- Technical Paper -

ANALYSIS OF HOOP STRESS GENERATED AT CROWN OF LINING CONCRETE IN NATM TUNNELS

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ABSTRACT

Stress generation at the crown in the second lining concrete of NATM double shell lining systems was studied using a finite element based system. The results of numerical simulation were compared to actual tunnel measurements in a past research. It was revealed that before the form removal, stress generation in the hoop direction leading to longitudinal cracking was governed by temperature variations. After the form removal, stress behaviour was governed by both self-weight and temperature decrease.

Keywords: NATM, concrete, second lining, longitudinal cracking, stress in hoop direction

1. INTRODUCTION

Demand for construction of highway tunnels has considerably increased in recent past in Japan, especially in Tohoku area in northern part of Honshu Island, recovering from the 2011 earthquake and tsunami disaster. Most of mountainous highway tunnels in japan are constructed by NATM method which consists of in-situ cast concrete double shell lining system, where a water proofing layer is sandwiched in between the inner shotcrete layer and the outer concrete layer. Some of recently constructed tunnels have suffered severe cracking in the outer concrete lining. As crack control is vital in concrete structures for the durability, it is necessary to adopt appropriate measures to reduce cracking.

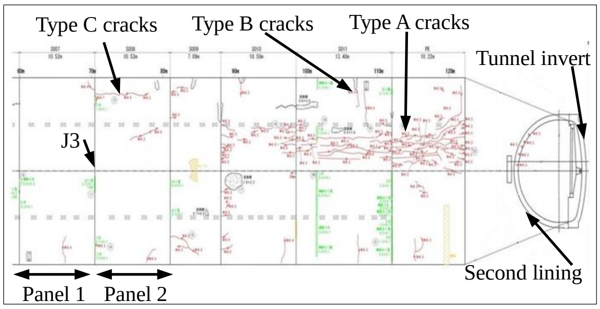

Fig.1 Crack map of a severely cracked tunnel

Several types of cracks can be identified from Fig.1, which shows an actual crack map of a severely cracked second lining of a tunnel. Type B, transverse cracks start from invert and propagate vertically and known to be penetrating cracks. Type C longitudinal cracks start from the joint between construction panels and propagate horizontally. Type A cracks can be seen close to the crown of the tunnel, and it is known from site investigations, that most of these cracks are non-penetrating cracks which propagate up to some depth of second lining.

Type B cracks are caused by the restraint from the invert to the volume change of second lining due to hydration heat and shrinkage. Type C cracks are caused presumably by the restraint from the adjacent panel. However for Type A cracks, a straight forward mechanism is difficult to assume because, many factors such as self-weight, volume change due to hydration heat, shrinkage, tunnel dimensions...etc., might affect this type of cracking. Compared to other types of cracks, avoiding type A cracks is important, besides durability aspects because, it is much difficult and laborious even to investigate the length and width of these cracks in site inspections.

In this study an attempt is made to explain the stress generation mechanism at the crown of second lining concrete of a double shell lining system in NATM tunnels using a multiscale concrete model and nonlinear structural mechanics in FEM based system. The objective of this study is to identify the causes of crown hoop stress causing Type A cracks and their degree of influence for short term behaviour of around one month. Efforts are made to simulate a measurement result in an actual tunnel conducted in a past research, and from practically calibrated simulation results the effects of environmental conditions, form removal time etc. on hoop stress generation are discussed.

2. COMPONENTS AND CONSTRUCTION OF NATM DOUBLE SHELL IN-SITU CAST TUNNEL LINING SYSTEMS.

Mountainous tunnels with in-situ cast double shell linings are studied and the components are shown in Fig.2. The tunnel construction process is summarized

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in this section as it is vital for modeling in this study

Excavation is done mainly by drilling and blasting where a single advancement is normally about 1.5m. Then after debris removal, a steel ring which follows the tunnel profile is installed near the blasted surface to increase the stability of the rock near blasted area and a shotcrete layer is installed to create the first lining. Then rock bolts are installed to strengthen the surrounding rock. Then the invert is constructed which is a special structural component that will be installed only in some areas with weaker rock or close to the tunnel mouth, to increase the stability of the second lining. Then a waterproofing membrane, which consists of a geotextile in the inner layer and a thick polyethylene sheet in the outer layer is installed on the surface of the first lining. Then concreting of the second lining is done in a sequential manner. A single concreting action which normally covers a length of 10.5m panel, is usually conducted every two or three days with a moving form, and the form is removed at the age of around 16 to 36 hours.

