Cracking Analysis of Shield Construction Segments Based on Boss Unevenness

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Abstract: As the most basic structural unit of shield tunnel, the segment will cause tunnel quality problems and ultimately affect the service life of the tunnel. Based on the actual project, this paper takes the segmental cracking phenomenon in a large diameter shield tunnel as the research object, and analyzes the influence of the three protruding bosses of the cracked segment itself and the adjacent small ring on the segment cracking. Mechanical analysis, and finite element simulation of the force form of the tube under the unevenness of the boss. Through analysis, it is found that the three bosses of the cracked tube itself have little effect on the cracking of the segment, and the unevenness of the annular seam is the main cause of cracking of the segment. The analysis of this paper can take effective control measures to reduce the impact of cracks in shield tunnels on the normal construction of shield tunnels.

1. Introduction

With shield tunneling method widely applied in tunnel construction, underwater large-diameter shield tunnels have been becoming a trend. Segment cracking is a common problem in the construction of large-diameter shield tunnels, which can seriously damage the overall waterproof performance of shield tunnels, and may ultimately affect the durability and safety of the tunnel [1]. This paper is aimed at an example of an underwater tunnel project, where slender longitudinal cracks and local leakage occur in the segment ring at the waistline of the segment and above around the bolt hole. Through the calculation of the internal force of the segment, the reasons for the segmental cracking are analyzed, and effective treatment measures are adopted to control the impact of the cracks on the normal construction of the shield.

Many scholars at home and abroad have conducted in-depth research on the causes of segment cracking. Mao Qiongliu (2017) [2] used the extended finite element method to study the cracking mechanism of shield tunnel segments under different loads. Liu Peng [3] (2011) analyzed the causes of the cracking of a subway segment during construction from the aspects of geology, the stiffness of the segment joints, and the influence of the force on the left line segment during the construction of the right line, and explored the influence of the stiffness change of the segment joint and the force of the left line segment during the construction of the right line Bi Xiangli (2014) [4] and Liu Xian (2013) [5] studied the shield tunnel reinforced with inner-tensioned steel rings by reinforcing the damaged shield segments with inner-tensioned steel ring and proved that inner-tensioned steel ring reinforcement method is a reasonable and effective reinforcement method. Shi Taiwei (2014) [6] took a subway shield tunnel damage project as an example and carried out reinforcement design work on the basis of the analysis of the tunnel damage mechanism. Wang Fei-Yang (2019) [7] analyzed the heterogeneous and
nonlinear performance of cracked tunnel lining affected by the concrete microstructure in the cracked area. Protopapadakis (2019) [8] proposed using deep learning and heuristic image post-processing technology to automatically detect cracks on the concrete surface of shield tunnel segments. Al-Juboori (2019) [9] analyzed the generation mechanism and influencing factors of shield segment cracks. In general, these researches mainly study the cracking mechanism and influencing factors of the segment from the perspective of experimental research and mechanism analysis, but there are few studies on actual engineering.

Based on this, this paper took an actual engineering project as an example, studied the segment cracking phenomenon that occurs in an underwater tunnel, expounded the effect of segment boss design on cracking, carried out mechanical analysis on the impact of the “cracked segment boss” and “adjacent small-sized ring segment boss” on segment cracking, made finite element simulation of the force form of segment under the uneven boss, and then proposed crack treatment methods to control the impact of cracks on the normal construction of shield tunnels.

2. General Introduction of the Engineering Project and the Segment Cracking Process

2.1. Soil condition
The tunnel is located in the alluvial delta area at the mouth of the sea, and the stratum is basically Quaternary alluvial layer. According to the existing drilling and geological survey data, the west bank and river bottom strata of the project are the interbedded cohesive soil layer and sand layer of the Quaternary Holocene alluvial sediment (Q4), mainly are sand layer, with thin cohesive soil layers interposed sand layer, and the sand layer sandwiched with a thin layer of cohesive soil. Cohesive soil is mainly in soft plastic state, and its engineering geological properties are poor. The surface layer on the east bank is the interbedded clay layer and sand layer of Quaternary Holocene alluvial sediment (Q4) and it is mainly sand layer. Under the surface layer are the imbedded cohesive soil layer and sand layer of the Quaternary Holocene alluvial sediment (Q4). Cohesive soil is mainly hard silty clay, and partially presents in a semi-diagenetic state.

