circular tunnel lining structures. The lining rings tested were of two kinds: one in Shanghai subway tunnel and the other in Guangzhou subway tunnel. The lining ring of Shanghai subway tunnel had an outer diameter of 6.2 m, inner diameter of 5.5 m, wall thickness of 0.35 m, and ring width of 1.0 m, while the one of Guangzhou subway tunnel had an outer diameter of 6.0 m, inner diameter of 5.4 m, wall thickness of 0.30 m and ring width of 1.2 m. The test provided basis for optimizing the tunnel lining structure of Shanghai subway tunnel and perfecting its design and calculating methods by comparing the tests of the two rings, calculating and analyzing the internal force and deformation of the lining structure and overall evaluating the two rings' deformation, internal force, anti-crack and water-proofing properties. The lining ring tested is a single one and shown in Fig. 1. The effects of adjacent lining rings and lengthwise pressure on the lining were not taken into consideration. Thirty-two hydraulic pressure jacks were employed to load along the radial direction inward to equally simulate the actual pressure on the lining. And the force was evenly acted onto the lining through pad beams. Shanghai Metro 8 is the first tunnel with double-circular lining in China [1]. For its successful completion, Tongji University carried out a horizontal 1:1 full-ring test in 2003 under three test cases, the lining ring strain, the strain of bolts ringwise and bolts lengthwise, the overall radial and tangential structure deformation, the opening of crack, etc., and

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got practical result for the engineering. The test model was composed of three parts: the upper half ring, middle full ring and lower half ring, stagger-jointed with three rings. Fig. 2 shows the test and loading system.

In Japan, the shield technique develops rapidly, and takes the lead in the world. In 2003, a full-scale structure test was carried out on double-circular rectangular shield lining, which brought forth a new cross-section of shield driven tunnels [2]. The lining was a double-circular rectangle, a composite lining structure with steel exterior and concrete interior. The loading test setup is shown in Fig. 3. The test models are of two kinds: one with central pillars and the other without. The models were loaded at 6 points, and they were stagger-jointed with three rings, considering the interaction between the rings. In another test of single-circular lining, prestressed tendon were employed ringwise to compensate for the inadequate axial force resulted from concentrative loading of jacks, see Fig. 4 [3].

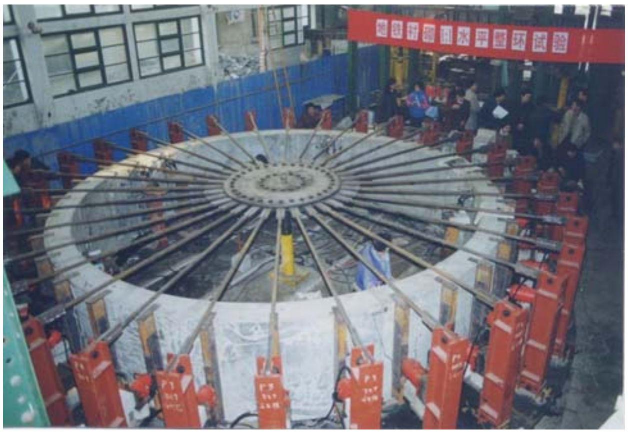

Fig. 1 Loading test of single-circular lining.

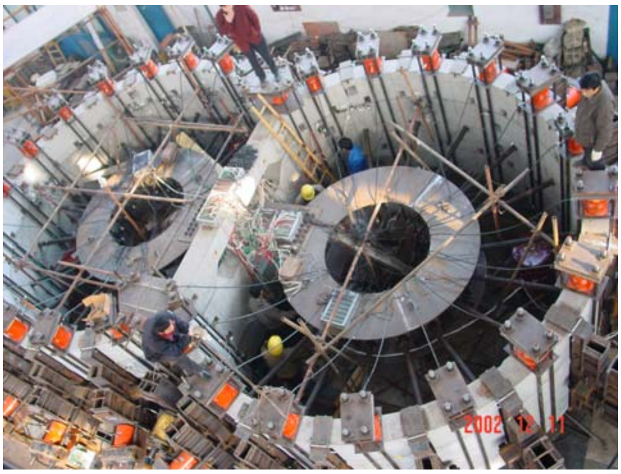

Fig. 2 Loading test of double-circular lining.

