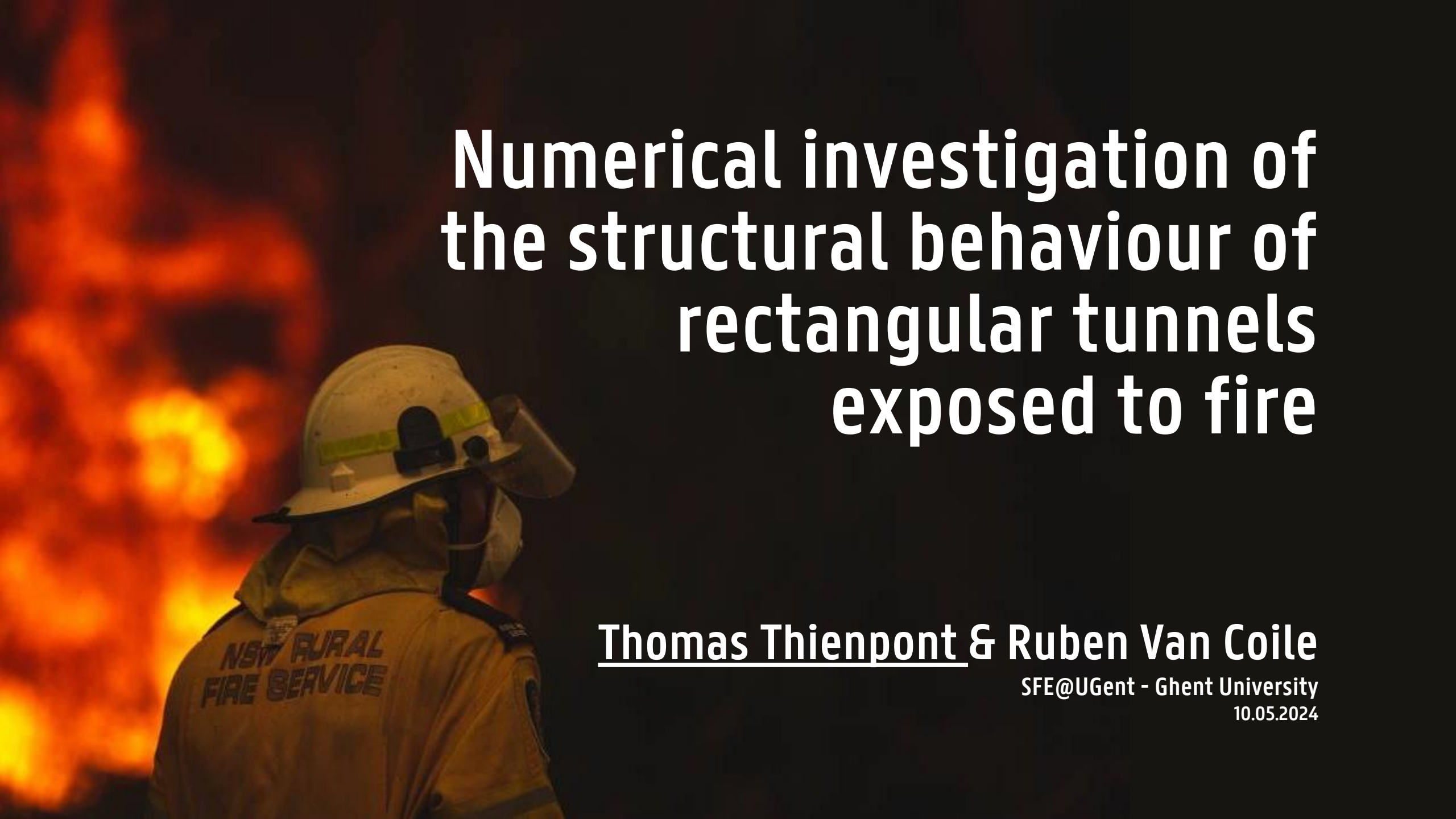


Numerical investigation of the structural behaviour of rectangular tunnels exposed to fire