2.2. Segment boss design
The shield segment is designed as a double-sided wedge-shaped universal ring with an outer diameter of 11800 mm, an inner diameter of 10800 mm, a ring width of 2 m, a wall thickness of 500 mm, and a wedge of 40 mm. The segment assembly is assembled in the form of 5+2+1, that is, 5 standard rings, 2 adjoining rings, and 1 capping ring (K block) are rotatably assembled in a staggered form according to the tunnel line shape and the tunneling attitude (determine the K block position). The segments are connected with oblique bolts, wherein the ring joints are connected by 16 M36 bolts, the longitudinal joints are connected by 46 M30 bolts, the lining concrete strength grade is C60, and the impermeability grade is P12.
There are bosses with a height of 4 mm on the facing jack surface at the position of the bolt holes on the circumferential and longitudinal end faces of the tunnel segments, as shown in Figure 1, so as to facilitate the transmission of the segment forces and increase the shear resistance of the segments; two boss areas are designed at the circumferential seam face of block F, three boss areas are designed at the circumferential seam faces of the connecting block and standard block respectively; meanwhile, there is a segment that is provided with bosses at only one end of the circumferential and longitudinal seam faces. A force-transmitting pad is set at the boss of the segment, which is designed with a full-paved buna-N force-transmitting gaskets, with a thickness of 3mm. The force-transmitting gaskets are 2mm in thick after compression.

2.3. The segment cracking process
On January 20, 2019, the project began to excavate with a steel sleeve assisted large-scale mud-water balance shield. Shield tunneling started from the 27th ring, and slender longitudinal cracks and local leakage occur at the waistline of the segment and above around the bolt holes, as shown in Figure 2. The cracks are longitudinal narrow cracks along the tunnel driving direction, located on the inner arc surface of the tunnel lining, extending backwards next to the position of the facing jack. The cracks penetrate the concrete near the bolt hole in the middle of the segment and extends to the center positioning hole or grouting hole. Water leakage occurs in part of the longitudinal cracks, and the water becomes drops along the inner arc surface. The cracks occur when the segment ring n+1 is tunneled (ring n+1 has not been assembled, and ring n has been assembled), cracks appear near the bolt holes of ring n and the bolt hole of ring n-1. In the excavation area (ring 54-80) where the segment floating is serious, there are more cracks near the bolt hole of ring n-1. In the relatively stable advancing zone (ring 26-53), there are more cracks near the bolt hole of the ring n.
3. Influence of uneven segment boss on the circumferential face on segment cracking

3.1. General introduction
Figure 3 shows the cracked segment ring N and its adjacent small ring N-1 and the next ring N+1. The names of all the segments of the rings (F, L1, L2, B1, B2, B3, B4, B5) and the number of the 23 segment bosses are shown in figure 3. The numbering principle of the segment bosses is “name of the segment where the boss is located” + “the position of the boss counting from left to right on the segment”. For example, the third boss on segment B1 is named as B1_3.

The sequence of the circumferential seam bosses on each ring is F_1, F_2, L2_1, L2_2, L2_3, B5_1, B5_2, B5_3, B4_1, B4_2, B4_3, B3_1, B3_2, B3_3, B2_1, B2_2, B2_3, B1_1, B1_2, B1_3, L1_1, L1_2, L1_3. When the bosses appear in triplet, in order to determine each specific boss, the number of the segment where the bosses are located (the part before the underscore), instead of the position of the boss (the part after the underscore), is indicated. The triplet of the bosses is named as “boss combination”. For example, the boss combination of F, L2 and L2 indicates the bosses corresponding to F_2, L2_1, and L2_2. In the subsequent statistics, all bosses appear in triplet, and the specific positions of the bosses are not indicted, instead, “boss combination” is used.

As Figure 3 shows, when the cracked segment is taken as the study object, the boundary conditions are "the bosses on the segment ring" and "the bosses on the adjacent small segment ring at the corresponding positions". For example, if cracking occurs on segment B5 of the cracked ring N, as shown in the figure, then segment B5 is taken as the analysis object. Compared with the thickness of the segment, the height of the boss is relatively low, so only the impact of boss contact on the cracked segment is taken into account when considering the small deformation of the segment due to force, the contact of other bosses is not taken into account. That is, the boundary conditions of segment B5 are the three bosses (B5_1, B5_2 and B5_3) on segment B5 of cracked ring N, the third boss (B5_3) on segment B5 of ring N-1, as well as the first two bosses (B4_1 and B4_2) on segment B4 of ring N-1. If
the cracking of segment B5 on ring N is caused by the uneven boss, then the responsible bosses are the six bosses listed above.

