Analytical study of anomalies in tunnel lining thickness: Critical temperature variations

Expanding Underground. Knowledge and Passion to Make a Positive Impact on the World – Anagnostou, Benardos & Marinos (Eds)

Analytical study of anomalies in tunnel lining thickness: Critical temperature variations

S. Aiello, V. De Biagi & B. Chiaia
Politecnico di Torino, DISEG, Dipartimento di Ingegneria Strutturale, Edile e Geotecnica, Turin, Italy

C. Alessio & L. Baccolini
TECNE Gruppo Autostrade per l'Italia S.p.A, Rome, Italy

R. Fantuz
ASPI Autostrade per l'Italia S.p.A, DT9 Udine Branch, Italy

ABSTRACT: In recent years, the scientific community has developed increasingly innovative, automated, and non-invasive techniques to indirectly assess structural conditions. One of the main reasons is the challenge related to ageing infrastructures approaching the end of their service life. Several monitoring campaigns carried out with the use of non-destructive surveys such as Ground Penetrating Radar (GPR) have revealed the presence of anomalies in the lining thickness of many Italian tunnels. This study proposes an analysis of the state of stress of the concrete lining of tunnel sections with thickness anomalies which are subject to significant temperature fluctuations.

The research related critical anomaly thickness values as a function of thermal fluctuations and loads on these areas of the lining.

This can enable parametric management of tunnel management companies' databases so that hazardous situations can be identified using artificial intelligence algorithms, making this type of method competitive in terms of time and cost.

1 THE RESEARCH BACKGROUND AND THE ITALIAN CONTEXT

In the framework of infrastructure safety, the topic of tunnels is deemed to be significant for the disastrous consequences that any accidents may cause and the related emotional impact on public opinion. Specifically, because of tragic accidents in the past decade, both national and European regulations have been made to ensure safety of road tunnels and for the assessment of the current structural state of the infrastructural heritage. Implementation of cost-effective maintenance plans that ensure a high degree of safety is possible through the development of automated systems (Chiaia et al., 2020, Rosso et al., 2021, Marasco, 2021, Chiaia et al., 2022). Therefore, the development of robust, reliable and timely structural health monitoring (SHM) programmers is particularly important for heavily used structures, such as bridges and underground structures (Davis et al., 2005, Bhalla et al., 2005, Chiaia, 2019, Dawood et al., 2020). In the case of tunnels, the number of structures approaching the end of their service life and thus particularly at risk is extremely high. Combining artificial intelligence techniques, such as deep convolutional neural networks (CNNs), that make use of transfer learning processes with traditional non-destructive structural inspection techniques has proven to be effective in many cases (Feng et al., 2019). With regards to the quality and quantity of data that can be obtained, Ground Penetrating Radar (GPR) stands out as one of the most relevant non-destructive methods. This technique overcomes the limitations of visual inspection, which only makes it possible to detect surface defects.

DOI: 10.1201/9781003348030-356

In August 2022 the Guidelines for 'Risk classification and management, safety assessment and monitoring of existing tunnels along state roads or highways managed by Anas S.p.A. or highway concessionaires' were approved in Italy. These refer to all existing tunnels, which are at least 200m long. The approach aims at pursuing a preventive conduct with respect to the emergence of potentially dangerous situations as well as planning the adoption of preventive maintenance interventions to avoid emergency interventions. The assessment stage of tunnels will be adjusted according to the state of alert. Based on this, the schedule of inspection, the start of preliminary safety assessments or the immediate start of thorough safety assessments will be defined. In the case of tunnels with a Medium-High state of alert, such as those considered as the subject of the research presented herein, the guidelines propose two types of assessments: that is, a preliminary assessment in the case of tunnels with a Medium-High state of alert, and in the absence of serious defects within the initial inspections, it deeply considers the different levels of investigation carried out in order to be able to confirm or increase the state of alert itself. In the event that we are in the presence of tunnels with a high state of alert, careful assessments should be carried out. The objective is to assess the safety margins associated with the tunnel elements and provide corresponding mitigation measures for each specific risk. The goal of this paper is to present the findings of some analyses based on research conducted in tunnels of the Italian highway network (DT1 and DT9, Autostrade per l'Italia). Insufficient lining thickness may occur in engineering practice due to the influence of poor construction conditions, improper construction methods, and inexperienced workmanship in tunnel construction (Ye et al., 2021, Lu et al., 2022). Indeed, GPR surveys on tunnel linings show local reductions in thickness at the vault's key. The specific goals of this paper are to present an analysis of the effects of thermal variation on the state of stress in the material of linings, as well as the possible implementation of artificial intelligence algorithms for the monitoring and optimized management of databases containing valuable information from survey campaigns. In addition, they can provide support in the decision-making process during the in-depth study of the risk level in order to properly address the state of alert according to the Guidelines mentioned above.