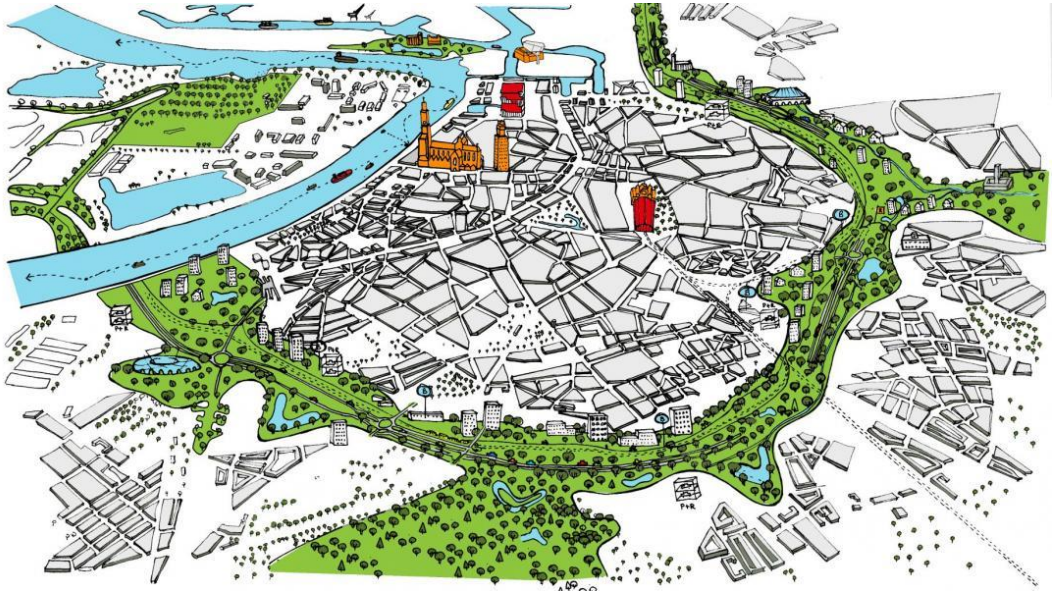
Thomas Thienpont & Ruben Van Coile

SFE@UGent - Ghent University

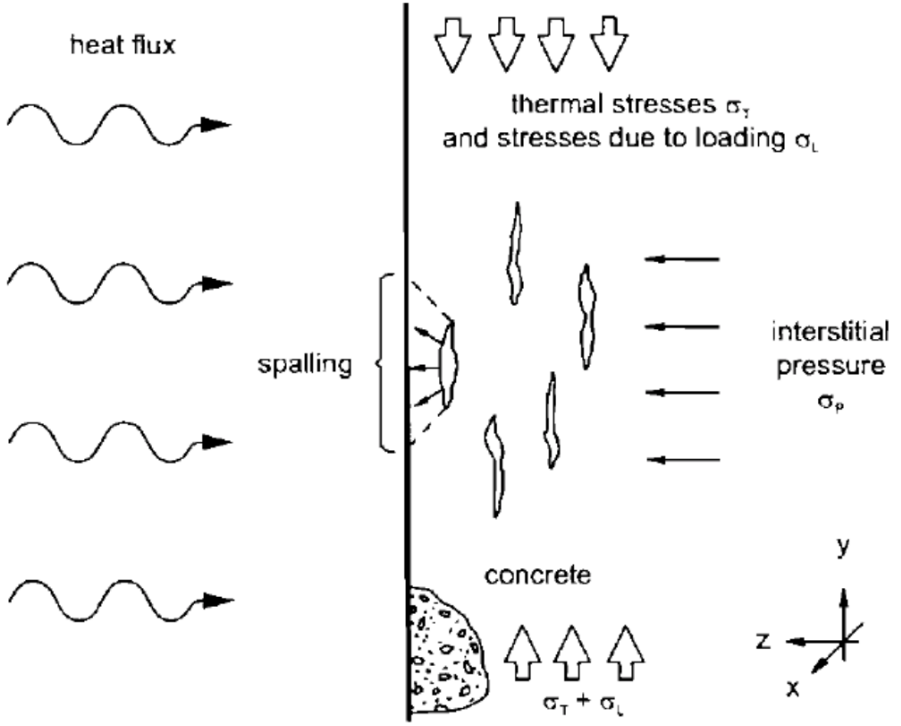
10.05.2024

Part 1
Introduction

Introduction



Introduction



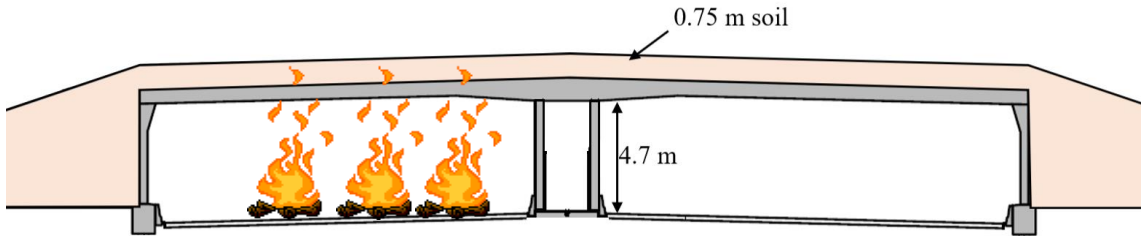
Maluk, C. (2017).

Jansson, R. (2013).