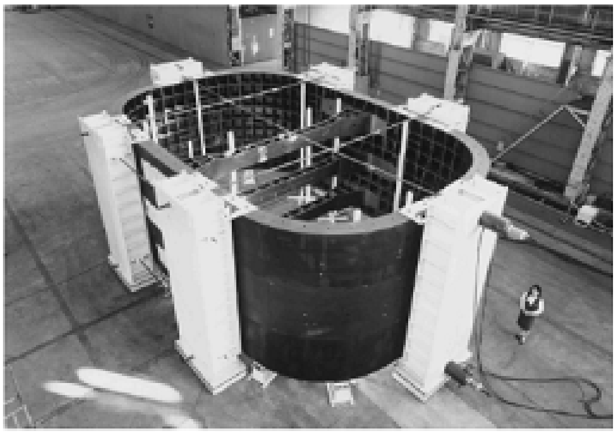

Fig. 3 Lining test of Kyoto municipal metro.

The fourth Elbe highway tunnel of Germany was the world's largest with its outer diameter of 13.75 m. Full-scale full-ring test was conducted to test the loading capacity and stability of the lining segments, see Fig. 5 [4]. The objectives of the test were: (1) to verify the loading capacity of the full lining ring; (2) to test the utmost deformation suffering of the lining ring; (3) to test the joint tolerance and allowance of the lining ring; (4) to test the sealing adaptability of segment joint to different displacement; and (5) to optimize the inner steel bars of the segments.

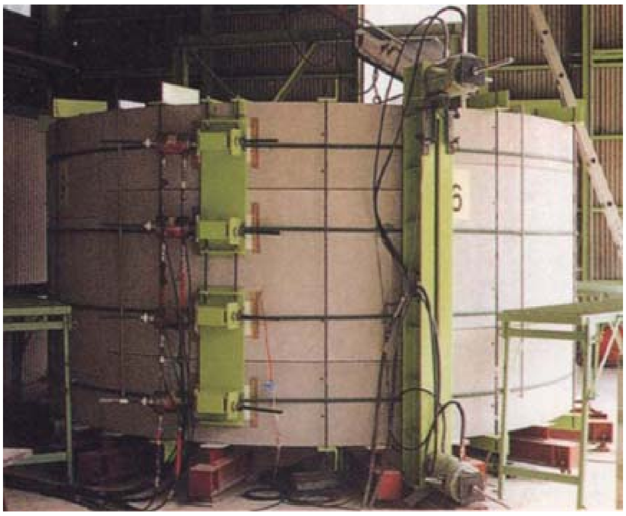

Fig. 4 Test of single-circular lining with ringwise prestressed.