2 MONITORING RESULTS

The Ground Penetrating Radar was chosen as one of several non-destructive testing (NDT) methods for defect characterization in engineering materials (Dwivedi et al., 2018, Tosti and Ferrante, 2019). Such an instrument proved to be a valuable tool for damage detection, localization, and classification due to its simple operation, transportation, and penetration capacity (Davis et al., 2005). The underground environment has one of the lowest electromagnetic background levels, and penetration can be excellent. GPR is a geophysical technique that uses an antenna with a frequency range of 10 to 2600 MHz to transmit high-frequency electromagnetic wave impulses into the investigated material (Cardarelli et al., 2003). The dielectric properties of the material influence the propagation of such an impulse. GPR surveys of tunnel linings on the Italian highway network show local thickness reductions at the vault key. This thickness anomaly exists because of the casting operations, since the top side of linings is very complex and difficult to manage. In the present case, thickness anomalies were found in some portions of the examined tunnels. The observed thickness is 1/3 of the designed thickness, i.e., 10cm as opposed to 30cm, as designed. Collapses of localized and limited portions of lining material observed in highway tunnels have clearly demonstrated how the problem of thickness anomaly is relevant to user safety (Jiang and Li, 2020, Ye et al., 2021). Local variations in lining geometry result in localized increases in axial and tangential stresses. In this regard, it is stated that halving the height of a section causes four times more normal stress than a defect-free section for the same bending stress. Even if the presence of thickness anomalies is considered as a risk factor for material collapse, the cause of the actual detachment is found in a state of stress that is incompatible with the strengths of the material in place.

It should also be noted that tunnel linings are typically weakly reinforced and lack the ductility that distinguishes inflected elements. Even though the thermal variation of linings is one of the possible causes of collapses, not enough attention is paid to these thermal stresses. In practice, the temperatures inside the tunnel and/or on the surrounding ground vary. Several studies have presented the reasons for temperature changes in tunnel linings. Variation in the temperature of the ground and surrounding air inside the tunnel can be influenced by the heat generated by vehicles during braking actions or by air conditioning systems (LUO Yan-bin1 2010). Seasonal variations in the environment and geothermal problems that can occur in such structural works are also factors that need to be taken into account (LUO Yan-bin1 2010). Added to this are potential emergency situations, such as fires, that cause sudden temperature increases, resulting in explosive spalling of the tunnel lining's concrete. The rock/soil placed at the extrados has a temperature that is almost constant due to geothermal flow (equal to about $42 mW/m^2$). It should be noted that the average geothermal gradient is 2-3°C/100m, with peaks of 0.6°C/100m and 14°C/100m due to special geological phenomena, and that the daily variation of the temperature of the atmosphere only affects the surface of the earth's crust. Because of the thermal inertia and low thermal conductivity of the soil, these variations have a decreasing amplitude with increasing depth and a temporally postponed peak.

3 LINING ANALYTICAL MODEL WITH ANOMALOUS THICKNESS REDUCTION

The one-dimensional model was created by extrapolating the schematic of the tunnel's typological section with the anomalous thickness in the key. Its definition was made possible by the following assumptions:

- the analyses are limited to the calotte portion, i.e. the area where the thickness anomaly can be found;
- the lining's curvature is assumed to be infinite. This assumption is supported by the fact that the extent of the defect is relatively limited;
- the lining portions considered are not stressed by compressive forces along the middle plane; the only forces at work are vertical forces (permanent load + soil buoyancy) and thermal ones;
- the soil has a consistent and uniform temperature of T_S:
- linear variation of the temperature along the lining thickness (uniform gradient), given that the internal temperature, T_i, is higher than the soil temperature and that the difference between the two temperatures is $2T$.