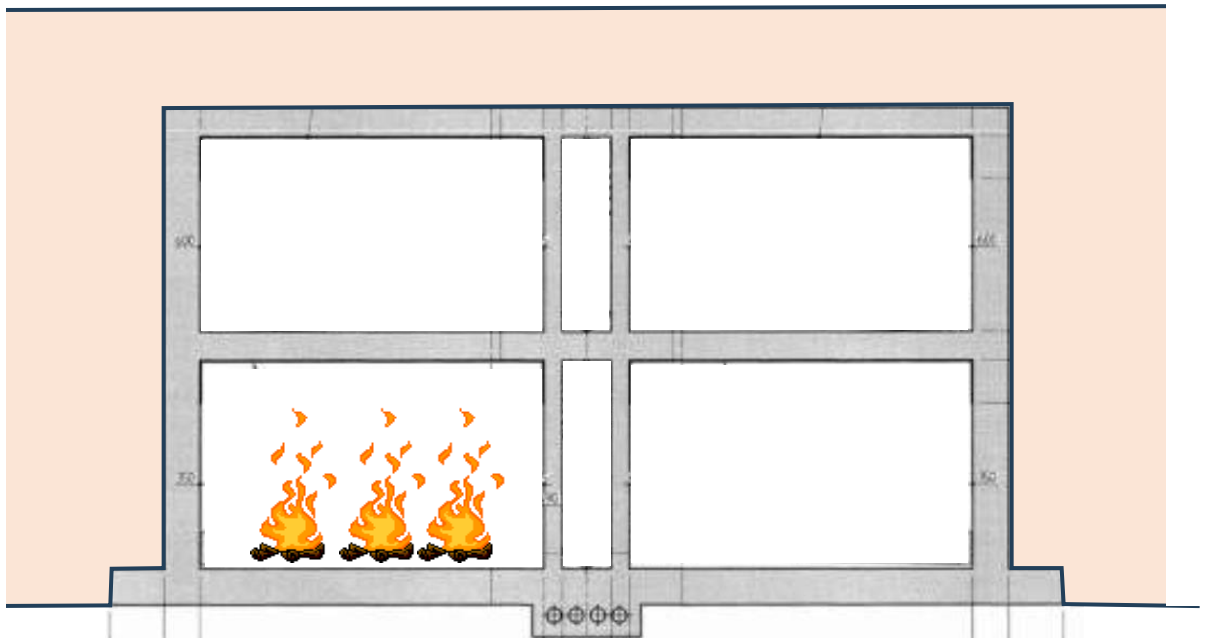
Introduction

How do shallow tunnels perform in case of fire, taking into account spalling?

CASE 1



CASE 2

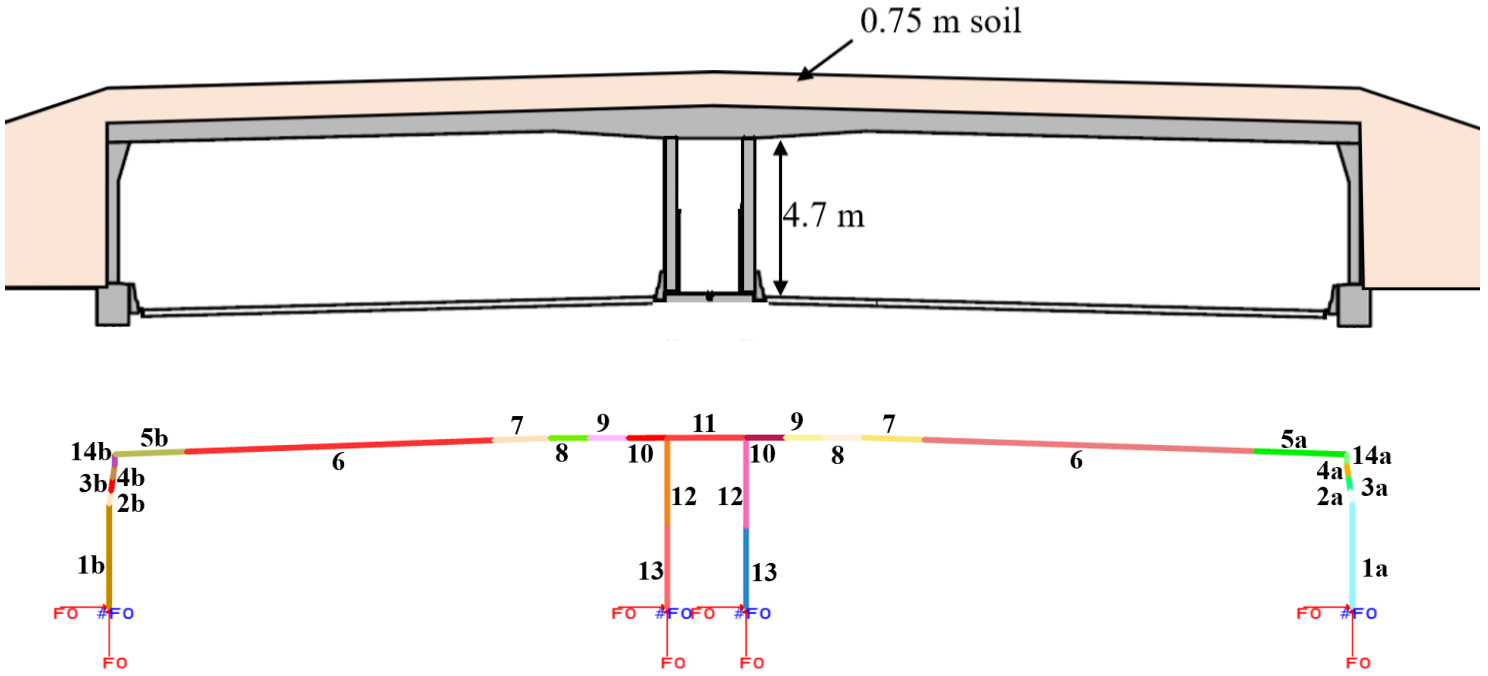


Part 2

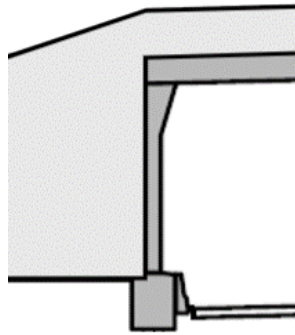
Model setup

Tunnel models

2D analysis

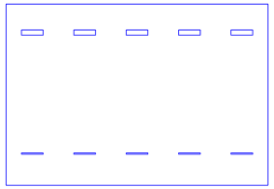
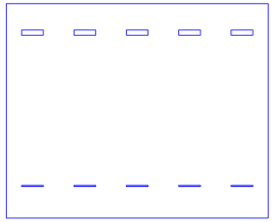
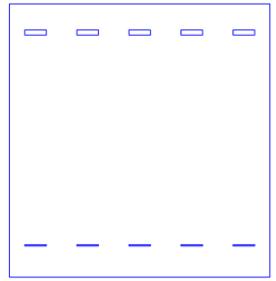


