Fire Performance Assessment of Tunnel Concrete Lining considering Thermal Properties Effect and Fire Curve Type

A. Emadi – Senior Associate Engineer, SMEC, Australia
A. Golshani – Principal Engineer, SMEC, Australia
J. Rinol – Senior Tunnel Design Coordinator, Gamuda Australia and Laing O'Rourke Consortium

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This paper presents comparative analyses of the performance of concrete structural lining for tunnels during fire event using the 500ºC isotherm method outlined in BS EN 1992-1-2:2004 Annex B. The analyses investigated the impact of different concrete thermal properties on the obtained time vs temperature curves, contrasting them with results from fire tests in panels. It also analyzed the impact of using different fire curves on temperature evolution at different lining depths, the influence of different fire exposure conditions on temperatures and the impact of the fire exposure on capacity curves for sections with different reinforcement rates. The analyses revealed valuable insights that can inform future designs and be used as basis for further investigations.

Keywords: Fire performance, Concrete structural lining, BS EN 1992-1-2:2004, RABT-ZTV, Specific heat, Thermal conductivity, Fire curves, Experimental validation.

1.0 Introduction

Major tunnel fires are catastrophic events that can lead to loss of life, significant property damage, prolonged service disruptions, and severe socioeconomic impacts (Casey, 2019). Historical events have shown that while tunnel fires may not always result in structural collapse, they can cause considerable damage to tunnel linings, leading to long-term traffic disruptions and major economic losses (Negar, 2022). The evaluation of structure-fire interaction involves three key steps:

a. determining the temperature–time fire curve (demand model)

b. performing thermal analysis (heat transfer), and

c. conducting structural analysis that accounts for thermal loads (capacity model)

This paper presents comparative analyses of the performance of concrete structural lining for tunnels during fire event using the 500ºC isotherm method outlined in BS EN 1992-1-2:2004 Annex B, including the following investigations:

- Effect of different concrete thermal properties on the obtained time vs temperature curves, contrasting them with results from fire tests in panels.
- Effect of using different fire curves on temperature evolution at different lining depths
- Effect of different fire exposure conditions on temperatures; and
- Effect of the fire exposure on capacity curves for sections with different reinforcement rates.

The section 2 presents the key inputs and assumptions used for the comparative analyses, whereas

section 3 presents relevant results and discussions obtained from the conducted assessments.

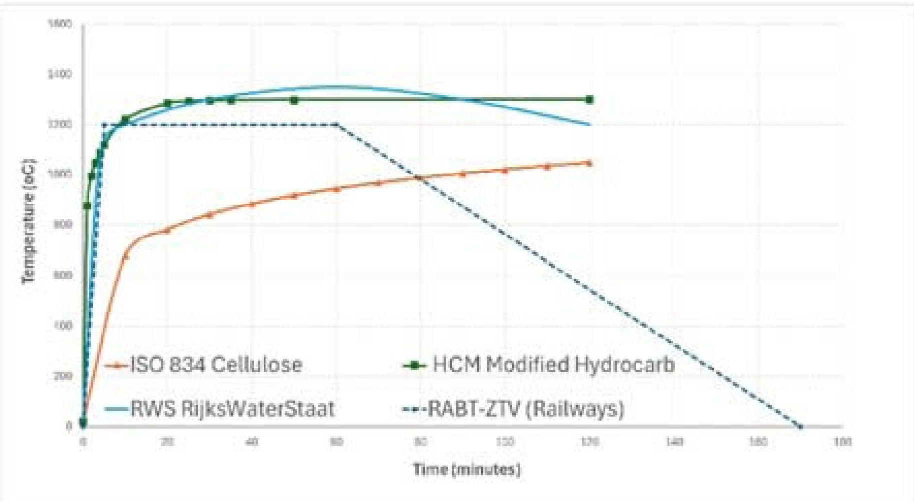
2.0 Basis for the Comparative Analyses

2.1 Analyzed time vs temperature fire curves

The following time vs temperature fire curves have been considered in this study (as shown in Figure 1):

- The RWS curve: it is specified by Rijkswaterstaat (the Netherlands Ministry of Transport) and is one of the most widely used fire load curves for tunnels.
- The HCM Modified Hydrocarbon curve: it was developed to meet French regulations.
- The RABT-ZTV fire curve: it is a German requirement for tunnel fires, primarily utilized for railway tunnels.
- The Cellulosic curve (ISO 834) curve: it is included in some national standards, such as BS 476, DIN 4102, and AS 1530. While originally intended for building applications, it has also been applied to tunnels.