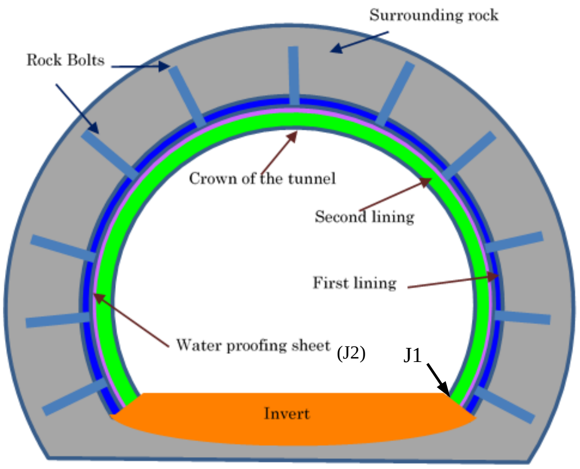


Fig.2 Components of double shell rock tunnels

3. MEASUREMENT RESULTS IN ACTUAL TUNNELS

Field measurement data for the current study was selected from a literature published by Taisei Corporation[1].The tunnel dimensions and the measurement points are shown in Fig.3.

Measurements include the longitudinal stress and strain measurements close to the invert at location P as well as strain measurements with non-stress meter close to the invert at location Q, and only transverse strain was measured at the crown. All measurements were conducted at the middle thickness of the second lining. Then comparing the structural strain measurements and the isolated concrete strain measurements done with non-stress meter, the effective strain was calculated for location P. By multiplying this effective strain with appropriate young's modulus, longitudinal stress was calculated for the same location. This calculation process was verified by comparing measured and calculated stresses. Then the same calculation process was applied to crown strain measurements assuming the isolated concrete strain measured at location Q remained

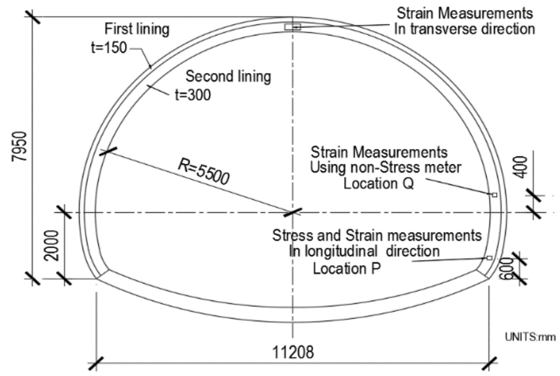


Fig.3 Tunnel profile and measurement points

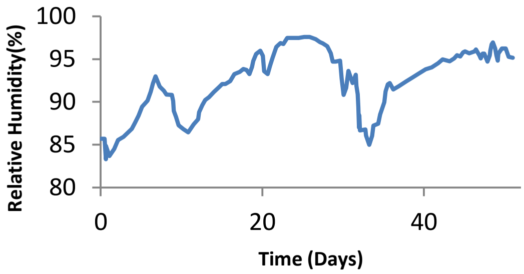


Fig.4 Relative humidity variation at site

constant in the whole structure. This computed stress at the crown was utilized for this study as it represented the major cause for longitudinal Type A cracks close to the crown.

In the same literature, other measurement results are also included such as the relative humidity variation at site as shown in Fig.4, the concrete temperature variations in the middle thickness of the lining at crown and Location P (Fig.7), concrete mix proportions, and curing conditions.

4. FINITE ELEMENT MODELING

4.1 Modeling tool

Finite element modeling was carried out in advanced concrete modeling software LINK3D, which is capable of modeling concrete performance with respect to time, environmental conditions, loading and damage. There are two major modules, namely DUCOM which is responsible for modeling the concrete material behaviour including cement hydration, microstructure development, moisture transport and thermodynamic equilibrium etc.[2], and COM3 which is responsible for structural behaviour and includes geometric and material nonlinear modeling with a four way fixed crack model[3].

4.2 Idealizations in modelling

As the objective is to investigate hoop stress behaviour at the crown part in the middle of the panel, a tunnel section was modeled in an idealized condition, only using a single element in the longitudinal direction assuming the effect of longitudinal behaviour is minimal on crown hoop stress conditions. It was assumed that longitudinal movement was not restricted and the model was created in two dimensional plane stress condition.

