Influence of constraint conditions on the seasonal variation of the concrete temperature cracks in a tunnel final lining

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Abstract. Temperature and shrinkage cracks are still not rare in tunnel and underground cast-in-place concrete linings. The features of the constraint conditions during temperature dropping stage of the lining in construction are rigorously concerned in terms of crack prevention and magnitude control. The width seasonal variations of the temperature cracks in a tunnel concrete final lining, monitored with vibrating strain gauges, imply that the constraint conditions, on which the temperature and shrinkage cracks developed in the lining concrete during the temperature dropping stage, are working and of successive features in the post-construction period. Therefore, the seasonal variation of the crack widths can partially indicate the constraint conditions of the cast-in-place lining concrete cracking in construction period. Considering the cracks beyond the planned allowable values, the results from this case imply that it is beneficial to apply a flexible layer on the outer surface of cast-in-place concrete lining in concrete crack resistance design and construction quality control, especially for a tunnel with cast-in-place concrete monolithic lining or two-pass lining.

1. Introduction

Tunnels and underground structures are of the key role in infrastructures, especially in the field of transportation system in mountain and urban areas. Of an infrastructure part, it is characteristic of high standard of safety and durability. For example, in a tunnel project with composite lining, the cracks in cast-in-place concrete final lining should be controlled to meet the specified requirements for safety, durability and water leakage preventing. However, temperature and shrinkage cracking in cast-in-place concrete linings are still not rare in practical cases [1-4]. In simplicity, the temperatures and shrinkage cracks appear and develop on the conditions of both the volume decreasing in responding to the concrete temperature dropping and moisture disappearing and the constraint features to the volume change. For a tunnel project, the magnitude and rate of the lining concrete temperature dropping are generally specified as the building is in a planned mode. The features of the temperatures and shrinkage cracks in the concrete lining under consideration depend on the constraint conditions [5] of the cast-in-place concrete lining in the period of temperature dropping and moisture disappearing. Mainly due to the project unique of the constraints in temperature and shrinkage cracking, the rule of the constraints in the occurring and developing of the temperature and shrinkage cracks in the cast-in-place lining concrete needs further study.

The monitored results of the temperature crack widths in three cast-in-place concrete final lining panels, where there are no waterproof and drainage sheets in their composite linings, indicate that the constraints to the temperature drop and shrinkage deformation of the concrete in its arch and sidewall
in construction stage still work in the period of post-construction. Therefore, the seasonal variation of the crack widths can partially indicate the constraint conditions of the cast-in-place lining concrete cracking during temperature deceasing stage in construction period. The results from this case study give a clue to apply a flexible layer on the outer surface of cast-in-place concrete lining in concrete crack resistance design and construction quality control, especially for a tunnel with cast-in-place concrete monolithic lining or two-pass lining.

2. Tunnel and concrete temperatures cracks in final lining
The concrete temperatures cracks presented here is from a 1022-m-long loess railway tunnel [6], which located in Pleistocene sandy clay, silty clay or silt layers. The loess is sound, and the mined section of the tunnel is built with top-heading and bench method following the principles of NATM.

2.1. Tunnel structures
The tunnel structures of the mined sections are a composite lining with invert, composed of 30-cm-thick shotcrete lining, with steel sets and steel meshes embedded, and 55cm-thick cast-in-place reinforced concrete final lining. The designed strength grades of the shotcrete and cast-in-place concrete are C30 and C45, respectively.

2.1.1. Construction procedure in general. The tunnel composite lining system is built with conventional method. The final lining is 30 m to more than 100 m behind the primary lining for a section. The final lining is built in two steps. For each of the lining panels, the invert is first casted and then followed by the filling concrete; the low wall of final lining is followed in several days. The times to build the arch and sidewall of the final lining panels are ten days to more than a month late, respectively.

2.1.2. Adjustment on the composite lining system. During tunnelling, the excavation face is “dry”. It seems that there is no function of the waterproof and drainage sheets in the composite lining system, such as in terms of building a dry tunnel. On the other hand, it is favorable to the project in terms of time and cost saving and avoiding voids behind the final lining, to cancel the water-proof membrane and drainage sheet. Upon an agreement by the involved groups, the membrane and sheet were cancelled in the sections about 100 m from the portal and then on.

It is a pity that cracks were identified in the final lining panels, in which the water-proof membrane and drainage sheets had been cancelled. The deformation monitoring results, including crown settlement and convergence, indicated that the excavations under the primary lining system are stable and that the final lining concrete cracking is not due to the ground pressures [7]. Considering the features of the potential thermal stresses in the final lining due to cancelling the interlayered sheets, the constraint conditions of the final lining would have a strong influence on the cracking of the built panels. So, the waterproof membrane and drainage sheets in the original composite lining design were applied before the final lining panels casting in the following tunnel sections. The cracking in the final lining panels is therefore under control.