The thermal variation shown in Figure 1 can be divided into a uniform heating and a linear (butterfly) thermal variation in which the lower flap is heated, and the upper flap is cooled.

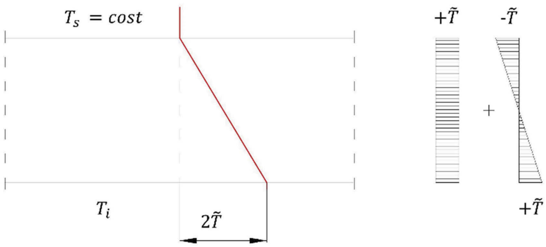

Figure 1. Linear variation of temperature along the lining thickness.

The uniform thermal variation, δT, is equal to the linear variation, abbreviated as ΔT. Both values are equal to $\tilde{T}$ (1).

$$\delta T = \Delta T = \frac{T_i - T_S}{2} = \tilde{T} \tag{1}$$

The present work is limited to the thickness anomaly of the calotte portion, which is considered as part of the design thickness portion. Thermal effects in the defect-free portion are assumed to be negligible (i.e., design thickness lining portion). With reference to Figure 2, the cross-sectional width of the defective portion is equal to 2l for symmetry reasons. The thickness of this portion is equal to h, which is less than the design value. The investigated portion's thickness can be modeled as an equivalent beam of rectangular cross-section, with height h and unit width that is confined at the ends.

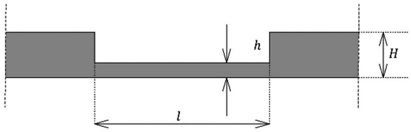

Figure 2. Detail of the linear geometry with thickness anomaly.

3.1 *Thermal action effect*

Thermal action on a hyperstatic structure generates stresses due to impeded deformation of the structure. Given a doubly confined beam, uniform heating generates an axial compressive stress:

$$N_t = -\alpha\delta TEA \tag{2}$$

where $\alpha = (10^{-5}\,^{\circ}C^{-1})$the thermal expansion coefficient of the material; E = material Young module; and A = section area.

The sign of axial stress (or normal stress) follows the rules of Construction and Material Science.

The butterfly thermal variation generates a bending moment that tends the extrados fibers:

$$M_t = \frac{2\alpha\Delta T}{h}EI \tag{3}$$

where $I = \left(h^3/12\right)$ the section Moment of Inertia.

3.2 *Acting stresses*

Previous effects are added to the stress generated by the vertical gravitational load. This load, defined as q, is to be considered as uniformly distributed and orthogonal to the axis of the equivalent beam, and summarizes the self-weight contribution of the lining with thickness anomaly and the load of the overlying soil (4).

$$q = \gamma h \tag{4}$$

where γ is the unit weight of concrete (generally equal to $24 - 25kN/m3$).

In case of thickness anomalies, the thrust of the upper soil is generally absent because the origin of such thickness anomalies is attributable to air bubbles between the lining and the rock. The bending moment diagram is a parabolic curve that tends the extrados fibers at the joints and the intrados one in the middle section.

To summarize:

- the thermal action of uniform heating generates a state of compression, N, in the model (5);
- the linear thermal action, with the intrados warmed and the extrados cooled, translates the self-weight parabolic bending moment diagram upward (6,7);

– the linear thermal action, when the temperature inside the tunnel is lower than the rock/soil temperature, produces an axial tensile stress and translates the self-weight parabolic bending moment diagram downward (6,7).

$$N(z = 0, l) = -\alpha\delta TEA \tag{5}$$

$$M(z = 0) = \frac{ql^2}{6} - 2\alpha\Delta TEI/h(\text{positive if it tends the lower fibers}) \tag{6}$$

$$M(z = l) = \frac{ql^2}{3} + 2\alpha\Delta TEI/h(\text{positive if it tends the upper fibers}) \tag{7}$$

3.3 *Stresses on the critical section*

Figure 3 shows the sign conventions for the stresses. Axial stress is positive if it induces tension, bending is positive if it tends the extrados (upper) fibers.