Another main idealization in the modeling was the modeling method of joints. There are three main joints for a newly constructed second lining panel, the horizontal joint between the invert and the second lining (J1 in Fig.2.), the weak joint formed due to installation of waterproofing sheet (J2 in Fig.2) and the vertical joint between the old panel and the new panel (J3 in Fig.1). But in the idealized model only J1 and J2 were required.

The joint between the invert and the second lining was assumed to be fixed, because the stiffness of the invert was very large compared to the stiffness of lining concrete in early age, and because in many locations reinforcing bars are penetrating the invert and the second lining to provide a rigid joint.

It is known that, in double shell lining systems, structural behaviour of the first and the second linings can be assumed as independent from each other[4]. Therefore the waterproofing sheet (J2) was modeled with nonlinear gap elements, which allow the second lining to be mechanically separated from the first lining. The moisture transfer between the first lining and the second lining was completely prevented to simulate waterproofing action, whereas for heat transfer, the mutual connection was always enabled through J2 due to software limitations.

Another major assumption was the modeling method of form removal, which was modeled as equal to the application of gravity load at the time of form removal. The restraint for volume change of concrete by the formwork before form removal was not modeled in the current simulation.

4.3 Model properties

A NATM tunnel was modelled in two dimensional conditions considering the symmetry of the structure along the crown line. The rock thickness of the model was selected as 2m. This thickness was sufficient to model the heat transfer behavior and the modeled rock thickness was not very significant in terms of structural behaviour due to the modeling nature of J2 with nonlinear bond elements. The completed model, structural boundary conditions and the mesh are shown in Fig.5

Thermal boundary conditions were such that full thermal connection was possible through all the joints at all the time and only the face of the second lining was defined as a thermal boundary between the structure and the environment. Based on the site measurements shown in Fig.7, it can be observed that the crown temperature is much higher than the temperature at location P. Based on the author's experience, the reason for this temperature difference was assumed to be because of the outside air temperature difference at these two locations. The air temperature difference might be mainly because, warm air due to hydration heat moved upward in a closed environment covered by a plastic sheet for curing during and after concreting. This covering sheet will be removed before the form is moved for the next concreting. Therefore in this simulation, the initial outside air temperature for 1.5m wide strip from the crown line was set to a higher value of 40 ^{0}C. But looking at the measured temperature at crown as shown in Fig. 7 at 20 days after concreting, the temperature difference between crown and location P is very small. Environmental temperature setting used in this research is shown in Fig.6. The initial temperature of the rock was set to a lower value of 20^{0}C based on the site observations and the shotcrete and the invert were assumed to have the initial temperature equal to the air temperature of 27^{0}C. Relative humidity of the outside air was set to a constant value of 85% based on Fig.4.

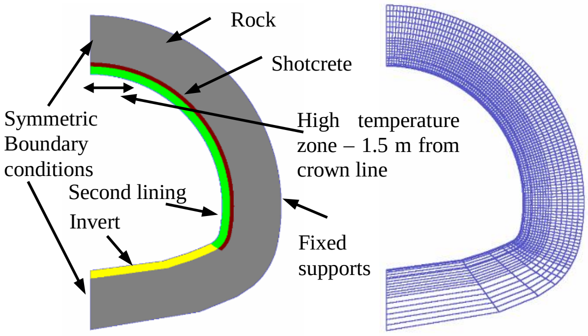


Fig.5 Boundary conditions and mesh division

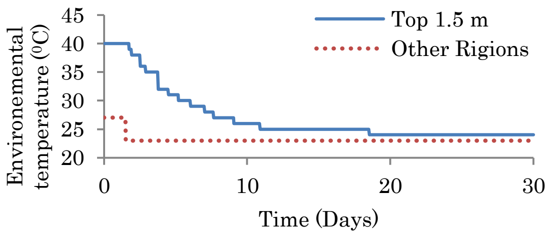


Fig.6 Environment temperature setting

Material properties for each component should be defined in both DUCOM module and COM3 module. In the current analysis concrete material simulations were done only for the second lining panel which was made of plain concrete. Input data was mainly the concrete mix proportions which was, 52.9% W/B ratio, ordinary Portland cement 319 kg/m^3, fine aggregates 788kg/m^3 and 20mm coarse aggregates 1031kg/m^3[1]. For other components multiscale concrete simulation was not conducted and a fixed microstructure was assumed. Thermal conductivity of the second lining, shotcrete layer and the invert was assumed to be equal to the value of concrete and was set to 2.6 W/(m^{0}C), for rock higher value of 3.1 W/(m^{0}C) was set complying to JCI guideline[5]. Heat transfer coefficient of the surface was set to a constant value of 10 W/(m^2 ^{0}C) for both periods before and after the form removal.