2.2. Type and features of the concrete temperatures cracks in the final lining
Cracks occurred in the lining panels with interlayered sheets cancelled. The cracks are observed shortly after formwork jumbo removing and are of temperature drop and shrinkage cracking features.

The cracks in the tunnel lining arch and sidewall concrete are longitudinal, circumferential, vertical and diagonal (Figure 1a) in terms of the relationship between the extension direction of the cracks and the tunnel axis line. The occurrences and features of the cracks are presented in Table 1.

The cracks are of the following general features. (1) The cracks appear in specified positions, respectively; (2) two longitudinal cracks generally appear in a panel, with the crack length varying among the panels; (3) the cracks may extend in an intermittent pattern, with snake shape and width varying. These features are of the characteristics of tensile cracks, with rough sidewalls and in a wavy
pattern under a crack width meter (Figure 1e, f). The cracks would cut through the thickness of the final lining and the width is almost same along the whole thickness, as tested by bored cores at a longitudinal crack (Figure 1b).

(a) Types and occurrences of the cracks in a concrete lining panel

(b) Crack features in a bored core

(c) Circumferential & longitudinal crack

(d) Diagonal cracks

(e) Enlarged crack features

(f) End of the enlarged crack

Figure 1. The types, occurrences and the features of the temperature cracks in a final lining panel.

| Crack type         | Occurrence                                                                 | Features                                                                                                                                   |
|--------------------|---------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------|
| Longitudinal crack | Nearly horizontal and parallel to the tunnel axis, mainly in the transitional position between the lining arch and sidewall | Most of the cracks are several meters in length or two cracks along a line; Crack may run through a panel but does not extend into neighbour panels |
| Circumferential crack | Extending vertically in the upper part of the sidewalls while circumferentially in the lining arch | Appearing above longitudinal cracks, with a length of 1.5 to 4.5m; Generally occurring at the middle of the panel length, with one crack at a sidewall in a panel |
| Vertical crack     | In the lower parts of the sidewalls, extending from about one meter above the top of the low wall of the final lining | One or two about two-meter long cracks in one sidewall, nearly halving or trisecting the length of the lining panel, respectively             |
| Diagonal crack     | Mainly appear in the lining crown with a diagonal to the tunnel axis        | The continuities of the diagonal cracks are not well, generally with branch in appearance                                                  |

3. Width changing of the cracks in responding to the temperature variation with seasons

3.1. Crack width monitoring

The cracks in the lining panels are generally harmful to tunnel safety and durability, since the widths of the cracks are beyond the target value, i.e., no more than 0.2 mm. The measured widths of the concrete cracks indicate a feature of changing with time, since the histograms of crack widths measured from two panels are different from the general frequency distribution features of the crack widths measured from the total observed panels about five months ago (Figure 2). 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 3). The longitudinal, circumferential and diagonal
cracks in three lining panels, numbered as panels I, II and III were monitored with 12 strain gauges, respectively. The gauges were installed (stuck to) perpendicularly crossing the monitored crack at a site (Figure 3).

The monitoring results from 11 effective strain gauges were read as changes of the widths of the cracks in strains in responding to the temperature variation with seasons (Figure 4). The temperature variation with seasons is presented in Figure 5, changing with the air temperature at the tunnel site. The features of the strain gauge recordings are discussed in the following sections.

(a) Width of the cracks measured early in panels with cracks being observed
(b) Width of the cracks measured in two panels about five months later

Figure 2. Histograms of crack widths showing difference as measured at different times.

(a) Sketch showing the cracks and monitoring sensors
(b) Crack width monitoring with vibrating strain gauges

Figure 3. Histograms of crack widths showing difference as measured at different times.
3.2. Features of the crack width changing with season temperatures

3.2.1. General features. Figure 4 shows that the widths of the monitored cracks generally increase with the air temperature dropping with season variation, while the crack widths decrease with the air temperature rising. The maximum increment in width appears in the early period of January for all of the cracks, though the magnitudes of the increments are different, as varying from about 0.05 mm to 0.25 mm. 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 or step-like somewhere in the curves, as shown by the dash lines in Figure 4. The reasons for this feature will be discussed in details in the following.
3.2.2. Discussion on the changing features of the crack width. To analyze the step-like features of the crack widths, for example, the relationship between the longitudinal crack width increment and temperature decrement and the relationship between the crack width decrement and temperature increment are presented in Figure 6. For each of the monitored cracks, the gradients for the regression lines of the relationships in terms of temperature decreasing and increasing stages are generally different. To show this feature, the coefficients of the regression lines for the monitored cracks are listed in Table 2, together with the temperatures, where there is step-like width variation.