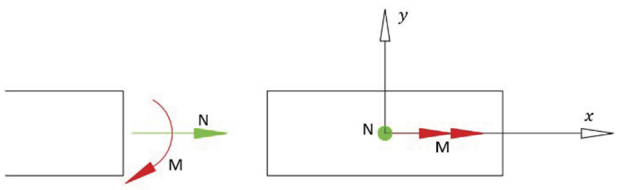

Figure 3. Stress sign conventions.

Normal stress is evaluated using Navier's formula. Considering the fixed joint section (z=l), the normal stress thus shows a linear behavior:

$$\sigma_z(z = l) = \frac{N}{A} + \frac{M}{I}y = -\frac{\alpha\delta TEA}{A} + \left(\frac{2\alpha\Delta TE}{h} + \frac{1}{3}\gamma hl^2\frac{12}{h^3}\right)y \tag{8}$$

Since the greatest stress is close to the fibers in the intrados, the conditions described below should be satisfied (9):

$$\begin{cases} \delta T > 0 \ e \ \Delta T > -\frac{2\gamma l^2}{\alpha Eh} \\ \delta T < 0 \ e \ \Delta T < -\frac{2\gamma l^2}{\alpha Eh} \end{cases} \tag{9}$$

The assumption of constant soil temperature, i.e., constant-temperature extrados, determines that the stresses in the extrados of the lining are not affected by any kind of thermal variation. The stresses in the extrados and intrados are therefore equal to:

$$\begin{cases} \sigma_z\left(+\frac{h}{2}\right) = +\frac{2\gamma l^2}{h} \\ \sigma_z\left(-\frac{h}{2}\right) = -2\left(\alpha\tilde{T}E + \frac{\gamma l^2}{h}\right) \end{cases} \tag{10}$$

where h is the height of section.

In the intrados, the variation of the internal temperature produces the stress distribution shown in Figure 4. If there is no temperature variation, $\tilde{T} = 0$, the flexural deflection is straight, and the extrados stresses have the same intensity (but opposite sign) as the intrados stresses. If there is heating of the air inside the tunnel, the compression in the intrados increases.

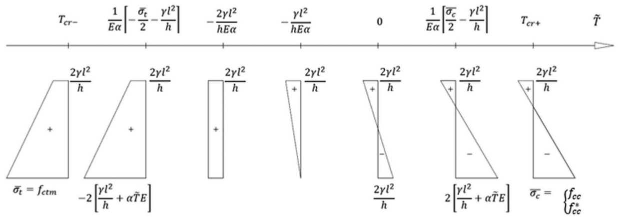

Figure 4. Distributions of stresses on the fixed joint section when the internal temperature of the tunnel changes.

In the analysis of the trends shown in Figure 5, two borderline situations are taken into account: the intrados tension is equal to a tensile limit value, where the average tensile strength of concrete can be considered as the tensile limit value and the intrados tension reaches a value that makes the spalling phenomenon appear.

4 RESULTS: CRITICAL TEMPERATURE VARIATIONS

Two critical temperatures can be defined according to the tensile limits reached in intrados fibers. The compressive borderline condition is reached when the difference between the temperature at the intrados (hot) and the temperature at the extrados (cold) is equal to the critical heating T_{cr+}. As a result of this borderline condition, the stress spreading in concrete generates the phenomenon of concrete spalling. To better understand this phenomenon, Figure 5 shows the trend of stress redistribution in the transition zone between the area with thickness anomaly and the area with integral thickness. The stress model for the thickness anomaly area shows the intrados fibers subjected to compression (shown in light blue) and the fibers in the extrados subjected to tension (shown in red).

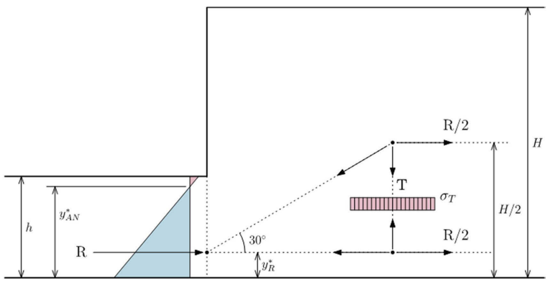

Figure 5. Scheme for the stress redistribution-induced tensile calculation.