Figure 1: Time vs temperature fire curves considered for comparative analyses



It is noted that in Australia, the RABT-ZTV and ISO 834 fire curves are the common fire curves used for evaluating the performance of tunnels concrete structures.

2.2 Thermal analysis approach and capacity curve assessment

For the analysis of the performance of concrete structural lining for tunnels during fire event using the 500ºC isotherm method outlined in BS EN 1992-1-2:2004 Annex B, the heat transfer through the concrete section has been modeled using a three-dimensional finite element numerical analysis with the Strand7 software.

The fire temperature curve has been applied as a node temperature load. Strand7's transient heat solver module has been used to calculate the temperature profile within the concrete section at various time increments after them fire initiation. Concrete block models have been used for the analysis. The concrete material properties for thermal analyses have been selected in accordance with BS EN 1992-1-2 and are summarized in Table 1.

Table 1: Concrete material property.

Property	Value
Ambient temperature (ºC)	20
Unit weight (kN/m3)	25
Poisson's ratio v	0.2
Thermal Expansion	0.00001
Specific heat vs temperature	Fig 3.6 (a) BS EN 1992-1-2
Thermal conductivity vs temperature	Fig 3.7 BS EN 1992-1-2

For the calculation of capacity curves, the following criteria is applied in accordance with the 500ºC isotherm method:

- A general reduction in the cross-section size shall be considered for the 500ºC (or greater)heat affected zones of exposed concrete faces.
- During a ULS fire event, all load factors are 1.0.
- The strength reduction curves from EN 1992-1-2 are then used to determine the loss of yield strength in the bars and strands

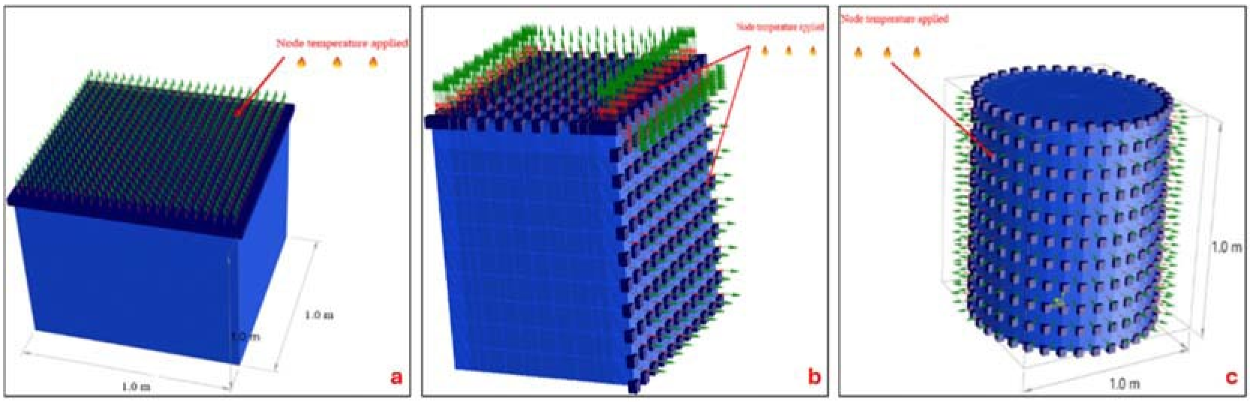
For the calculation of the effective cross section, the reduced cross section calculated from the depth of the 500ºC isotherm method along with the average spalling specified for the project, shall be considered. Fire test results are usually used to validate spalling limit assumed in the fire design. In the present study, results from the Western Tunneling Package of Sydney Metro West project are considered, as explained in section 2.4.