To sum up, a total of six bosses cause the cracking of a shield tunnelling segment, including “the bosses on the cracked segment” and “bosses on the segment of the adjacent small ring at the corresponding positions”.

3.2. Mechanical analysis on the influence of the three bosses on the cracked segment

In this part, it is assumed that cracking occurs on segment B2 of the cracked ring N. The positions of segment B2 and bosses of the cracked ring N as well as the positions of the three corresponding bosses on the adjacent small ring N-1 are shown in Figure 4.

Figure 4. Demonstration diagram of the positions of segment B2 and bosses of cracked ring N, as well as the corresponding bosses on adjacent small ring N-1

The boundary conditions of the cracked segment B2 are the three bosses B2_1, B2_2, B2_3 on segment B2 and three bosses B4_3, B3_1, B3_2 on the adjacent small ring N-1 at the corresponding positions. From the perspective of force analysis, the three bosses (B2_1, B2_2, B2_3) of segment B2 bear the transferred load of the adjacent large ring N+1. The three bosses (B4_3, B3_1, B3_2) at the corresponding positions of the adjacent small ring N-1 are used as the support of segment B2 to provide the support reaction force for it. When the three bosses (B2_1, B2_2, B2_3) on segment B2 are uneven, the load acting on segment B2 will be uneven. The load on the higher boss is larger, and the load on the lower boss is smaller. When the three bosses (B4_3, B3_1, B3_2) at the corresponding positions of the adjacent small ring N-1 are even, they can support segment B2. In this case, the transmitting path of the load acting on the three bosses (B2_1, B2_2, B2_3) of segment B2 is clear, that is, the load on B2_1 will be directly borne by the support B4_3 at the corresponding position, the load on B2_2 will be directly borne by the support B3_1 at the corresponding position, and the load on B2_3 will be directly borne by the support B3_2 in the corresponding position. Therefore, no matter how uneven the three bosses (B2_1, B2_2, B2_3) of segment B2 itself are, and how uneven the load it bears, according to the above-mentioned force transmission path, the load that segment B2 bears under the action of B2_1 and B4_3, B2_2 and B3_1, B2_3 and B3_2 is even, that is, segment B2 will not crack.

Based on the premise, when the three bosses at the corresponding positions of the segment ring N-1 that is adjacent to one segment, no matter how even the three bosses on the segment itself are, the segment will not crack. Therefore, if a segment cracks, then the three bosses at the corresponding positions of its adjacent small segment ring N-1 are uneven for sure. From the perspective of "the boundary conditions of segment cracking", among the six bosses that accounting for segment cracking,
the three bosses on the cracked segment have little effect on its cracking, while the three bosses at the corresponding positions of its adjacent small ring N-1 take the main responsibility.

3.3. Mechanical analysis of the impact of the bosses at the corresponding positions of the small segment ring adjacent to the cracked segment

The cracked segment can be regarded as a beam with its own "bosses" as the load points, and the "bosses at the corresponding position of its adjacent small segment ring" as the support beam. Due to the unevenness of the bosses, the higher bosses are out of contact with the segment and cannot transmit load or provide supporting force.

Based on the analysis of the various contact conditions of the bosses and considering the force balance conditions of the cracked segment, the stress forms of the cracked segment can be divided into four categories according to the cracking timing, namely, “simple support”, “two-point cantilever beam”, “two cantilever beams” and “two-point cantilever beam”, as shown in Table 1.

Table 1. Stress form of cracked segment

| Cracking timing | Stress form          |
|-----------------|----------------------|
| Segment ring N cracks when the shield excavates into ring N+1 | Simple support |
|                  | Two-point cantilever beam |
|                  | Two cantilever beams   |
|                  | Two-point cantilever   |

As shown in Table 1, segment ring N-1 cracks when the shield excavates into ring N+1, and the stress forms are simple support and two-point cantilever beam. Segment ring N cracks when the shield excavates into ring N+1, and the stress forms are two cantilever beams and two-point cantilever.