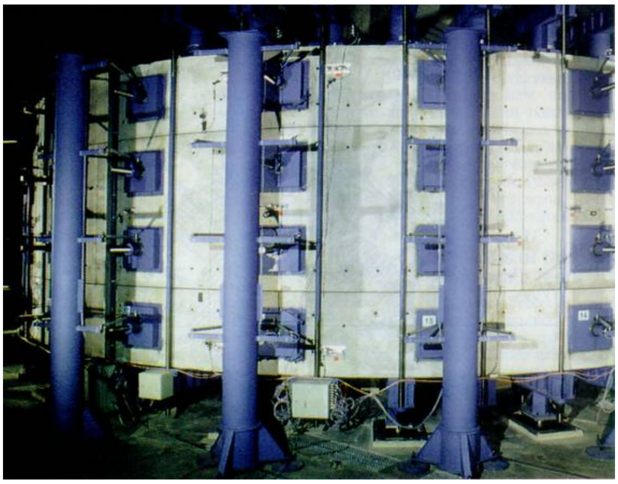

Fig. 5 Test of the lining structure of 13.75-meter Elbe highway tunnel

In the full scale full-ring lining test of Elbe highway tunnel, the tested lining was composed of one full ring and two half rings, with an outer diameter of 13.75 m, an inner diameter of 12.35 m, a thickness of 0.7 m, and a height of 4m. A friction-reducing bearing was fixed between the lining ring bottom and the floor of the lab to minimize the influence of bottom friction. A concentric ring with an inner diameter of 7 m, as a force reaction apparatus, was located at the middle of the lining ring, connected with the lining ring by 96 hollow jacks. In the test the jacks simulated the actual water and earth pressure on the lining segments by intensifying pressure on the lining ring through pull-rods. 150 displacement meters were installed on the surface of the lining ring to measure the deformation of the ring, and another 100 sensors to measure the opening and contracting degree of the segment joints. The testing process was controlled by a special test system.

In the design of the tunnel lining structure of "Green Heart", a tunnel in Holland, three-dimensional simulated analysis were made by the FEM codes of ANSYS and DIANA. For a further study, a full-scale test was conducted on the three-ring lining structure, see Fig. 6, and a comparative analysis was also brought out on the test result by FEM codes [5]. In addition, other tests, like the test of the lining-ring deformation, were also carried out.

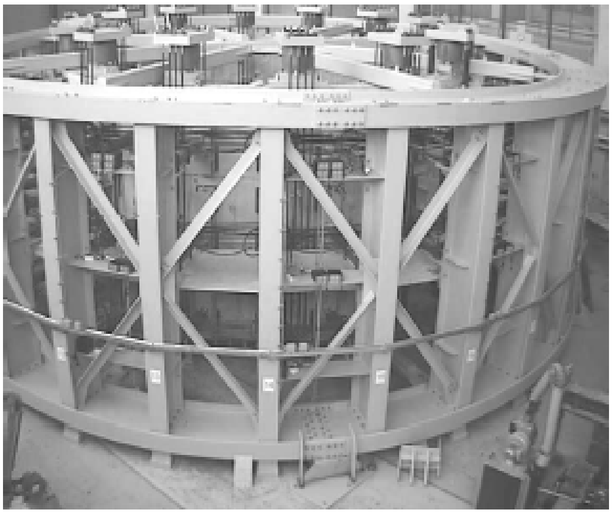

Fig. 6 Full-ring test of the lining structure of Holland's "Green Heart" tunnel.

2. The Objectives and Contents of the Test

2.1 Test Objectives

The construction of Changjiang Tunnel is one of the greatest infrastructures in Shanghai and in China as well, with a design reference period of 100 years. The tunnel will be of the world's largest diameter, with an outer diameter of 15.0 m, an inner diameter of 13.7 m, lining ring width of 2.0 m, and it is to be shield-driven and stagger-jointed with popular wedge-shaped lining segments. To test the loading capacity and stability of the lining ring and to control the structure pressure and deformation under construction load, a full-scale full ring test of the lining will be necessary. The objectives of the test are:

(1) To test the loading capacity of the lining rings under different design phases, including different burying depths and different side pressure coefficients;

(2) To test the utmost deformation endurance of the lining ring;

(3) To justify the calculated analysis parameters by comparing the test data with theoretical calculated results;

(4) To get the stiffness variation limits of the joints ringwise and joints lengthwise and to get the largest opening angle, and also to verify the water-proofing and adaptability of the joints; and

(5) To test the safety and stability of the lining structure during operation stage.

2.2 Tunnel Lining Test Model

The lining ring of Shanghai Changjiang Tunnel has an outer diameter of 15.0 m with the ring thickness of 0.65 m. The whole ring is composed of 10 segments, of which one is for enveloping, two for connecting, and the rest are standard. In the test, a 2-meter-wide middle full ring, a 1-meter-wide upper half ring and a 1-meter-wide lower half ring are employed. Ring segments are fastened as a whole by bolts ringwise, and rings are stagger-jointed and made a whole by lengthwise bolts, which makes a stagger-jointed shield-driven lining structure. According to the designed lining structure scheme, no more than three to five through-joints are allowed in the test model, and an axial force lengthwise is made to simulate the thrust force of the shield machine. The test model under assembling is shown in Fig. 7.