Table 1 structural properties

Component	Tensile strength (N/mm^2)	Young's modulus (N/mm^2)
Second Lining	0.92	1000
Shotcrete	-	21560
Rock	-	37700
Invert	-	21560

Structural properties which should be defined on the COM3 module are shown in Table 1.The Second lining was modeled with plain concrete material model, which is capable of modeling stress release after cracking, whereas the other components were modeled with elastic material model without any special nonlinear capabilities. Material parameters such as Young's modulus and tensile strength of the second lining should be large enough to stabilize the initial calculation steps as shown in Table 1, however in later stages, those parameters were calculated based on hydration and strength development model. Initial value for tensile strength was set based on JCI guideline [5]in such a way that it was equal to the value at time of form removal. Young's modulus of the rock was set to a higher value to simulate the higher stiffness (1.75 times concrete) of stabilized rock with rock-bolts. For other components, general values recommended in LINK3D were assumed to be fair. The gravity load was applied to the model at 1.5 days simulating the form removal. Curing period of the measured structure was 1 day after the form removal and included in the model by setting a higher relative humidity at the lining surface.

Two joints J1 and J2 were modeled with bond element with no physical thickness and the properties are shown in Table 2. The Friction coefficient was defined as the tan value of assumed friction angle between the surfaces according to Mohr Coulomb theory. The stiffness values of J1 were set to very high values to obtain a fixed joint and the friction coefficient was also increased as a safer option in case where generated stresses exceeded the specified limited values. Joint J2 was modeled with negligible friction, shear stiffness and normal stiffness due to the reasons explained in section 4.2, and the penetration stiffness was set to a higher value. Friction was automatically activated only in places where compressive stresses were generated.

Table 2 Joint properties

Bond Parameters	J1	J2
Shear stiffness in close mode (N/m^3)	0.00001	0.00001
Penetration stiffness in close mode (N/m^3)	100	100
Friction coefficient	0.8	0.00001
Shear stiffness in open mode (N/m^3)	100	0
Normal stiffness in open mode (N/m^3)	100	0

4.4 Calibration results

The site measured and the simulated temperature variations are shown in Fig.7. It can be observed that the simulation results show same trend as the site measured results although the values do not fully agree. The difference is partially due to the software limitations where the heat transfer through joints is fully enabled all the time. As the objective of this paper is to discuss the stress generation mechanism, the obtained level of accuracy shown in Fig.7 for temperature results was expected to be sufficient because the stress generation pattern mainly depends on the temperature variation pattern rather than the exact values.

The main concern of this study is the stress variation pattern at the crown in the hoop direction and

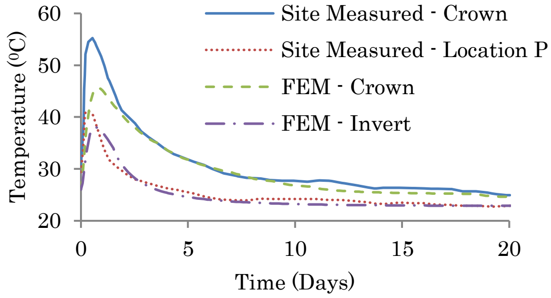


Fig.7 Temperature variation, Measured and FEM

shown in Fig.8. Although the site measurements were conducted at the mid depth of the lining, FEM results were extracted at 0.6 of the lining thickness from the surface of the lining based on gauss point locations.

It can be observed that for initial period,

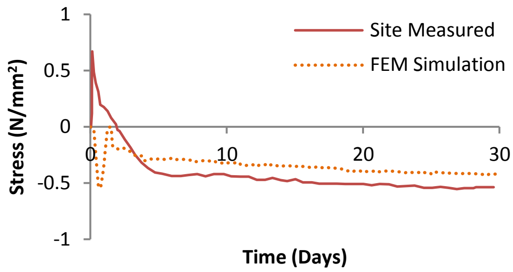


Fig.8 Crown hoop stress, measured and FEM

especially before the form removal, the measured and the simulation results are completely different from each other but after the form removal, simulation results start to follow the pattern of the measured values. The reason for this large initial difference is explained in section 5.5. Main concern here is, from Fig.8, any cracking risk is not pronounced for the crown region as the stress conditions are mainly in compression at the middle thickness. The stress variation with time for different locations at the crown of the second lining in thickness direction from the surface is shown in Fig.9. Location is indicated as a ratio to the lining thickness from the surface towards thickness direction (middle point of the lining in thickness direction would be shown as 0.5). It can be seen that the outer elements show tensile stresses that might cause longitudinal crown cracking when they exceed the limit value. Saw tooth behaviour in the outer most element is due to drying shrinkage and surface

