Features of the Temperature Cracks in a Tunnel Final Lining

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Abstract. Cast-in-place concrete lining, which is the major structure of a tunnel with composite or monolithic lining, requires high safety, durability and waterproof performance. The prevention and control of lining concrete cracks are of great concern. However, the temperature and shrinkage cracks in the arch and wall of a cast-in-place concrete lining are common construction quality defects in practical cases. This contribution presents the changing features of temperature crack widths in responding to the temperature variation with seasons in several cast-in-place final lining panels, where there are no waterproof and drainage sheets in their composite linings. The crack width changing features imply that the constraints to the temperature drop and shrinkage deformation of the concrete in its arch and wall in construction stage still work in the period of post-construction. Considering the cracks beyond the planned allowable values, the information on the width changing features presents clue to determine the rule on the occurring and developing of the temperature and shrinkage cracks in the cast-in-place lining concrete, as well as crack resistance design and construction quality control.

1. Introduction

The numbers and dimensions of the tunnels and underground structures are increasing, especially in the fields of transportation in China. On the other hand, safety and durability are of the concern of the involved groups in a tunnel project. For example, the cracks in the cast-in-place concrete final lining should be under control to meet the specified quality control requirement, such as in terms of water leakage preventing.

However, the cases with defects in lining concrete seem not rare due to various reasons[1-2]. For example, although the reasons of the concrete cracking during construction are of project unique, temperature and shrinkage cracking is one of the common reasons in practical cases[3-5]. In simplicity, crack appears as the imposed loads exceeding the bearing capacity of a concrete member. For example, lining crack appears as the tensile stress is over concrete tensile strength. Of the temperature and shrinkage cracks, which occur and develop in a cast-in-place concrete lining during construction, is closely related to the features of the constraints to the temperature drop and shrinkage deformation of the concrete. Mainly due to the project unique of the constraints in temperature and shrinkage cracking, the rule on the occurring and developing of the temperature and shrinkage cracks in the cast-in-place lining concrete needs further study.

This contribution presents the changing features of temperature crack widths in responding to the temperature variation with seasons in several cast-in-place final lining panels, where there are no waterproof and drainage sheets in their composite linings. The crack width changing features imply that the constraints to the temperature drop and shrinkage deformation of the concrete in its arch and wall in construction stage still work in the period of post-construction. Considering the cracks beyond the planned allowable values, the information on the width changing
features of the cracks in these lining panels is beneficial to determine the rule on the occurring and developing of the temperature and shrinkage cracks in the cast-in-place lining concrete. The results would serve for the cast-in-place lining concrete crack resistance design and construction quality control in tunnel and underground engineering.

2. The Tunnel and the Final Lining Building

The 1022-m-long tunnel is one of the loess tunnels in the Menghua Railway line passing through the west of the Henan province. The landform of the tunnel site is of tableland feature and the maximum overburden of the tunnel is about 100 m. The surrounding rocks of the tunnel consists of Pleistocene sandy clay, silty clay or silt, which is characteristics of the old loess in China, with water content less than their plastic limits. The ground around the excavations is mainly silty clays. Top-heading and bench method is applied in tunnelling, with special reference to the principles of New Austrian tunnelling Method.

2.1. Lining System

A composite lining system with invert is applied in the mined section of the tunnel. The primary lining is 30-cm-thick shotcrete, with steel sets and steel meshes embedded, and the final lining is 55cm-thick cast-in-place reinforced concrete. The strength grades of the shotcrete and cast-in-place concrete are C30 and C45, respectively. There is a waterproof and drainage sheet between the linings in the original design.

2.2. Building of the Final Lining

2.2.1. Construction procedure in general. The tunnel lining system is built with conventional method, in a two-pass mode. The final lining is built in two stages (Figure 1). A section of invert is first casted in a length of two times of the formwork jumbo length and then followed by the filling concrete in a short time period. And then the low wall of the final lining is built in a few days for each section of the corresponding invert. The sidewall and arch of the final lining are late, with a time lag varying from around ten days to more than a month. In general, the sidewall and the arch of a final lining is 30 m to more than 100 m behind the shotcrete lining in a section.