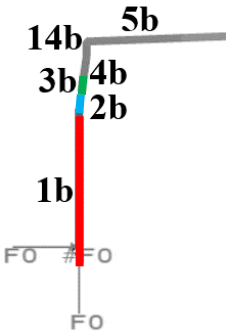
Tunnel model



2D analysis

- Divided into sections
- Lumped rebars

Section 1b	Section 2b	Section 3b
L = 500 mm B = 350 mm R1 = 494 mm² R2 = 1163.55 mm² C1 = 73.2 mm C2 = 61.1 mm	L = 500 mm B = 408.33 mm R1 = 494 mm² R2 = 2072.6 mm² C1 = 73.2 mm C2 = 61.1 mm	L = 500 mm B = 525 mm R1 = 494 mm² R2 = 2072.6 mm² C1 = 73.2 mm C2 = 61.1 mm
Cold  Hot	Cold  Hot	Cold  Hot



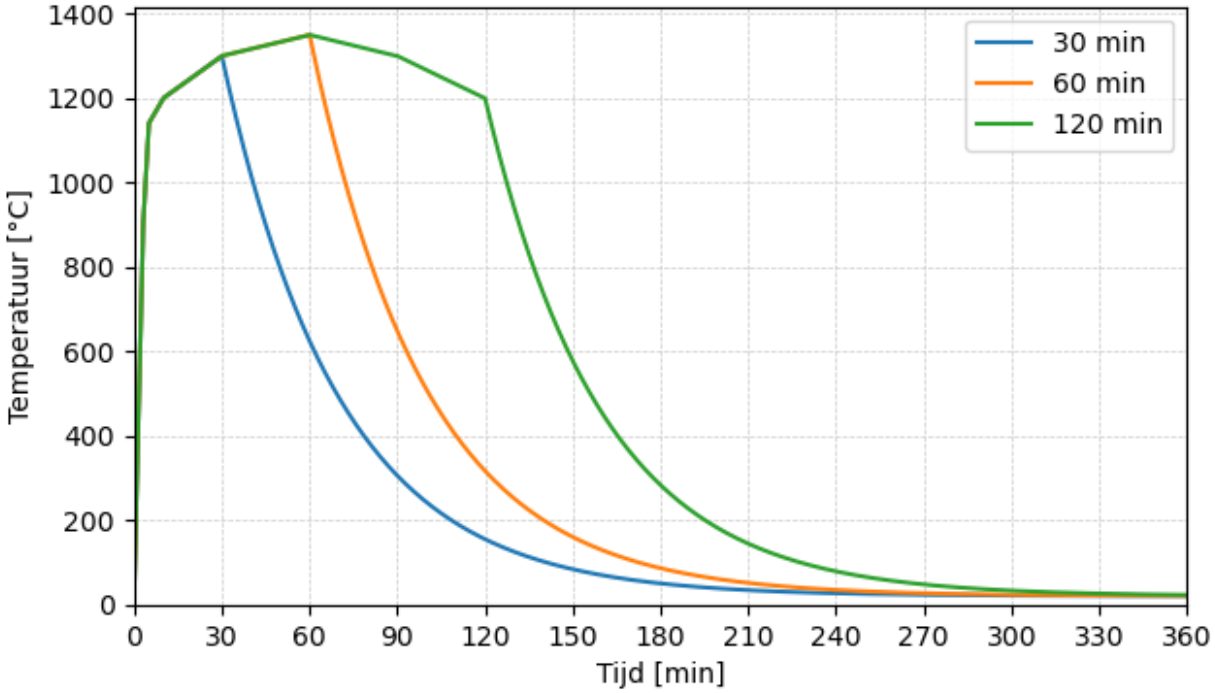
Heat transfer analysis

Fire regime

- RWS curve
- incl. exponential cooling

$$\theta_c - \theta_{ref} = (\theta_{RWS} - \theta_{ref})exp(-b(t - t_{RWS}))$$

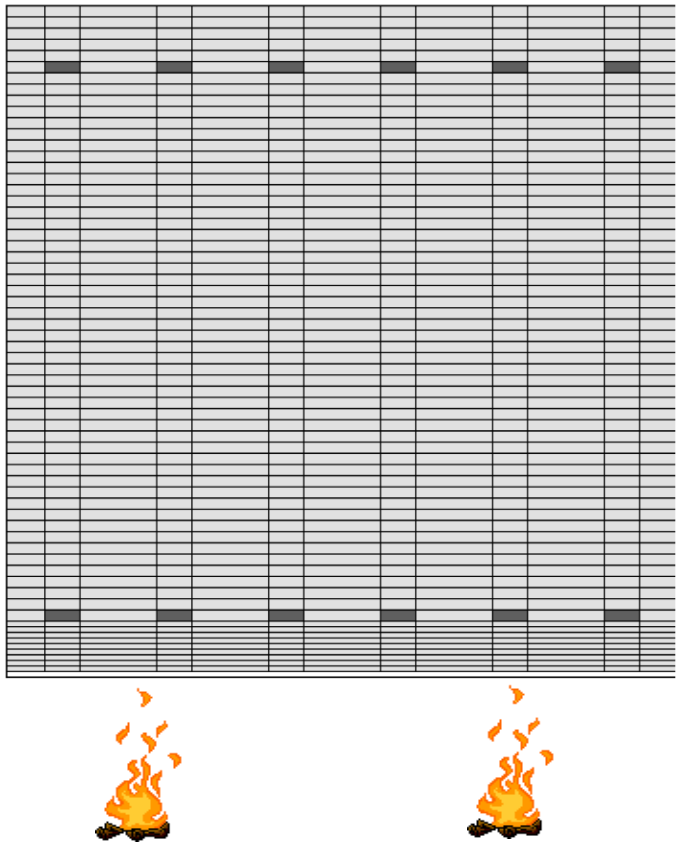
where:
θ_{ref} = reference temperature (20°C)
θ_{RWS} = temperature at the end of exposure to RWS curve
b = parameter for controlling rate of cooling (set to 0.025 min^{-1})
t = time (in minutes) since onset of cooling phase
t_{RWS} = time (in minutes) of since onset of RWS fire



Heat transfer analysis

Spalling model

- Constant spalling rate (e.g. 5 mm/min)
- Onset of spalling = 1 minute
  (deemed conservative)
- Spalling stops when rebar is reached,
  or at onset cooling phase