2.3 Analyzed fire exposure conditions

The analyzed fire exposure conditions are listed below and shown in the respective Figures:

- Exposure Case 1: Typical tunnel condition, where the exposed surface is flat (Figure 2a)
- Exposure Case 2: Concrete block with two flat faces exposed to the fire, such as in the case of corbels or internal structures (Figure 2b)
- Exposure Case 3: Elements with curved exposed surface, such as piles which are commonly used to support for top-down structures (Figures 2c).

Figure 2: a) Model for Transient Heat Analysis- one exposed flat surface b) Model for Transient Heat Analysis- two exposed flat surface c) Model for Transient Heat Analysis- one exposed curved surface



The results of the analysis shall provide a temperature profile within the concrete section at various time increments after fire commencement.

2.4 Analyzed fire exposure conditions

Fire test results from the Western Tunneling Package of Sydney Metro West project (WTP) are used for the verification of the conducted finite element models. The fire test was conducted on four simply supported concrete large-scale panels (i.e., 9A, 10A, 11A and 12A), in general accordance with Sections 2 of AS1530.4:2014, Efectis R0695:2008, and EFNARC132F r3:2006 (Specification and Guideline for Testing of Passive Fire Protection for Concrete Tunnel Test). specimen details are provided in Table 2. Overall size of specimen has been1800 mm wide × 1800 mm length × 250 mm thick.

Table 2: Test Specimen

Item	Detail
Concrete Panels – IDs below	1800x1800x250mm Concrete Panels composed of various concrete mixes instrumented with 18 thermocouples in situ at various locations T1-T9 in accordance with EFNARC 132F r3:2006. The specimens also contained 4 lifters on the top surface and 2 side lifters (all panels). The panel IDs were 9A, 10A, 11A, & 12A.

The test utilized in-situ thermocouples to monitor temperature variations throughout the fire exposure period. Each concrete panel contains 18 Type K thermocouples cast in situ. The layout of the thermocouples is illustrated in EFNARC. Specimens' conditions after the fire tests are shown in Figure 3. For the thermal effects investigation, only the central 800 mm x 800 mm area of the specimen are considered. In accordance with the WTP design criteria, this central area shall not experience an average concrete surface spalling depth greater than 20 mm, nor a maximum spalling depth exceeding 40 mm.

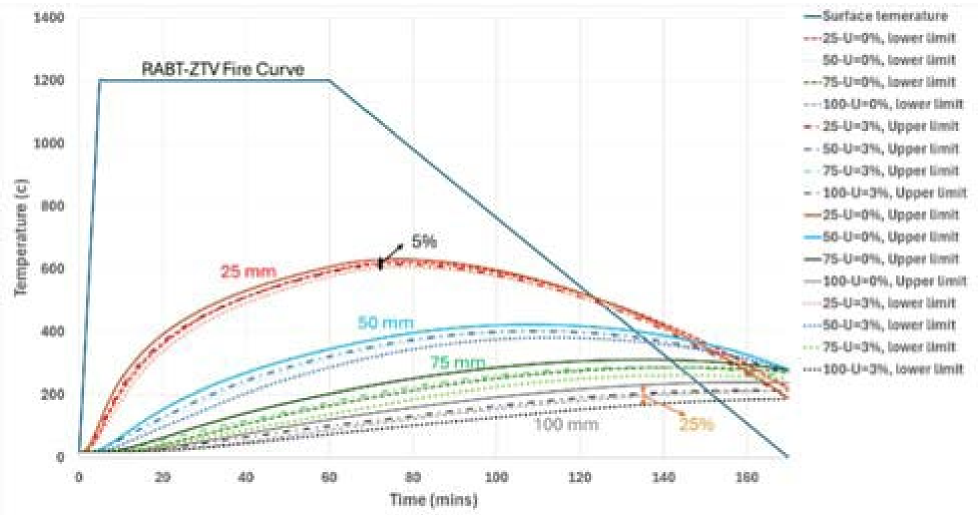
Figure 3: View of the test specimens after fire test whilst in the frame holder

3.0 Results and Discussions

3.1 Effect of different concrete thermal properties and correlation to conducted fire tests on panels

This section discusses the thermal properties of concrete, and their verification based on the material properties outlined in Section 2.3. The specific heat ($Cp(\theta)$) of the concrete is influenced by moisture content (U). For this analysis, U is considered as 0% and 3% of the concrete weight. Additionally, the Eurocode specifies upper and lower limits for thermal conductivity, both of which are considered to ensure a comprehensive evaluation of the concrete's thermal performance. The results of the analysis for the RABT ZTV fire curve and varying thermal properties are presented in Figure 4. The findings indicate that, at a depth of 25 mm, the variation between different thermal properties results in a change of up to 5% of the temperature. At a depth of 50 mm, this change increases to 10%. However, at a depth of 100 mm, the variation can be as much as 25% of the temperature.