2.3 Test Cases and Design of Test Load

The maximal burying depth of Changjiang Tunnel is 27 m. Since the results of the test could be of guidance to the future construction, the test was made more pertaining. According to the actual case, the covering earth depth of the lining ring was made 15 m and 27 m separately. Accordingly, six test cases were set up as shown in Fig. 8.

In the test cases 1 to 3, equivalent concentrative force was exerted with a burying depth of 15 m and the side pressure coefficients of 0.68, 0.70, and 0.72 respectively, to find out the stress distribution, deformation and crack of the lining structure in this covering depth and to see the load endurance of bolts lengthwise between rings.

Fig. 7 Test model under assembling.

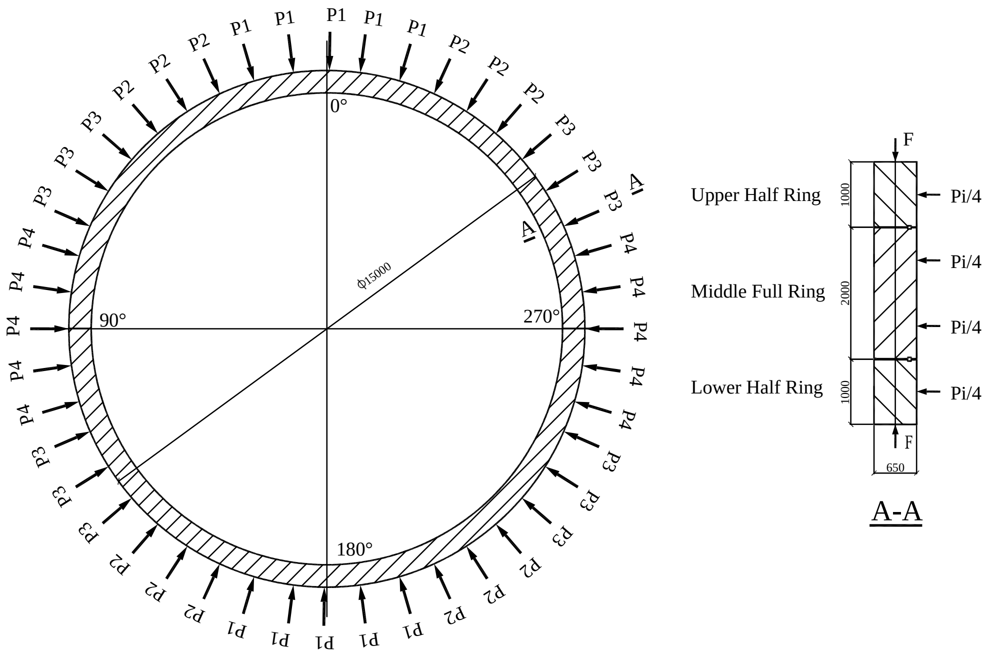

Fig. 8 Layout of horizontal equivalent load.

In the test cases 4 to 6, equivalent concentrative force was exerted with a burying depth of 27m and the side pressure coefficients of 0.68, 0.70, 0.72 respectively, to find out the stress distribution, deformation and crack of the lining structure in this covering depth and to see the impact of staggered-joints on the structure.

The concentrative force design was controlled by simulating the actual pressure and the internal forces of the key sections. In the test, the internal forces of the key sections was simulated by the radial force from 44 jacks distributed outside the lining ring to find out the loading capacity of the key sections and the optimization potential of the structure steel bars. The maximal horizontal thrust force of the jacks was about 2250 kN per point. Loading was fulfilled in 10 steps, and a set of intensified force was obtained in each step. When stable status of the structure was obtained, the test data were collected, and unloading was done likewise. To simulate the equivalent force of shield jack thrust in construction, 44 vertical jacks were placed around the whole ring exerting thrust force on the lining top and bottom. In cases with thin earth covering, the thrust force of the vertical jacks was 1500 kN per point, and in those with thick earth covering, the thrust force was 3000 kN per point.