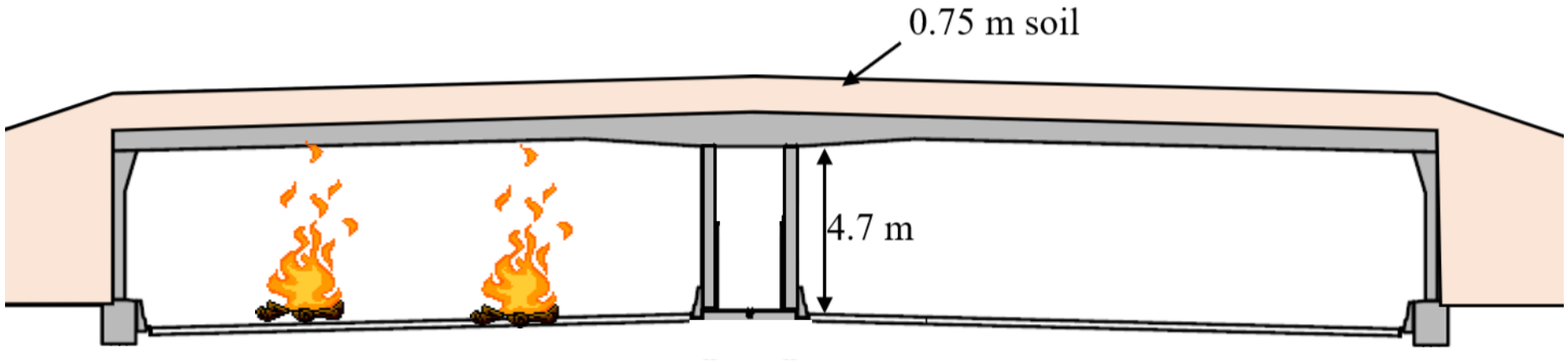


Part 3

Four-lane tunnel

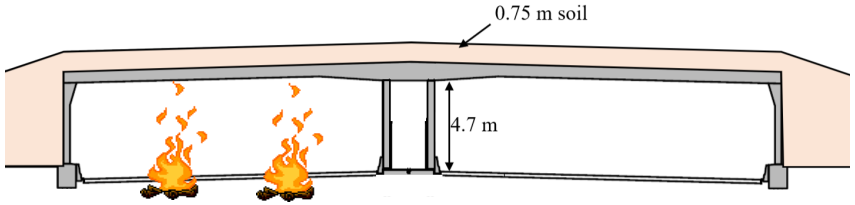
CASE 1

Four-lane tunnel

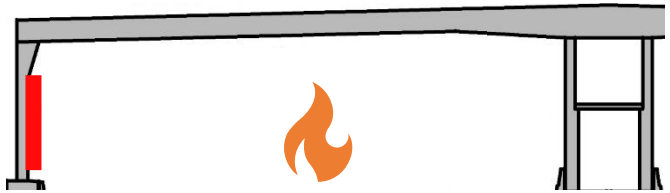


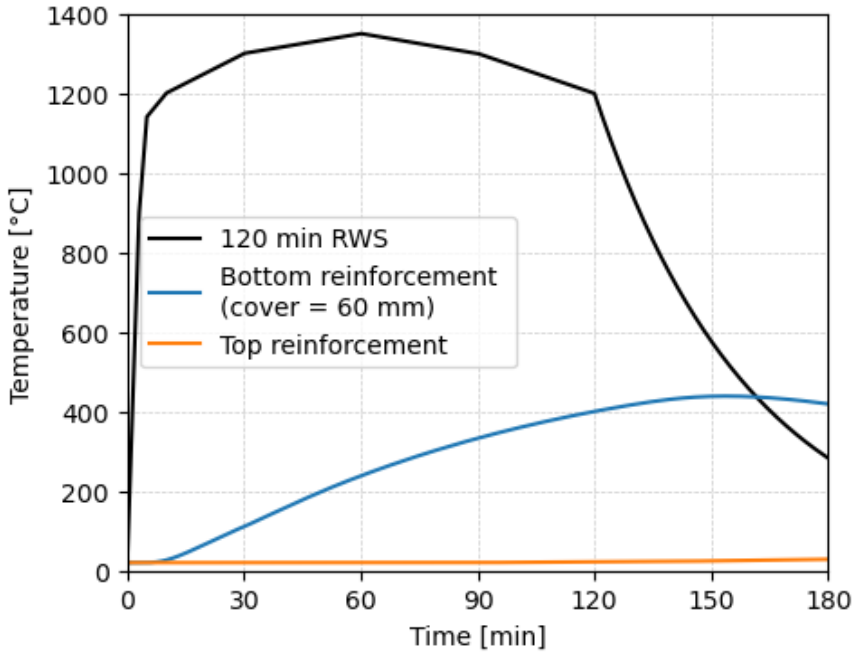
Heat transfer analysis