2.2.2. Cancelling the interlayered waterproof and drainage sheets. During tunneling, no water dripping appears in the excavations. It seems that the functions of the waterproof and drainage sheets in the composite lining system have no working chance. On the other hand, it is favorable to the project in terms of time schedule and cost saving, as well as avoiding voids behind the final lining, the waterproof membrane and geotextile sheets was canceled and the composite lining structures were tuned accordingly in the following lining panels.
2.2.3. Applying the interlayered waterproof and drainage sheets. It is a pity that cracks was identified in the final lining panels, in which the waterproof and drainage sheets had been canceled in the composite lining system. Because the monitoring results of the crown settlement and the convergence of the shotcrete linings in some sections of the tunnel indicate that the excavations under the primary lining system are stable, final lining concrete cracking is not due to the ground pressures and the shotcrete lining deformation[6]. Considering the features of the potential thermal stresses in the final panels, with interlayered sheets cancelled, the constraint conditions of the final lining (Figure 1) would have a strong influence on the cracking of the built panels. So, the structures of the composite lining system were set back to the original design and the cracking in the new built lining panels, with waterproof membrane and geotextile sheets applied, is under control.

3. The Occurrence Features of the Concrete Temperatures Cracks in the Final Lining

Cracks occurred in the lining panels with interlayered sheets cancelled. The cracks are observed in the sidewall and arch of the final lining concrete shortly after formwork jumbo removing and are of temperature drop and shrinkage cracking features[1-2].

3.1. Type and Occurrence

Based on the relationship between the crack extension directions and the tunnel axis line, three types of cracks are recognized in the tunnel lining arch and sidewall concrete, i.e., longitudinal, circumferential, vertical and diagonal cracks (Figure 2a), respectively.

3.1.1. Longitudinal cracks. The longitudinal cracks are nearly horizontal and parallel to the tunnel axis, mainly in the transitional position between the lining crown arch and sidewall (Figure 2a). The longest longitudinal crack run through a concrete panel, but most of the cracks are several meters in length or two cracks along a line. A longitudinal crack does not extend into neighbor panels.

3.1.2. Circumferential cracks. The circumferential cracks extend as a vertical crack in upper part of the tunnel sidewalls (Figure 2c) while as circumferential cracks in the lining arch. In general, the cracks are above a longitudinal crack and extend upward, with a length of 1.5 m to 4.5m. In most of the lining panels, circumferential cracks appear nearly around the middle of the panel length. There generally is one circumferential crack at one sidewall in a panel.

3.1.3. Vertical cracks. The vertical cracks appear in the lower parts of the sidewalls (Figure 2a). There is one or two cracks in one sidewall, with a feature of nearly halving or trisecting the length of the concrete panel, respectively. In general, the vertical cracks starts from about one meter above the top of the final lining low wall and extend upward about 2 m.
3.1.4. **Diagonal cracks.** Diagonal cracks mainly appear in the lining crown (Figure 2d). A diagonal crack extends along a line with an oblique angle to the lining panel edge line and the features of intermittent extension. There often is a branch in the extension of a diagonal crack.

3.2. **Features of the Cracks**
The cracks are of the following general features: (1) the cracks appear in specified positions, respectively; (2) two longitudinal cracks generally appear in each panel; (3) the cracks may extend in an intermittent pattern, with snake shape and width varying. These features are of the characteristics of cracks due to tensile stresses. Under a crack width meter, the sidewalls of a crack are much rough and in a wavy pattern (Figure 2e, f). The bored cores indicate that the longitudinal cracks cut through the thickness of the final lining and the crack width is almost same along the whole thickness (Figure 3).

4. **Width Changing of the Cracks in Responding to the Temperature Variation with Seasons**

4.1. **Crack Width Monitoring in General**
The cracks in the lining panels are a type of defect in terms of quality control, since the widths of the cracks (Figure 4) are beyond the target value, no more than 0.2 mm. To observe the changing features of the cracks, vibrating strain gauges, with temperature meter, are applied to monitoring the variation of the crack widths (Figure 5). The longitudinal, circumferential, vertical and diagonal cracks in three lining panels, numbered as panel I, II and III, were monitored with 11 strain gauges, respectively. The gauges were installed (stuck to) perpendicularly crossing the monitored crack at a site.

The monitoring results include the strain gauge recordings, which are read as changes of the widths of the cracks in strains in responding to the temperature variation with seasons. The temperature variation with seasons is presented in Figure 6, which is changing with the air temperature at the tunnel site. The features of the strain gauge recordings are discussed in the following chapter.