The redistribution of the compressive force R (11) in the section with integral thickness follows the strut and tie model. The tensile force T (12) is generated by assuming that the resulting compressive force is transferred equally with a diffusion angle equal to β. Considering an equivalent section of width equal to H/3, the induced tensile force allows us to derive the tensile stresses that the tensioned concrete is required to support (13).

$$R = -\left(\alpha\tilde{T}E + \frac{\gamma l^2}{h}\right)y^*_{A.N.} \tag{11}$$

Where R is the compression stress resulting and $y^*_{A.N.} = \frac{1}{2}\left[\frac{\alpha\tilde{T}Eh^2}{\left(2\gamma l^2+\alpha\tilde{T}Eh\right)} + h\right]$ is the neutral axis position.

$$T = \frac{R}{2} tan\beta \tag{12}$$

Where R is the compression stress resulting, T is the tensile force and β is the diffusion angle.

$$\sigma_T = \frac{3T}{H} = \frac{3}{2}\frac{R}{H}\tan\beta \tag{13}$$

Where σ_T is the tensile stress and H/3 is the section width.

Critical warming is the temperature difference between intrados (warm) and extrados (cold) for which σ_T is equal to the average tensile stress, f_{ctm}. It could be approximated by writing the formula at varying rates l^2/h and H/h (14). Table 1 shows various critical warming values for different classes of concrete.

$$T_{cr}^{+} \approx \frac{2f_{ctm}}{3E\alpha\tan\beta}\left(\frac{H}{h}\right)\left[\sqrt{1+\frac{6\gamma\tan\beta}{f_{ctm}}\left(\frac{h}{H}\right)\left(\frac{l^2}{h}\right)}+1\right] \approx \frac{4f_{ctm}}{3E\alpha\tan\beta}\left(\frac{H}{h}\right) \tag{14}$$

Critical cooling, on the other hand, is the temperature difference between intrados (cold) and extrados (warm) where the self-weight term is negligible. Table 2 shows the critical cooling temperature values as a function of concrete class.

$$T_{cr}^{-} = -\frac{1}{E\alpha}\left(f_{ctm} + 2\frac{\gamma l^2}{h}\right) \approx = -\frac{f_{ctm}}{E\alpha} \tag{15}$$

Table 1. Critical warming values (°C) for different classes of concrete and different value of H/h rate.

H/h	1.5	2	2.5	3	3.5	4	4.5	5
C20/25	25.4	33.9	42.3	50.8	59.3	67.7	76.2	84.7
C25/30	29.1	38.7	48.4	58.1	67.8	77.5	87.2	96.8
C30/37	30.4	40.6	50.7	60.9	71.0	81.2	91.3	101.5
C35/45	32.6	43.5	54.3	65.2	76.1	86.9	97.8	108.7
C40/50	34.6	46.2	57.7	69.3	80.8	92.4	103.9	115.5
C45/55	36.6	48.8	60.9	73.1	85.3	97.5	109.7	121.9

Table 2. Critical cooling values (°C) for different classes of concrete.

C20/25	-7.3
C25/30	-8.4
C30/37	-8.8
C35/45	-9-4
C40/50	-10.0
C45/55	-10.6

5 CONCLUSION AND FUTURE DEVELOPMENTS

In this work, the authors presented the results of the analysis carried out on the monitoring of some tunnels of the Italian motorway network. Among the different data obtained from the monitoring, attention was focused on the frequent anomalies in the thickness tunnel concrete lining. Improper construction methods and inexperienced labor in tunnel construction are among the most common causes of these types of defects. The study focuses on the effects that the thermal variation may have on the state of stress of the material. The values of critical temperature differences (i.e., soil temperature outside the tunnel and internal temperature) were obtained under the condition of reaching the tensile strength on the fibers of the concrete lining intrados, providing the occurrence of the spalling phenomenon. The first situation occurs on the fibers in a lining intrados with the thickness anomaly. The other one occurs in the sections with undamaged thickness due to the redistribution of the compression forces of the section with thickness anomaly.