Four-lane tunnel, 120 min RWS, no spalling

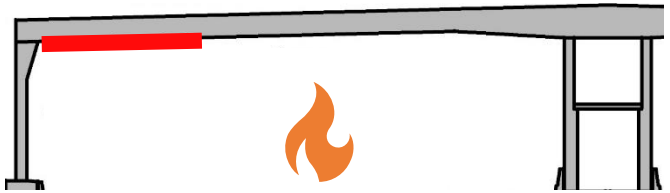


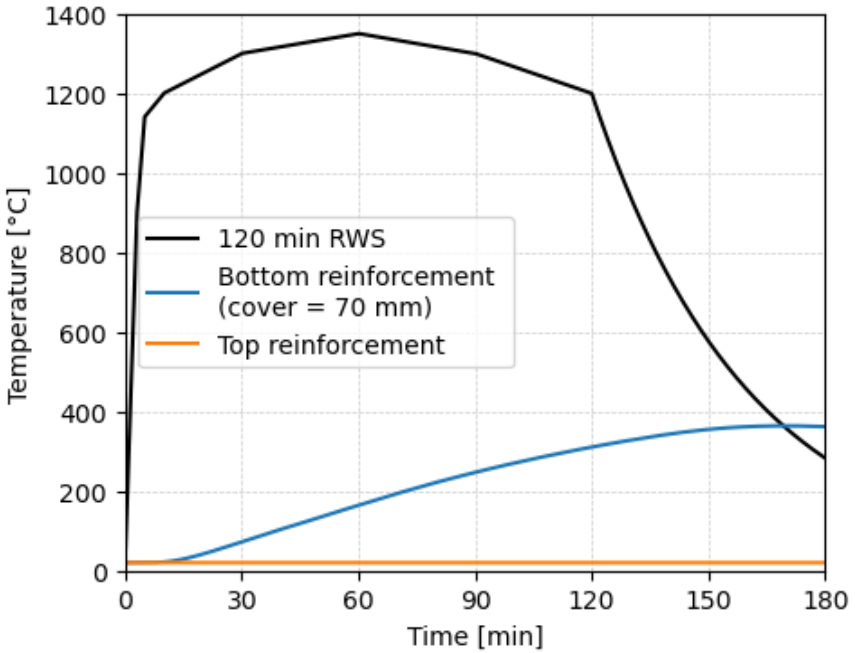
Outer wall





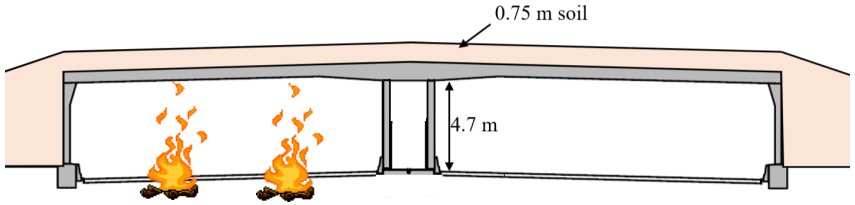
Roof slab



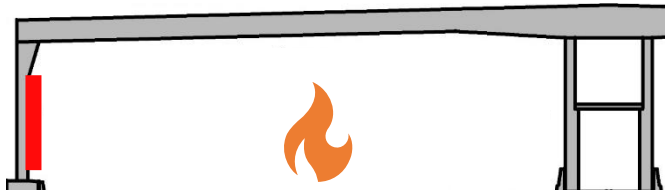