![Figure 3. Crack features in a bored core.](image)

![Figure 4. The width of the cracks.](image)

4.2. **Features of the Crack Width Changing with Season Temperatures**

4.2.1. **General features.** In general, the widths of the monitored cracks increase with the air temperature decreasing with season variation, while the crack widths decrease with the air temperature rising, as shown in Figure 7. In a cycle of the seasons, the width changes of a monitored crack are minor. Therefore, the changes of the crack widths can generally be attributed to the concrete properties of concrete expansion and contraction due to the temperature rising and falling in responding to the season variation at the tunnel site and the contribution of the other reasons is negligible. On the other hand, the curves presenting the width changes of a monitored crack with time are not smooth and there are variations with a jump somewhere in the curves (Figure 7). The reasons for this feature will be discussed in details in the following chapter.
Figure 5. Crack width monitoring with vibrating strain gauges.

Figure 6. Temperature changing with the seasons.

Figure 7. General features of the crack widths in responding to the temperature variation with seasons.

4.2.2. Discussion on the changing features of the crack width. As the above-mentioned, the monitored temperature and shrinkage cracks are in the cast-in-place lining panels, where there are no waterproof and drainage sheets interlayered in their composite linings. Of the mechanism of temperature and shrinkage cracks in construction, two parameters are of dominate features, i.e., the magnitude of temperature decreasing and constraints to the lining concrete contraction during temperature falling, which determine the features of thermal stress in a lining panel. In this case history, the magnitude of temperature decreasing can generally be considered same in different lining panels, since the structure features and building procedure are same for all of the panels, such as in terms of design and construction plan. So, the difference of the constraint conditions between the lining panels, with or without waterproof and drainage sheets, is the key factor. In simplicity, the constraint conditions of the lining system without waterproof and drainage sheets interlayered are favorable to the development of temperature and shrinkage cracks and the magnitudes of constraints are large enough to meet the requirement of cracking tensile stress.

To analyze the influence of the constraint conditions of the final lining panels on the changing features of the crack widths in the season variation, the width changes of a crack is presented in terms of temperature rising and falling, respectively. In Figures 8 to 10, the changing features of the crack widths in the season variation are of variations with a jump somewhere, when there is a temperature decrement about 5 to 10 °C or an increment about 15 °C. On the other hand, the width changing at the different parts of a crack is not synchronized in a temperature rising or falling period (Figure 8c). These features imply that the constraints to the lining concrete expansion and contraction due to the temperature rising and falling may vary with positions and that the influence of the constraints from the outer side and side-end the lining panels still work in the period of post-construction. There seems mutual confirmation between the multiple reasons of the constraints (Figure 1) and the types and occurrences of the cracks, as well as the difference in width changing under same temperature variation. The jumping features, i.e., the crack width changing on the conditions of certain temperature decrement or increment, imply that a large thermal stress is required to overcome the constraints to the expansion and contraction due to the temperature rising and falling.
Considering the cracks beyond the planned allowable values in this case, the influence of the constraint conditions of typical structure types on the mechanism of temperature and shrinkage cracking in the lining concrete is of importance, especially for a composite lining system, in terms of the cast-in-place lining concrete crack resistance design and construction quality control.

5. Conclusions

Based on the width changing features of the temperature cracks in the cast-in-place lining panels, where there are no waterproof and drainage sheets interlayered in their composite linings, in responding to the temperature variation with seasons, the following conclusions can be drawn.

1. The widths of the monitored cracks increase with the air temperature decreasing with season variation while the crack widths decrease with the air temperature rising, and the changes of the crack widths can be attributed to the lining concrete properties of concrete expansion and contraction due to the temperature rising and falling in the season variation, respectively.

2. The changing features of the crack widths in the season variation are of variations with a jump somewhere, when there is a temperature decrement about 5 to 10 °C or an increment about 15 °C. On the other hand, the width changing at the different parts of a crack is not synchronized in a temperature rising or falling period. These features imply that the constraints to the lining concrete expansion and contraction due to the temperature rising and falling may vary with positions and that the influence of the constraints from the outer side and side-end the lining panels still work in the period of post-construction.

3. In terms of the cast-in-place lining concrete crack resistance design and construction quality control, the influence of the constraint conditions of a composite lining, with or without interlayered sheets, on the mechanism of temperature and shrinkage cracking in the lining concrete is of key factor.

Acknowledgments

The China Railway Seventh Bureau Group Co., Ltd. is acknowledged for financial support of this research project, under the No. 17A13.
Figure 9. Features of the circumferential crack width changes with season temperatures.

Figure 10. Features of the diagonal crack width changes with season temperatures.

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