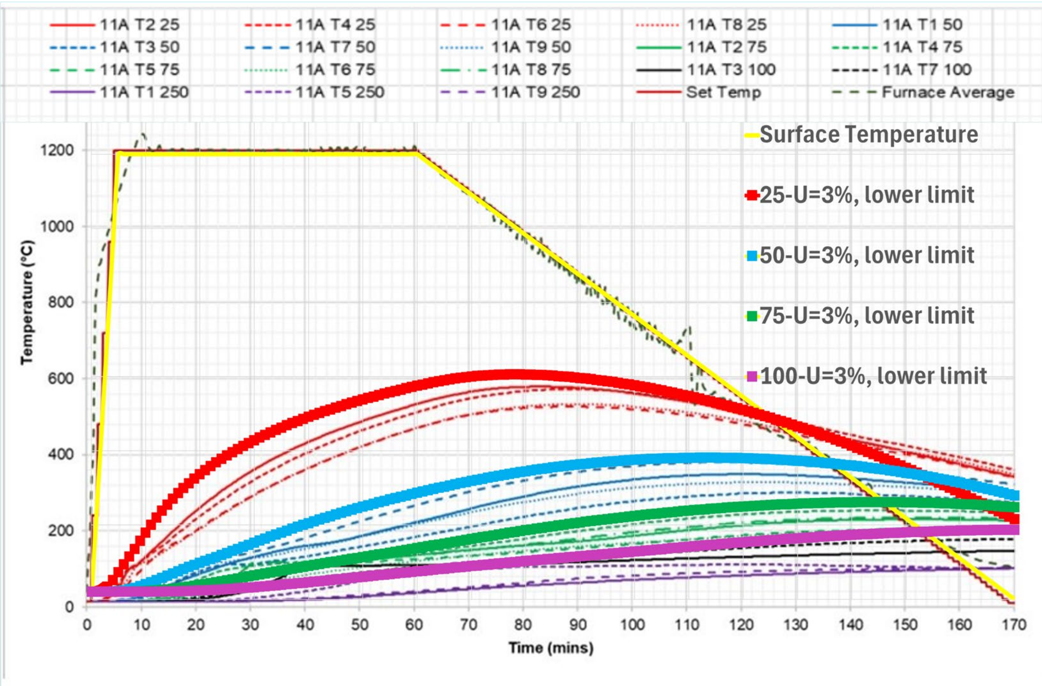
Figure 4: Temperature (°C) vs. Time (mins) at Depths of 25, 50, 75, and 100 mm for Different Moisture Contents, Including Upper and Lower Limits of Thermal Conductivity By comparing the analysis results with the test results, it has been demonstrated that the lower limit of thermal conductivity, with a moisture content of 3%, exhibits the best correlation with the test findings. Figure 5 illustrates the correlation between the finite element analysis and the test results, validating the reliability of the finite element models.



3.2 Effect of using different fire curves

Research has indicated that tunnel fire scenarios are influenced by various factors, including tunnel geometry, ventilation conditions, and fuel types (Carvel et al., 2005). According to EFNARC, several fire curve types are commonly used in industry. Each one of the existing fire curves has been developed based on certain assumptions and conditions. Hence, the selection of an appropriate fire curve is crucial when evaluating the performance of concrete structures, particularly in the context of tunnels and transportation infrastructure. The evaluation procedure for extreme fire loading scenarios, where the rapid rise in temperature exceeds 1000°C, involves several uncertainties, including the intensity and duration of the fire, as well as the response of the tunnel structure, concrete liner, and surrounding ground.