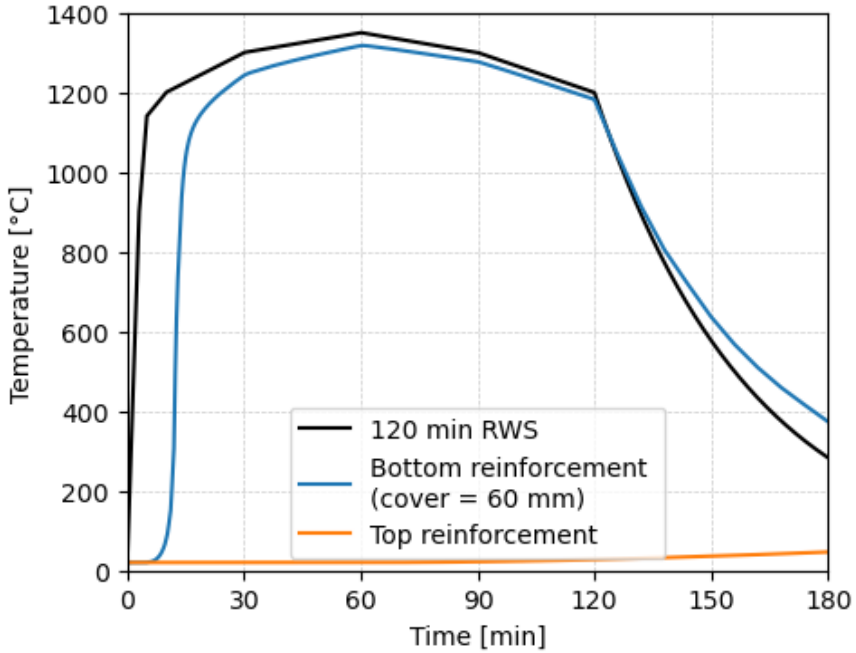
Heat transfer analysis

Four-lane tunnel, 120 min RWS, spalling 5 mm/min

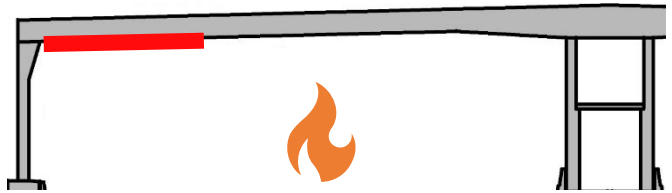


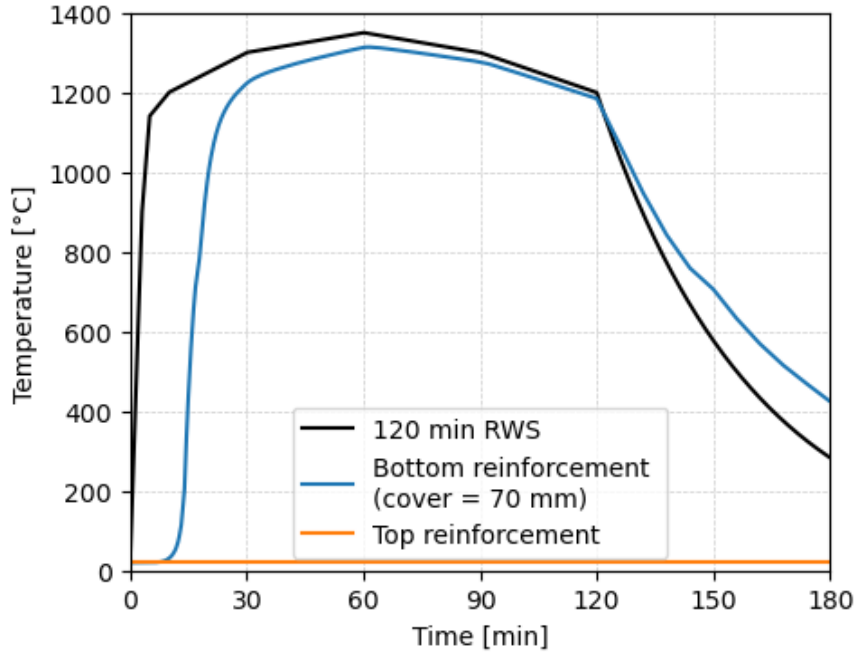
Outer wall