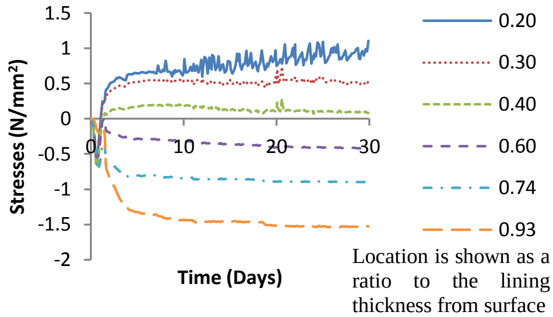
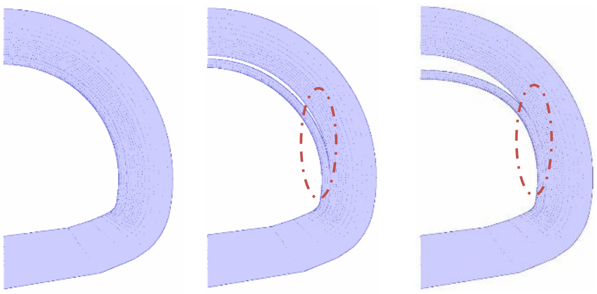


Fig.9 Hoop stress variation across lining thickness

micro cracking in the simulation scheme.

Another important result is the deformation pattern of the second lining with time, which is shown in Fig.10 with 1000 times magnification. After the application of the gravity load, the second lining was separated from the shotcrete layer due to the self-weight. The separation just after the application of the gravity load was about 1mm and the total separation after 30 days was 3.2mm in the simulation. The deformation increase is mainly due to the temperature decrease. It should be noted that there was a slight separation before the application of the gravity load due to the contraction of the second lining caused by the temperature decrease. This slight separation must have been caused by the modelling method of formwork, which was assumed to be equal to the application of the gravity load without modeling the external restraint applied by the real formwork.



At 1.25 days (a) | Just before form removal (b) | Just after form removal (c)

Fig.10 Deformation patterns of the second lining in simulation

5. STRESS GENERATION MECHANISM AT CROWN IN HOOP DIRECTION

5.1 Approach

The target of this section is to explain the stress generation pattern at the crown in the hoop direction mainly with respect to the temperature variation and self-weight. For this purpose, hoop stress at three gauss points in the second lining at the crown and the crown temperature variation are shown for 5 days period in Fig.11.

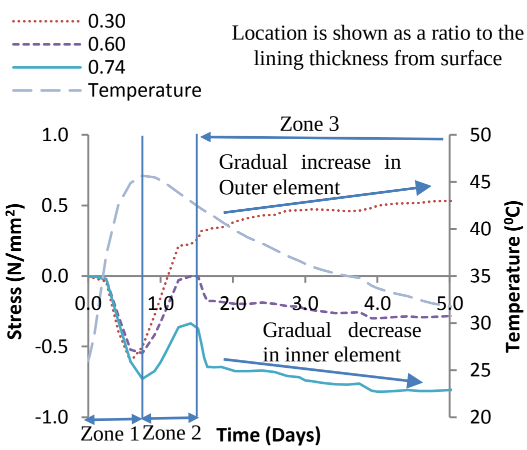


Fig.11 Hoop stress and temperature variation at crown

Hoop stress behaviour was analyzed in three zones based on the temperature variation and the stress variation pattern. Zone 1 includes the temperature rising period from the initial concreting temperature to the peak value due to the heat of hydration. This period covers from 0 to 0.75 days in the simulation. Zone 2 is from the temperature peak up to the time of the form removal which covers from 0.75 days to 1.5days. Zone 3 is from the point of the form removal up to the end of the simulation

To help understanding the mechanism in the three zones, another small analysis was done only for the second lining, by removing all other components in the same model. This imaginary model was assumed to be in the adiabatic condition and analysis was conducted without gravity load for a temperature rise similar to hydration heat. The model and the stress conditions at the crown part are shown in Fig.12. It could be observed that the stress conditions in the outer elements were in compression (ratio 0.01, 0.03) and those in the inner elements (ratio 0.74, 0.93) were in tension. The deformation at the crown was in the vertical upward direction.