Figure 5: Correlation between the finite element analysis and the fire test results



To demonstrate the effect of different fire curves on the temperature evolution, the fire Exposure Case 1 (Figure 2a) has been subjected to the fire curves introduced in Section 2.1. Results of temperature versus time during exposure at different depths of 20 mm, 50 mm, 70 mm, and 100 mm are presented in Figure 6. The maximum temperature at these depths occurs under the HCM Modified Hydrocarbon curve while the lowest temperature is recorded under the ISO 834 fire curve. The temperature difference between the maximum and minimum results at a depth of 20 mm is approximately 25%. However, as the depth increases, the disparity in temperature results among the different fire curves diminish.

3.3 Effect of fire exposure conditions

The blocks, i.e., case 1, case 2 and case 3used to model fire exposure, as introduced in Section 2.3, have been subjected to the RABT-ZTV fire curve. Figure 7 illustrates the temperature penetration into the depth of the block after 90 minutes from the start of the fire for case 1 and case 2. Additionally, Figure 8 presents the temperature versus time results at various depths of 20 mm, 50 mm, 70 mm, and 100 mm. In typical tunnel conditions, where the exposed surface is either flat or curved, the temperature measurements are taken perpendicular to the surface. However, to assess the worst-case scenario—where two faces of the concrete block are exposed to fire—the depths were recorded using orthogonal nodes. The nodes utilized for these measurements are depicted in Figure 8.

Figure 6: Temperature (°C) vs. Time (mins) at Depths of 20, 50, 70, and 100 mm for Different Fire Curves

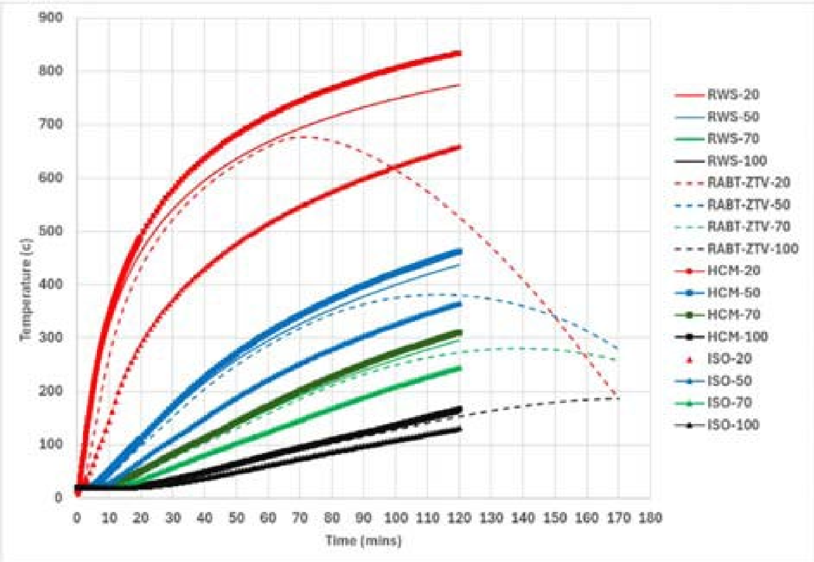
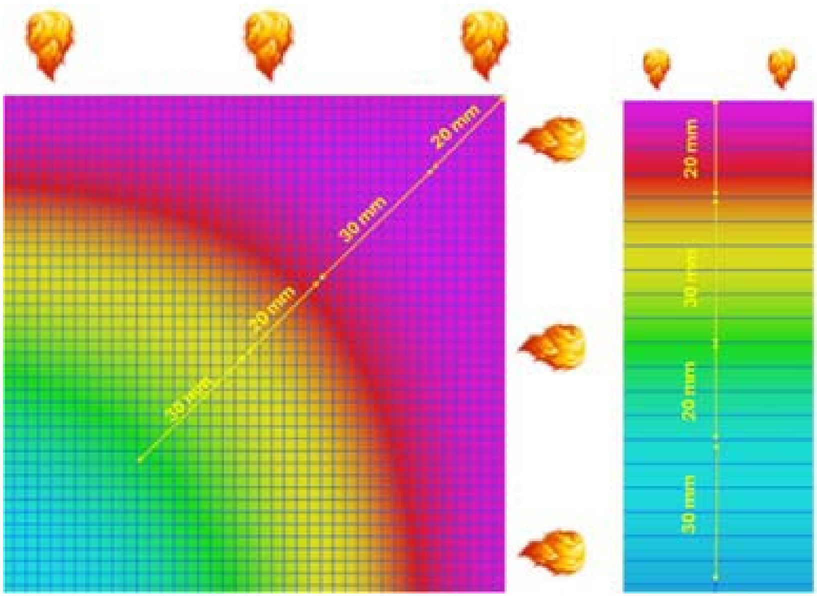
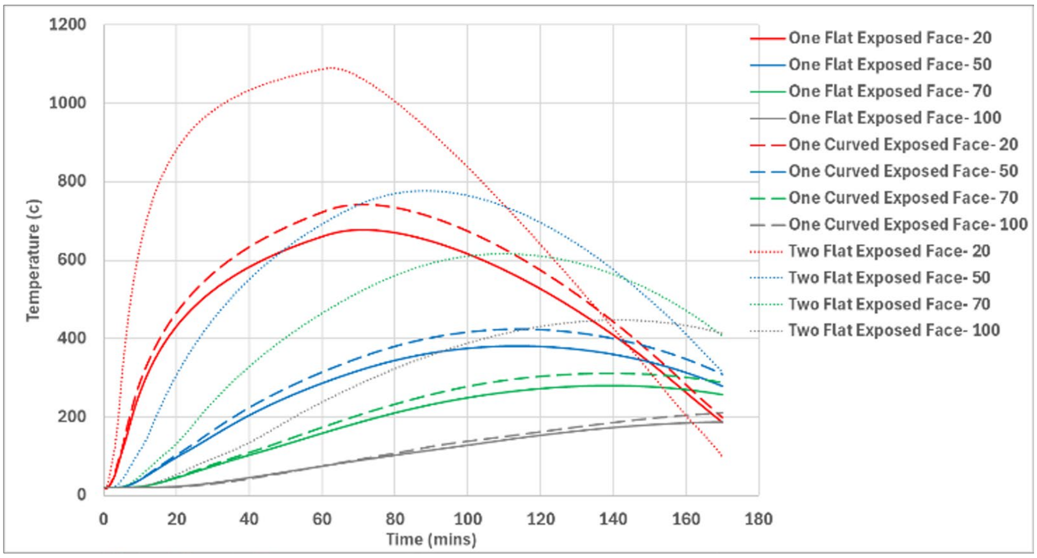