2.4 Allocation of the Measure Points

During the test, 346 strain gauges and 152 displacement meters were placed around the lining ring model to measure the physical variables, shown in Table 1. Besides, rectangular griddings were made both inside and outside of the model to observe and record the start and development of cracks in each load step.

Table 1 Number of sensors used in the test.

	Strain gauges			Displacement meters			
Physical variables	Strain of steel bars	Concrete strain	Bolt strain	Overall radial deformation of the lining ring	Overall tangential deformation of the lining ring	Stagger value at joints	Open angle value at joints
Total of sensors	280	40	26	16	16	40	80

3. Test Loading Apparatus

Concentrative force on stagger-jointed lining structure included the thrust force of the shield machine as well as soil and water pressure, resistant force of stratum and overload of the ground. In testing, the test model, placed horizontally on the test platform, was thrust horizontally inward by 44 jacks around it to simulate the soil and water pressure, resistant force of stratum and overload from the ground. On top of the test model, 44 jacks were placed downward to simulate the thrust force of the shield machine. Fig. 8 shows the places where the horizontal equivalent forces were applied. The principle of loading design is that the actual load on the structure was replaced with the equivalent load produced by jacks, so as to ensure the internal force of key sections in the test model equals to that of the designed load. Based on this principle, horizontal and vertical loading apparatuses were designed and fulfilled.

3.1 Horizontal Loading Apparatuses

According to the test objectives, horizontal equivalent loading was carried out under above six test cases, under which the testing model was loaded and unloaded with 44 jacks. The concentrative force from all loading points converged at the central steel reactive setup, constituting a self-balancing loading system. Each loading point was made up of force distributing beams and steel pull rods, and all the loading points were grouped into four: P1, P2, P3, and P4 (see Fig. 8), which were equipped with 10, 12, 12, and 10 jacks respectively to find out the deformation, strength and anti-crack property of the staggered-joint lining ring.

The details are shown in Figs. 9~11. Concentrative force in each test case was gained gradually in 10 steps, and the maximal horizontal force exerted is shown in Table 2.

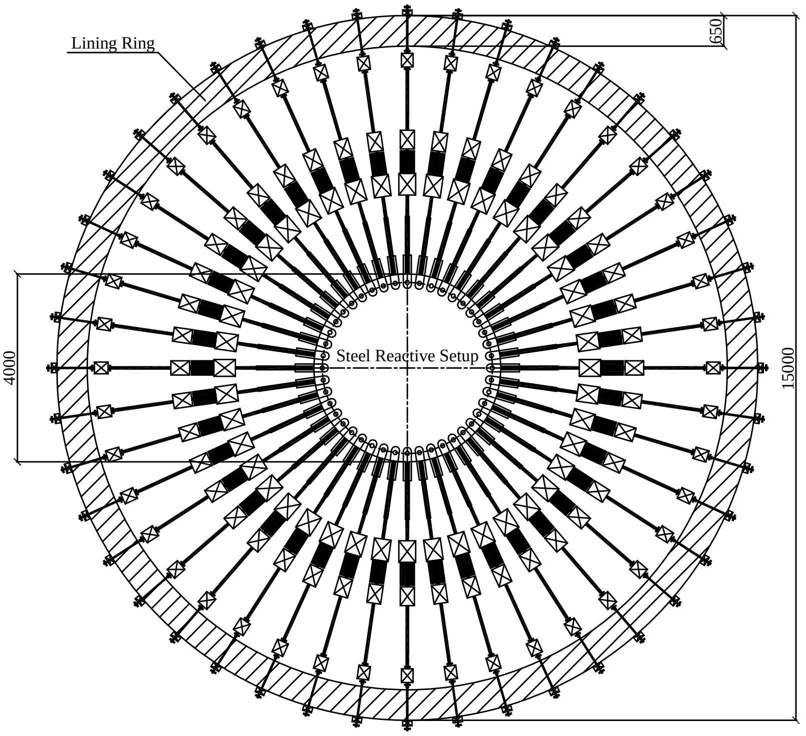

Fig. 9 Plane of loading apparatus.