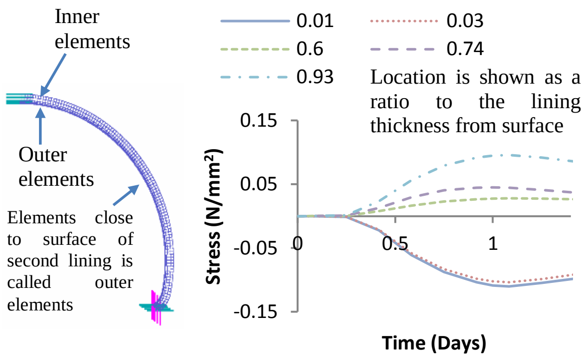


Fig.12 Isolated behaviour of second lining

5.2 Behaviour in Zone 1

Stress variation in Zone 1 is very different from the isolated lining behaviour discussed above. The full model showed compressive stresses throughout the second lining. This difference was caused by the restraint from the stiffer shotcrete layer and the bed rock which restrained the vertical upward movement of the second lining. The restraints prevented the radial expansion of the second lining leading to the compressive stresses.

5.3 Behaviour in Zone 2

With the decrease of temperature, the thermal strain generated in Zone 1 was gradually reduced. Because of the strain reduction, the compressive stress was also reduced. In Fig.11, it can be noted that stress state in the outer element changed in to tension while compressive stress was kept in inner elements. The reason for this behaviour was thought to be a higher rate of temperature decrease of outer elements exposed to the environment.

Then it can be observed from Fig.11 that, just before the start of Zone 3, all the stress patterns showed a slight deviation. This small deviation was caused by the separation of the second lining from the shotcrete layer due to thermal contraction as shown in Fig.10.(b) before the form removal. But it is important to note that this separation might not be possible in a real structure due to the existence of formwork.

5.4 Behaviour in Zone 3

The stress behaviour in Zone 3 can be considered as the most important for practical applications as these stress variations occur after the form removal. Two main stress variation patterns can be observed up to 5 days in Zone 3. The first one is the sudden stress variation just after adding gravity load simulating the form removal. It can be observed that, at the inner two gauss points compressive stress was increased, while at the outer gauss point, tensile stress was increased. This behaviour can be explained with the deformation pattern of the second lining as shown in Fig.10. (b) and (c). Some portions of the second lining detached in Fig.10. (b) had got re-contacted with the first lining in Fig.10.(c). Due to this re-contact, the top portion behaved in a similar way to a fixed end beam generating tension in bottom fibers (close to outer surface in this case) and compression in inner fibers.

The second behaviour pattern in Zone 3 is the gradual variation of stresses which follow the sudden variation explained above as shown in Fig. 11. This gradual stress variation must have been caused by the gradual temperature decrease and can be explained considering reversed conditions shown in Fig.12.

5.5 Discussion on initial stress difference between simulation and measurement results

Here, the difference in the initial part of stress variation in Fig.8 will be discussed. In the idealized simulation conditions compressive stress generation due to confinement as explained in section 5.2 is obvious. Therefore the initial tensile stress in actual measurements might have occurred due to some imperfections of real structures. One of such imperfection can be suggested as follows. When stress generation pattern of the imaginary isolated lining was considered as shown in Fig.12, the inner elements were in tension. Therefore, a small gap between the second lining and the first lining due to construction imperfections can generate tensile stresses during temperature rising period.

6. CONCLUSIONS

Stress variation at the crown of the second lining of double shell in-situ cast NATM tunnels was studied utilizing the finite element method. Stress generation mechanism was discussed expecting that, the understanding of mechanism might contribute to mitigate longitudinal cracking at crown. Main conclusions can be summarized as follows

1. Appropriate modeling method of joints in the double shell lining systems is of utmost importance to simulate mechanically isolated behaviour of the second lining.
2. In Zone 1 and Zone 2 before the form removal, stress generation was governed by temperature variations.
3. In Zone 3, after the form removal, stress behaviour was governed by both self-weight and temperature decrease. Stress conditions might considerably depend upon the cooling rate of crown region.
4. In the outer elements near the surface, tensile stress was generated leading to the risk of longitudinal cracking at the crown.
5. The difference between the measured and the simulated stress in a very initial period might be explained by considering imperfections in actual structures.

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