Figure 7: Temperature Penetration into the Concrete Block at 90 Minutes of Fire Exposure with One (Case 1) and Two (Case 2) Exposed Faces and Node Locations



According to Figure 8, the results for a single exposed surface —whether flat (Exposure Case 1) or curved (Exposure Case 3) — show minimal variation, with a maximum discrepancy of approximately 10%. As the depth increases, this discrepancy diminishes. However, the difference between an element exposed on two faces and one face is significant. Even at a depth of 20 mm, the results can be nearly double, highlighting the critical importance of corner concrete cover and the sensitivity of corner areas that may be subjected to simultaneous two-faced exposure.

Figure 8: Temperature Results for Single and Double-Faced Fire Exposure at Various Depths



3.4 Capacity curve after exposing to RABT fire curve

Three sections (Capacity Cases 1 to 3) have been examined to investigate the effect of fire exposure on the capacity curve. The base section, which is unexposed to fire, has a depth of 400 mm, reinforced with N25-200 steel and concrete cover of 60mm, as shown in Figure 9. Following exposure to fire (one face exposure By RABT ZTV fire curve), the depth of this section is reduced due to thermal effects. Based on the temperature diagram in Figure 10, the effective depth decreases to 345 mm, with 35 mm eliminated due to temperatures exceeding 500°C and considering an additional 20 mm section loss due to spalling. Two reduced sections have been considered, for the first one, both concrete and steel strengths have been decreased according to Eurocode guidelines where temperature is below 500°C (Figure 11). for the second one, common industry practice has been applied, which involved only reducing the steel strength while maintaining the concrete strength where temperature is below 500°C (Figure 12). This approach reflects a typical assumption in the field, where the reduction in concrete strength is often not considered (Just elimination is considered).