When the stress forms are "simple support" and "two cantilever beams", the contact situations of the cracked segment and the bosses at the corresponding positions of its adjacent small segment ring are the same. The differences lie in that the loads acting on the three bosses of the cracked segment are different. As for "simple support", segment ring N-1 cracks when the shield excavates into ring N+1. In this case, the load on the three bosses of the cracked segment ring N-1 is transmitted from the segments of its adjacent large ring N. Due to the unevenness of the three bosses of the cracked ring N-1, the loads on the three bosses are uneven, or not all the three bosses bear the loads. As for "two cantilever beams", segment ring N cracks when the shield excavates into ring N+1. In this case, the segments on the cracked ring N bear the pushing force of the jack, and all the three bosses on the cracked ring bear the load.

When the stress forms are "two-point cantilever beam" and "two-point cantilever", the contact situations of the cracked segment and the bosses at the corresponding positions of its adjacent small segment ring are the same. The differences lie in that the loads acting on the three bosses of the cracked segment are different. As for "two-point cantilever beam", segment ring N-1 cracks when the shield excavates into ring N+1. In this case, the load on the three bosses of the cracked segment ring N-1 is transmitted from the segments of its adjacent large ring N. Due to the unevenness of the three bosses of the cracked ring N-1, the loads on the three bosses are uneven, or not all the three bosses bear the loads. As for "two-point cantilever", segment ring N cracks when the shield excavates into ring N+1. In this case, the segments on the cracked ring N bear the pushing force of the jack, and all the three bosses on the cracked ring bear the load.

When the stress forms are "two-point cantilever beam" and "two-point cantilever", the contact situations of the cracked segment and the bosses at the corresponding positions of its adjacent small segment ring are the same. The differences lie in that the loads acting on the three bosses of the cracked segment are different. As for "two-point cantilever beam", segment ring N-1 cracks when the shield excavates into ring N+1. In this case, the load on the three bosses of the cracked segment ring N-1 is transmitted from the segments of its adjacent large ring N. Due to the unevenness of the three bosses of the cracked ring N-1, the loads on the three bosses are uneven, or not all the three bosses bear the loads. As for "two-point cantilever", segment ring N cracks when the shield excavates into ring N+1. In this case, the segments on the cracked ring N bear the pushing force of the jack, and all the three bosses on the cracked ring bear the load.

Taking segment B2 cracking as an example, the four stress forms of “simple support”, “two cantilever beams”, “two-point cantilever beam” and “two-point cantilever” are described in detail. In the figure, ○ indicates “in contact”, and × indicates “not in contact”.

Figure 5 shows that the stress form of the cracked segment B2 is "simple support". Among the three bosses of segment B2 (B2_1, B2_2, B2_3), boss B2_1 and boss B2-3 of segment B2 are in
contact with the adjacent large segment ring and bear the loads. Boss B2_2 is not in contact with the adjacent large segment ring and bears no load. Among the three bosses at the corresponding positions of the small segment ring which is adjacent to segment B2, boss B3_1 is in contact with segment B2 and becomes the support of segment B2. In this case, it can be regarded that segment B2 is supported by a simple beam. Bending cracks and shear oblique cracks occur on segment B2, wherein the bending cracks are in the middle of the span near the large segment ring, and the shear oblique cracks developed from boss B2_1 and boss B2_3 to boss B3_1 at the corresponding position of the adjacent small ring.

Figure 5. Demonstration diagram of cracked segment under “simple support”

Figure 6 shows that the stress form of the cracked segment B2 is "two cantilever beams". All the three bosses of segment B2 (B2_1, B2_2, B2_3) directly bear the force of the shield tunneling jack, and therefore bear the loads. Among the three bosses (B4_3, B3_1 and B3_2) at the corresponding positions of the small segment ring which is adjacent to segment B2, boss B3_1 is in contact with segment B2 and becomes the support of segment B2. Boss B4_3 and boss B3_2 are not in contact with segment B2 and cannot support segment B2. In this case, the middle part of segment B2 is fixed, and the two sides can be regarded as cantilever beams. Thus the stress form is called "two cantilever beams". Bending cracks and shear oblique cracks occur on segment B2, wherein the bending cracks are in the middle of the span near the large segment ring, and the shear oblique cracks developed from boss B2_1 and boss B2_3 to boss B3_1 at the corresponding position of the adjacent small ring.