The authors are currently developing an operational tool based on the analysis presented, to recognize situations of imminent danger depending on recorded temperature data. The above was carried out with the intention of being able to define a decision tool to support the companies managing infrastructures such as tunnels. The ability to implement it automatically will also be of considerable importance in order to promptly identify - with low operational costs - situations of imminent danger based on recorded temperature data. Since, following several inspections, the presence of anomalies in the thickness of linings has been found to be frequent, the objective of this work is also to provide effective support during the Preliminary Assessment and Accurate Evaluation phases at the heart of the current Guidelines on the risk classification of tunnels. Future developments of the present work may virtually involve the expansion of the model used considering the theory of plates, by studying in detail the modelling of the transition zone when thickness anomalies are found. This, together with a defined tool of databases, can contribute to the development of a more reliable system for automated road tunnel lining management.

REFERENCES

Bhalla, S., Yang, Y. W., Zhao, J. & Soh, C. K. 2005. Structural Health Monitoring Of Underground Facilities – Technological Issues And Challenges. *Tunnelling And Underground Space Technology*, 20, 487–500.

CARDARELLI, E., MARRONE, C. & ORLANDO, L. 2003. Evaluation Of Tunnel Stability Using Integrated Geophysical Methods. *Journal Of Applied Geophysics*, 52, 93–102.

Chiaia, B., Marasco, G. & Aiello, S. 2022. Deep Convolutional Neural Network For Multi-Level Non-Invasive Tunnel Lining Assessment. *Frontiers Of Structural And Civil Engineering*, 16, 214–223.

Chiaia, B., Marasco, G., Ventura, G. & Zannini Quirini, C. 2020. Customised Active Monitoring System For Structural Control And Maintenance Optimisation. *Journal Of Civil Structural Health Monitoring*, 10, 267–282.

Chiaia, B., Ventura, G., Quirini, C.Z., Marasco, G 2019. Chiaia, B., Ventura, G., Quirini, C.Z., Marasco, G.: Bridge Active Monitoring For Maintenance And Structural Safety. In: International Conference On Arch Bridges. Pp. 866–873. Springer (2019).

Davis, A. G., Lim, M. K. & Petersen, C. G. 2005. Rapid And Economical Evaluation Of Concrete Tunnel Linings With Impulse Response And Impulse Radar Non-Destructive Methods. *Ndt & E International*, 38, 181–186.

Dawood, T., Zhu, Z. & Zayed, T. 2020. Deterioration Mapping In Subway Infrastructure Using Sensory Data Of Gpr. *Tunnelling And Underground Space Technology*, 103.

Dwivedi, S. K., Vishwakarma, M. & Soni, P. A. 2018. Advances And Researches On Non Destructive Testing: A Review. *Materials Today: Proceedings*, 5, 3690–3698.

Feng, C., Zhang, H., Wang, S., Li, Y., Wang, H. & Yan, F. 2019. Structural Damage Detection Using Deep Convolutional Neural Network And Transfer Learning. *KSCE Journal Of Civil Engineering*, 23, 4493–4502.

Jiang, X. & Li, K. 2020. Analysis And Safety Assessment Of Lining Thickness Defects In Highway Tunnels. *IOP Conference Series: Materials Science And Engineering*, 741.

Lu, P., Qiao, D., Wu, C., Wang, S., He, X., Zhang, W. & Zhou, H. 2022. Effect Of Defects And Remediation Measures On The Internal Forces Caused By A Local Thickness Reduction In The Tunnel Lining. *Underground Space*, 7, 94–105.

Luo Yan-Bin, C. J.-X., Qiao Xiong, Wang Meng-Shul 2010. Mechanics State Analysis Of Secondary Lining Concrete Structure On Tunnel Based On Temperature Effect.

Marasco, G., Chiaia, B., Ventura, G 2021. AI Based Bridge Health Assessment.

Rosso, M. M., Cucuzza, R., Di Trapani, F., Marano, G. C. & Ji, J. 2021. Nonpenalty Machine Learning Constraint Handling Using PSO-SVM For Structural Optimization. *Advances In Civil Engineering*, 2021, 1–17.

Tosti, F. & Ferrante, C. 2019. Using Ground Penetrating Radar Methods To Investigate Reinforced Concrete Structures. *Surveys In Geophysics*, 41, 485–530.

Ye, F., Qin, N., Liang, X., Ouyang, A., Qin, Z. & Su, E. 2021. Analyses Of The Defects In Highway Tunnels In China. *Tunnelling And Underground Space Technology*, 107.