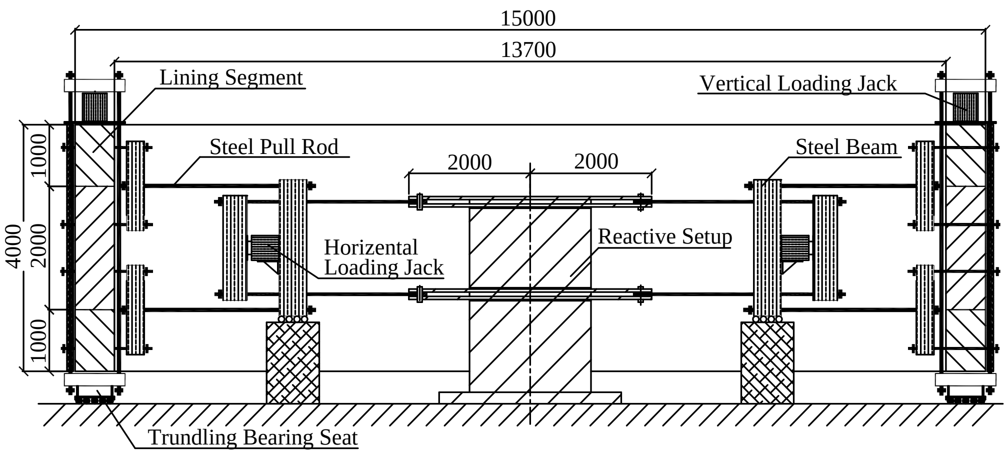

Fig. 10 Cross-section of loading apparatus.

Table 2 The maximum concentrative forces under each case (kN)

	P1	P2	P3	P4	remarks
Case 1	1260	1156	1074	1148	Burying depth: 15m, side pressure coefficient: 0.72
Case 2	1260	1140	1060	1116	Burying depth: 15m, side pressure coefficient: 0.70
Case 3	1260	1124	1044	1084	Burying depth: 15m, side pressure coefficient: 0.68
Case 4	2240	1970	1846	1980	Burying depth: 27m, side pressure coefficient: 0.72
Case 5	2240	1960	1826	1940	Burying depth: 27m, side pressure coefficient: 0.70
Case 6	2240	1940	1806	1892	Burying depth: 27m, side pressure coefficient: 0.68

3.2 Vertical Loading Apparatuses

There were 44 vertical loading points evenly distributed on top of the test model, see Figs. 10~11. Each point was in a self-balancing system, composed of upper and lower steel beams and four steel rods. Each vertical concentrative force was loaded twice with 1500 kN and 3000 kN to simulate the thrust force of the shield machine jacks under the test cases of thin earth covering and thick earth covering.

The top of the test platform was covered with a thin steel plate of 2 mm, and 44 trundling bearing seats were fixed under the test model to reduce the force of friction between the model bottom and the top of platform and to keep free deformation of the lower part of the model. Each seat contains ten lubed steel balls, 100 mm in diameter. The balls and the seat are shown in Fig. 12.

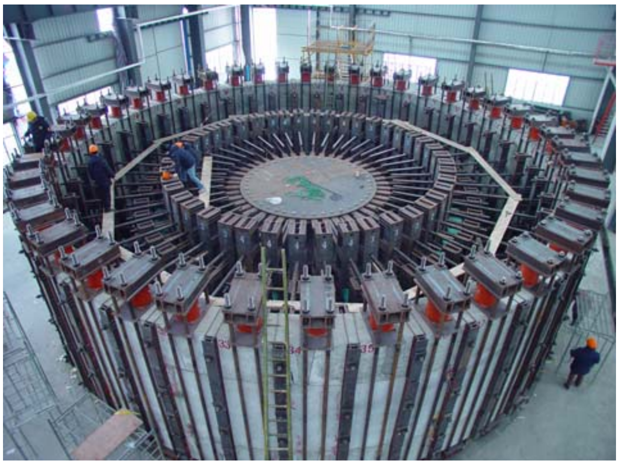

Fig. 11 Overall view of tunnel lining model test.