Figure 9: Unexposed Section – Base Section

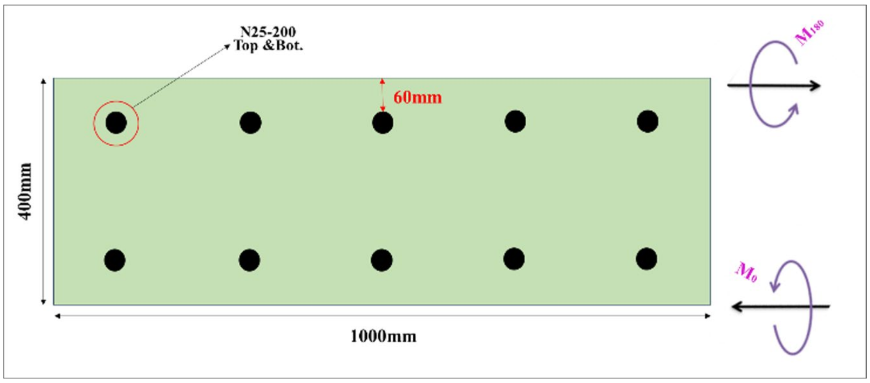


Figure 10: Temperature Vs. Time at different depth within the section

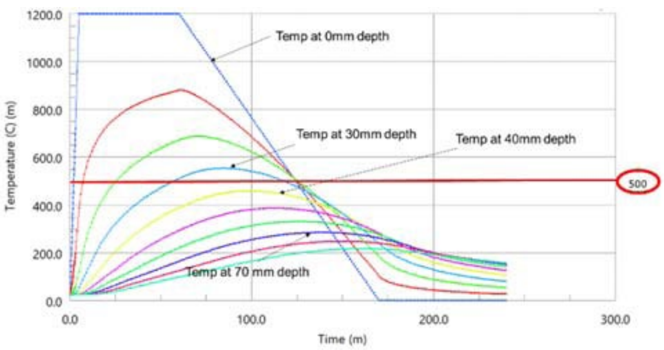
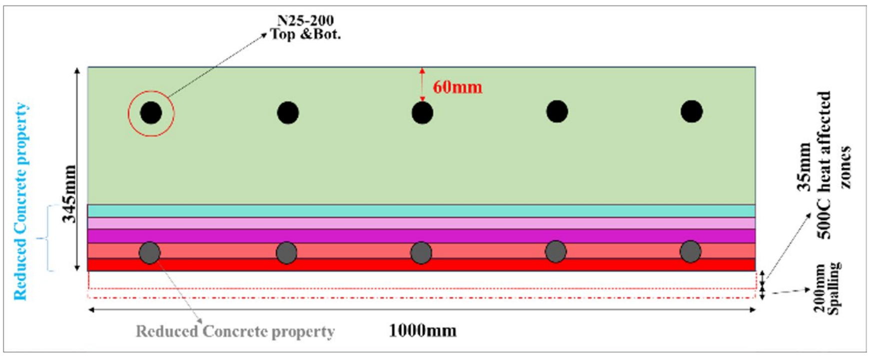


Figure 11: Exposed Section- reduced steel and concrete property



Comparative analysis of these sections in Figure 13 reveals differences in capacity for three different cases. In the compression-controlled region, the capacity reduction for the section exposed to fire (with both concrete and steel strength reductions) shows a decrease of approximately 20% for the 0-degree curve and up to 35% for the 180- degree curve. In the tension-controlled region, capacity decreases range from about 5% to 20%. Notably, the reduction in concrete strength can impact the 180-degree capacity curve up to 5%.