Figure 6. Demonstration diagram of cracked segment under “two cantilever beams”

Figure 7 shows that the stress form of the cracked segment B2 is "two-point cantilever beam". Among the three bosses of segment B2 (B2_1, B2_2, B2_3), boss B2_1 and boss B2_3 are in contact with the adjacent large segment ring and bear the loads. Boss B2_2 is not in contact with the adjacent large segment ring and bears no load. Among the three bosses (B4_3, B3_1 and B3_2) at the corresponding positions of the small segment ring which is adjacent to segment B2, boss B4_3 and boss B3_1 are in contact with segment B2 and become supports of it. Boss B3_2 is not in contact with segment B2 and cannot support it. In this case, segment B2 can be regarded as a cantilever beam with only one load point, and thus it is called “two-point cantilever beam”. Bending cracks and shear oblique cracks occur on segment B2, wherein the bending cracks are near the supporting end of the large segment ring, and the shear oblique cracks developed from boss B2_3 (as cantilever beam) and to the supporting end.
Figure 7. Demonstration diagram of cracked segment under "two-point cantilever beam"

Figure 8 shows that the stress form of the cracked segment B2 is "two-point cantilever". All the three bosses of segment B2 (B2_1, B2_2, B2_3) directly bear the force of the shield tunneling jack, and therefore bear the loads. Among the three bosses (B4_3, B3_1 and B3_2) at the corresponding positions of the small segment ring which is adjacent to segment B2, boss B4_3 and boss B3_1 are in contact with segment B2 and become supports of it. Boss B3_2 is not in contact with segment B2 and cannot support it. In this case, segment B2 can be regarded as a cantilever beam with two load points, and thus it is called "two-point cantilever". Bending cracks and shear oblique cracks occur on segment B2, wherein the bending cracks are near the supporting end of the large segment ring, and the shear oblique cracks developed from boss B2_3 (as cantilever beam) and to the supporting end.

Figure 8. Demonstration diagram of cracked segment under “two-point cantilever”

4. Infinite Element Simulation of the Stress Form of the Segment

According to analysis, the stress forms of the segment due to uneven bosses are divided into simple support, two cantilever beams, two-point cantilever beam and two-point cantilever. ANSYS is used to stimulate the four stress forms of the segment to analyze the reasons for its cracking.

Figure 9. The stress distribution diagram of the segment under “simple support”

Figure 9 is the stress distribution diagram of the segment under "simple support". In Figure 9, the arrow indicates the load points transmitted from the adjacent large segment ring to the bosses of this ring and the support points of the bosses on the adjacent small ring. It can be seen from Figure 9 that there is a large tensile stress area in the middle of the segment, near the big ring. In this area with greater tensile stress, the segment is easier to crack. The cracking position of the segment calculated
by the finite element is consistent with the crack distribution obtained by the analysis of the segment as a beam in Figure 5.

Figure 10. The stress distribution diagram of the segment under “two cantilever beams”

Figure 10 is the stress distribution diagram of the segment under “two cantilever beams”. It can be seen from Figure 10 that there is a large tensile stress area in the middle of the segment, near the big ring. In this area with greater tensile stress, the segment is easier to crack. The cracking position of the segment calculated by the finite element is consistent with the crack distribution obtained by the analysis of the segment as a beam in Figure 6.

Figure 11. The stress distribution diagram of the segment under “two-point cantilever beam”

Figure 11 is the stress distribution diagram of the segment under “two-point cantilever beam”. It can be seen from Figure 11 that there is a large tensile stress area in support position of the boss of the adjacent small ring, near the big ring. In this area with greater tensile stress, the segment is easier to crack. The cracking position of the segment calculated by the finite element is consistent with the crack distribution obtained by the analysis of the segment as a beam in Figure 7.

Figure 12. The stress distribution diagram of the segment under “two-point cantilever beam”

Figure 12 is the stress distribution diagram of the segment under “two-point cantilever beam”. It can be seen from Figure 12 that there is a large tensile stress area in support position of the boss of the adjacent small ring, near the big ring. In this area with greater tensile stress, the segment is easier to crack. The cracking position of the segment calculated by the finite element is consistent with the
crack distribution obtained by the analysis of the segment as a beam in Figure 8.

Through the finite element simulation of the stress forms of the segment under the condition of uneven bosses, the crack distribution pattern obtained through the "beam" analysis above is consistent with the finite element calculation result of this section. This proves that it is rational to simplify segment into beam when it is under force. The finite element simulation proves the impact of uneven bosses of the circumferential beams on segment cracking, that is, the uneven bosses on the circumferential beams of the segment is the main cause of segment cracking. Figure 13 shows the unevenness of the bosses on the circumferential beams of the segment inferred from crack data.