![Figure 6](image)

**Figure 6.** Features of the longitudinal crack width changes with season temperatures.

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 dropping [7-9], which determine the features of thermal stress in a lining panel. Considering that the magnitude of temperature decrement is generally same in the panels, since the structure features and building procedure are same for all of the panels, the difference of the constraint conditions between the lining panels, with or without waterproof and drainage sheets, is the key factor. 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. 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.

Figure 5 shows that the minimum and the maximum air temperatures appear about the first ten-day period of January and the middle ten days of July, respectively. According to the features of the crack width variations (Figs. 5 and 6), the temperature dropping period can be presented with two stages, i.e., temperature decrement of 5 to 10 ºC and 13 to 18 ºC, respectively. In the temperature rising period, the crack widths are generally decreasing until the end of May, 2018, when there is a temperature increment about 13 to 16 ºC and the widths of monitored cracks return to their original conditions, respectively, as shown in Figure 4. This indicates that crack widths variations are attributed to the
season air temperature changes. The monitored results of the crack widths can generally present the expansion and contraction features in responding to the air temperatures rising and dropping.

**Table 2.** Coefficients of the regression lines and temperatures of width variations with a jump.

| Crack type     | Lining panel | Temperature dropping stage | Temperature rising stage |
|----------------|--------------|-----------------------------|--------------------------|
|                |              | Coefficient 1 | Coefficient 2 | Coefficient 1 | Coefficient 2 | Coefficient 1 | Coefficient 2 |
| Longitudinal   | I            | -0.0039        | -10           | -0.0019       | -18           | -0.0043       | +16           |
| crack          | II           | -0.0044        | -5            | -0.0003       | -13           | -0.0025       | +13           |
|                | III          | -0.0116        | -5            | -0.0068       | -13           | -0.0164       | +13           |
| Circumferential| I            | -0.0073        | -6            | -0.0039       | -13           | -0.0150       | +13           |
| crack          | II           | -0.0049        | -6            | -0.0084       | -13           | -0.0141       | +13           |
|                | III          | -0.0084        | -10           | -0.0017       | -18           | -0.0130       | +16           |
| Diagonal crack | I            | -0.0021        | -6            | -0.0065       | -13           | -0.0057       | +13           |
|                | II           | -0.0022        | -6            | -0.0060       | -13           | -0.0006       | +13           |
|                | III          | -0.0011        | -5            | -0.0023       | -13           | -0.0026       | +13           |

On the other hand, the width changing at the different parts of a crack is not synchronized in a temperature rising or falling period, as shown in Figure 6(c), which presents the variation features of two monitored positions of one longitudinal crack. 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 7) 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, respectively. Therefore, the seasonal variation of the crack widths can partially indicate the constraint conditions of the cast-in-place lining concrete cracking during temperature deceasing stage in construction period.
Figure 7. Sketch showing the building procedure of the final lining and the constraints to the temperature drop and shrinkage deformation of the concrete in its arch and sidewall

The crack width variation features are related to the types and their position of the cracks. Therefore, it is important to consider the influence of the constraint conditions of typical structure types on the mechanism of temperature and shrinkage cracking in tunnel cast-in-place concrete lining. In this tunnel, the concrete cracking is well controlled in the final lining panels, where the waterproof membrane and geotextile sheet are applied in the composite lining system. This indicates that interlayer, which is of flexible properties when there is a tendency of relative displacement between the dual lining layers (Figure 7), can decrease the magnitude of the final lining outer side constraints to such a degree, that the thermal stress is too small to crack the concrete. Considering the cracks beyond the planned allowable values in this case, the results give a clue to apply a flexible layer on the outer surface of cast-in-place concrete lining in concrete crack resistance design and construction quality control, especially for a tunnel with cast-in-place concrete monolithic lining or two-pass lining.

4. Conclusions
Following conclusions can be drawn from the seasonal variation of the concrete temperature cracks:

1. The crack widths variations are due to the season air temperature changes and generally present the expansion and contraction features in responding to the air temperatures rising and dropping.

2. The seasonal variation of the crack widths partially indicates that the constraint from the outer side and side-end of the cast-in-place concrete lining panels with cracks during temperature dropping stage in construction period still work in the period of post-construction.

3. The crack types and their position imply that it is important to consider the influence of the constraint conditions of typical structure types on the mechanism of temperature and shrinkage cracking in tunnel cast-in-place concrete lining.

4. It is beneficial to apply a flexible layer on the outer surface of cast-in-place concrete lining in concrete crack resistance design and construction quality control, especially for a tunnel with cast-in-place concrete monolithic lining or two-pass lining.

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