Figure 12: Exposed Section- reduced steel property only

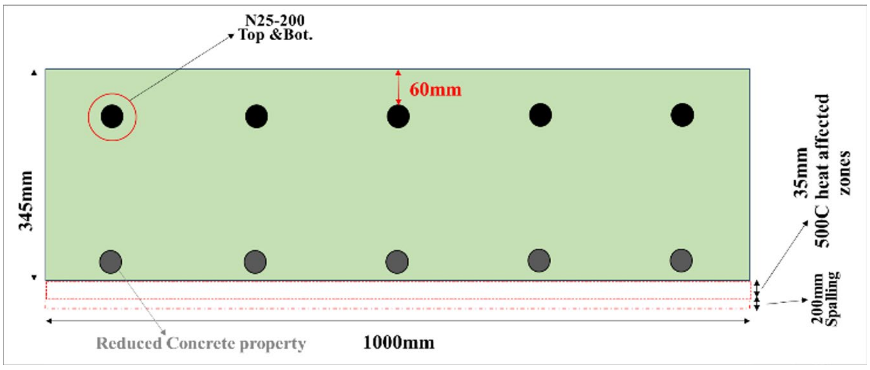
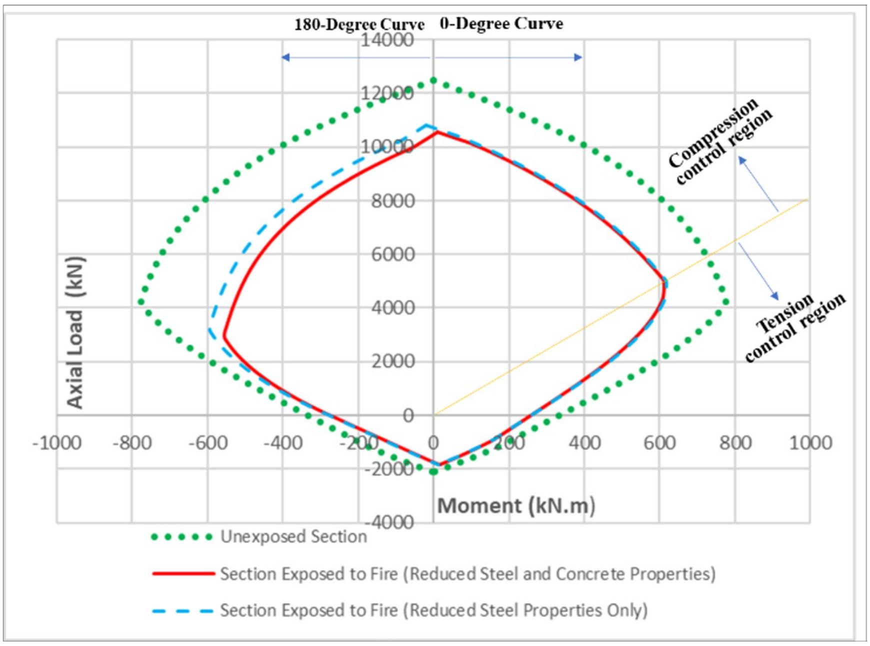


Figure 13: Comparative capacity curves



Conclusion

This study evaluates the performance of concrete structural linings in tunnels during fire exposure, using the 500°C isotherm method from BS EN 1992-1-2:2004. The investigation into the thermal properties of concrete revealed that variations in specific heat and thermal conductivity affect temperature penetration at different depths. For instance, at a depth of 25 mm, variations can lead to changes of up to 5%, increasing to 10% at 50 mm and reaching 25% at 100 mm. The analysis identified that the lower limit of thermal conductivity, particularly at a moisture content of 3%, aligns most closely with experimental results. The evaluation of various fire curves showed that the maximum temperature occurs under the HCM Modified Hydrocarbon curve, while the lowest is recorded under the ISO 834 curve. The temperature difference between the maximum and minimum results at a depth of 20 mm is approximately 25%. However, as the depth increases, the disparity in temperature results among the different fire curves diminishes. with a temperature difference of about 25% at 20 mm depth.

Discrepancies between single and double face exposures were significant, underscoring the importance of corner concrete cover in areas subjected to simultaneous exposure. Additionally, the capacity analysis indicated structural capacity reductions of approximately 20% for the 0-degree curve and up to 35% for the 180-degree curve due to fire exposure. These findings emphasize the need for advanced fire performance assessments in the design and evaluation of tunnel concrete structures to ensure safety and integrity under fire conditions.

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Authors

A. Emadi
Senior Associate Engineer, SMEC, Australia

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Senior Tunnel Design Coordinator, Gamuda Australia and Laing O'Rourke Consortium