Figure 13. Demonstration of the height of the bosses

5. Treatment Method for cracking
Based on the analysis on segment cracking caused by uneven bosses on the circumferential beams of segment rings in the construction of shield tunneling, treatment methods include adding force transmitting gaskets between segment rings and sponge slurry-blocking gaskets.

5.1. Force transmitting gaskets
According to the construction records, in order to improve the flatness between the ring joints of the segments, the Buna-N force transmitting gaskets of different thicknesses are paved on between the rings. Force transmitting gaskets of 2mm thickness are used in rings 26-46 and in rings 70-72; no force transmission gaskets are used in rings 47-51; force transmitting gaskets of 3mm thickness are used in rings 52-53; force transmitting gaskets of 1.5*2mm thickness are used in rings 54-69; force transmitting gaskets of 4mm thickness are used in rings 73-80.

On-site application proves that gluing force transmitting gaskets can avoid large area of cracks and falling-off of surface concrete, but segment cracking cannot be eliminated.

5.2. Simultaneous mortar injection
According to construction records, in order to control tunnel coming up, mortar injection method is used in construction, and the proportion and amount of mortar are different.

5.2.1. Mortar proportion. In the excavation process from segment ring 1 to 80, mortar of three proportions is used, as shown in Table 2.

| Rings | No. | Mortar proportion (cement: coal ash: sand: water) | Mortar density (kg/m³) | Time needed for setting (h) |
|-------|-----|-----------------------------------------------|------------------------|---------------------------|
| Ring 1-26 | 1   | 154:288:840:494:78 | 1839 | 9 |
| Ring 27-60 | 2   | 179:263:840:494:78 | 1886 | 8 |
| Ring 61-80 | 3   | 204:238:840:78:494 | 1896 | 6.5 |

Time needed for setting of mortar No. 1, mortar No. 2 and mortar No. 3 decreases successively, so the floating force borne by segments when demolding from the shield decreases in the three ranges: ring 1-26, ring 27-60 and ring 61-80. Therefore, reducing time needed for mortar setting is helpful in controlling segments going up. Segments go up the most in the position of ring 60, and the phenomenon doesn't change after the mortar proportion is changed and the time needed for setting is reduced to 6.5 hours.

5.2.2. Injection amount. According to construction records, the curve relationship between injection amount and rings are shown in Figure 14.
Figure 14 shows the curve of injection amount, wherein the black lines indicates theoretical amount (13.54 m³). The simultaneous injection amount after ring 26 is larger than theoretical amount. The injected mortar from ring 69 to 80 decreases greatly, but is still more than theoretical amount. A small amount of mortar is injected in rings 69-73 and the centroid of segments becomes lower.

6. Conclusion
Based on actual engineering project, this paper studied the problem of segment cracking occurs in large-diameter underwater tunnels, and analyzed the impact of segment boss design on cracking. It is concluded that:

1) From the perspective of “boundary conditions of segment cracking”, among the six bosses around the cracked segment, the three bosses of the cracked segment had little influence on its cracking, while the three bosses at the corresponding positions of its adjacent small segment ring N-1 had a significant influence on its cracking. To sum up, the three bosses of the cracked segment had little influence on its cracking.

2) When the stress form of the cracked segment B2 was “simple support”, bending cracks and shear oblique cracks occurred on segment B2, wherein the bending cracks are in the middle of the span near the large segment ring, and the shear oblique cracks developed from boss B2_1 and boss B2_3 to boss B3_1 at the corresponding position of the adjacent small ring. When the stress form of the cracked segment B2 was “two-side cantilever beams”, bending cracks and shear oblique cracks occur on segment B2, wherein the bending cracks were in the middle of the span near the large segment ring, and the shear oblique cracks developed from boss B2_1 and boss B2_3 to boss B3_1 at the corresponding position of the adjacent small ring. When the stress form of the cracked segment B2 was “one-point cantilever beam, bending cracks and shear oblique cracks occurred on segment B2, wherein the bending cracks were near the supporting end of the large segment ring, and the shear oblique cracks developed from boss B2_3 (as cantilever beam) and to the supporting end. When the stress form of the cracked segment B2 was “two-point cantilever beam, ending cracks and shear oblique cracks occur on segment B2, wherein the bending cracks were near the supporting end of the large segment ring, and the shear oblique cracks developed from boss B2_3 (as cantilever beam) and to the supporting end.

The finite element simulation proves that the "beam" analysis is consistent with the finite element calculation and that it is rational to simplify segment into beam when it is under force. The unevenness of the bosses on the circumferential beams is the main cause of segment cracking.

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