Fig. 12 Trundling supporting seat.

4. The Process and Results of the Test

In the test, cracks were observed and the following variables were obtained under different load steps: overall deformation of the structure, the strain of the reinforcing bar of segments, the strain of concrete and connecting bolts and the staggered value and open angle of joints in the connecting parts. The strain was measured with strain gauge, and the displacement was measured with displacement meter. Before the test, all loading devices and measuring meters were verified and calibrated. The resolving power of the loading devices was 0.1 kN and the tolerance of the loading devices was less than 0.3 kN.

After analyzing the test data, the overall distribution of axial force and bending moment along the ring and the overall deformation were obtained in each case. Figs. 13-15 show the internal forces and deformation

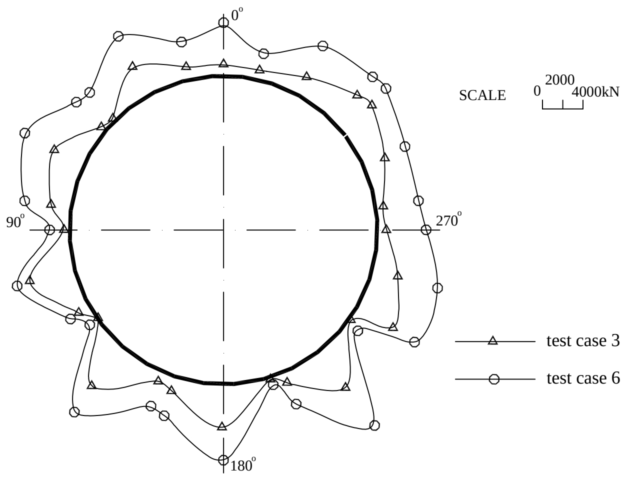

Fig. 13 Axial force distributions along the lining ring under maximum load.

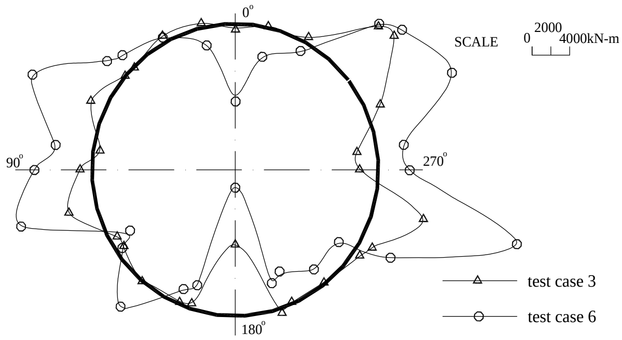

Fig. 14 Bending moment distributions along the lining ring under maximum load.

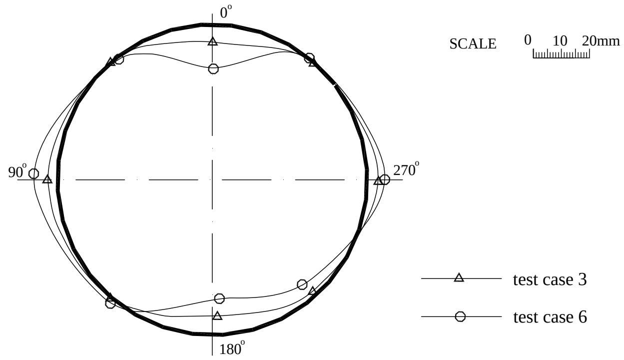

Fig. 15 Overall deformation of test model under maximum load.

of the middle full ring under maximum test concentrative load.

The results of the test showed that the strain of the reinforcing bars, the strain of the connecting bolts and the staggered value and open angle of joints in connecting parts of the lining segment were all within the permissible design value.

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