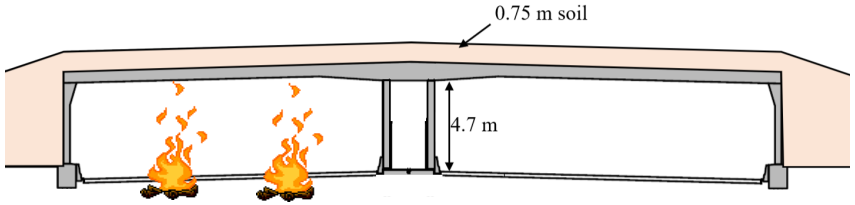
Roof slab

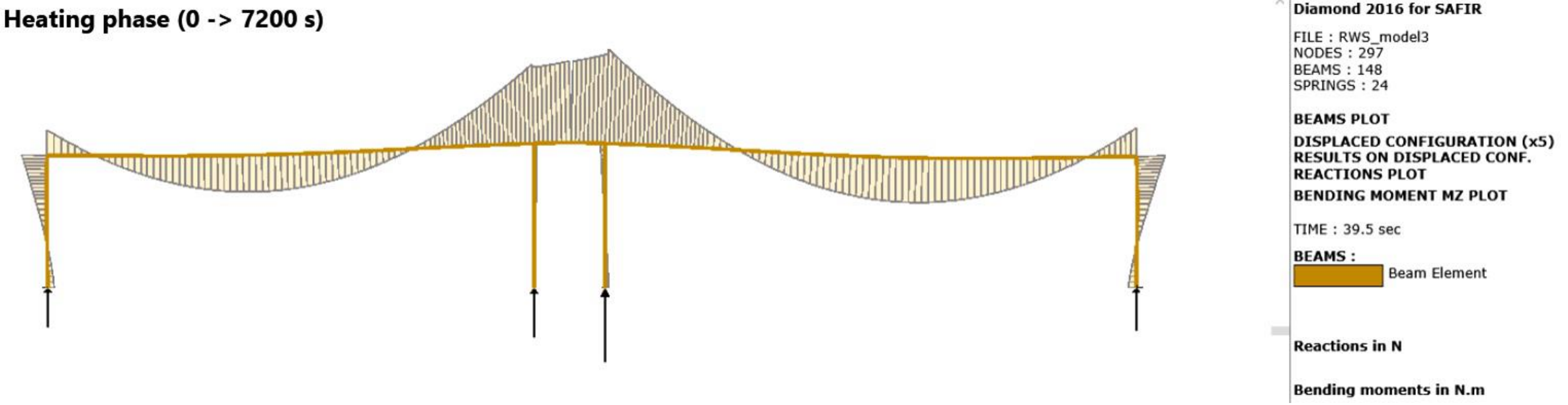




Mechanical analysis

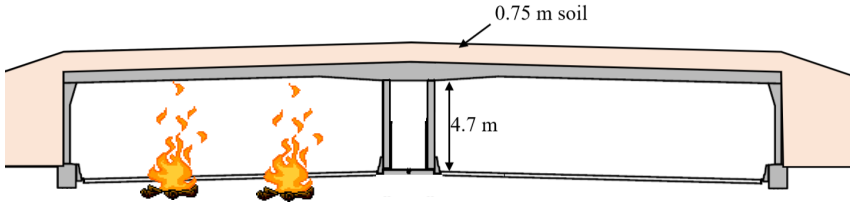
Four-lane tunnel, 120 min RWS, no spalling

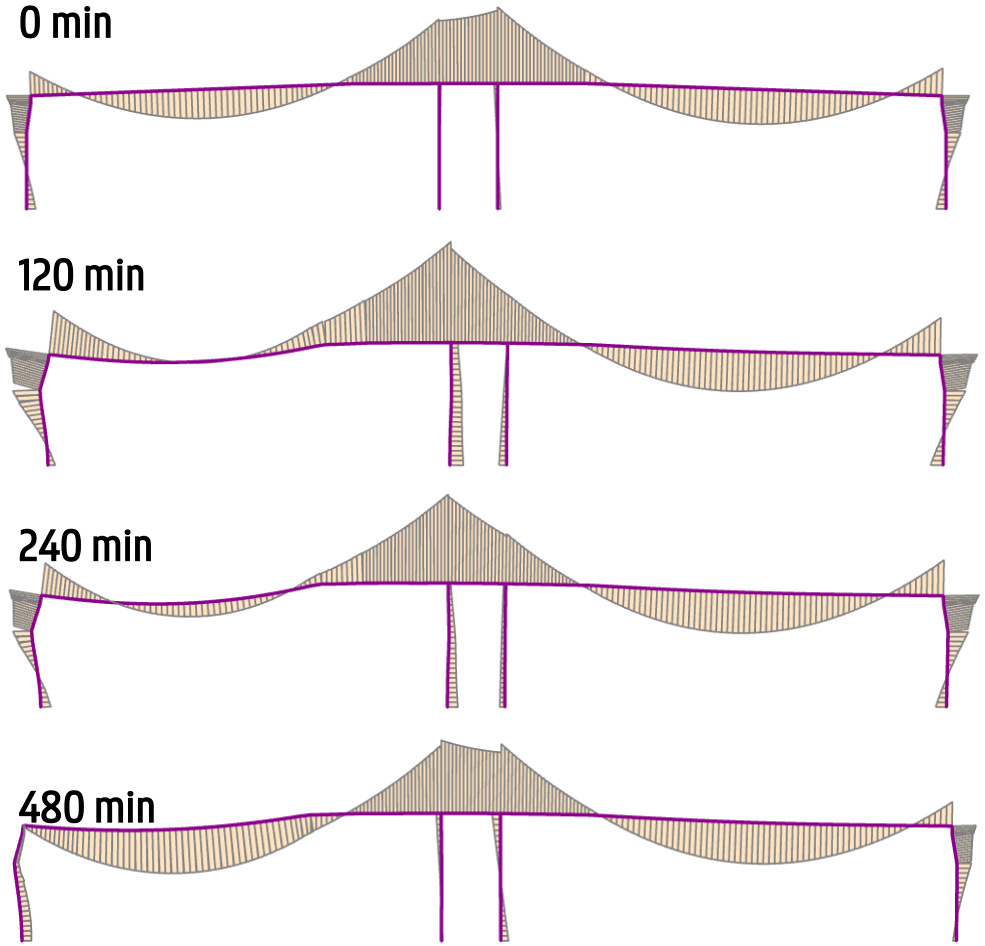


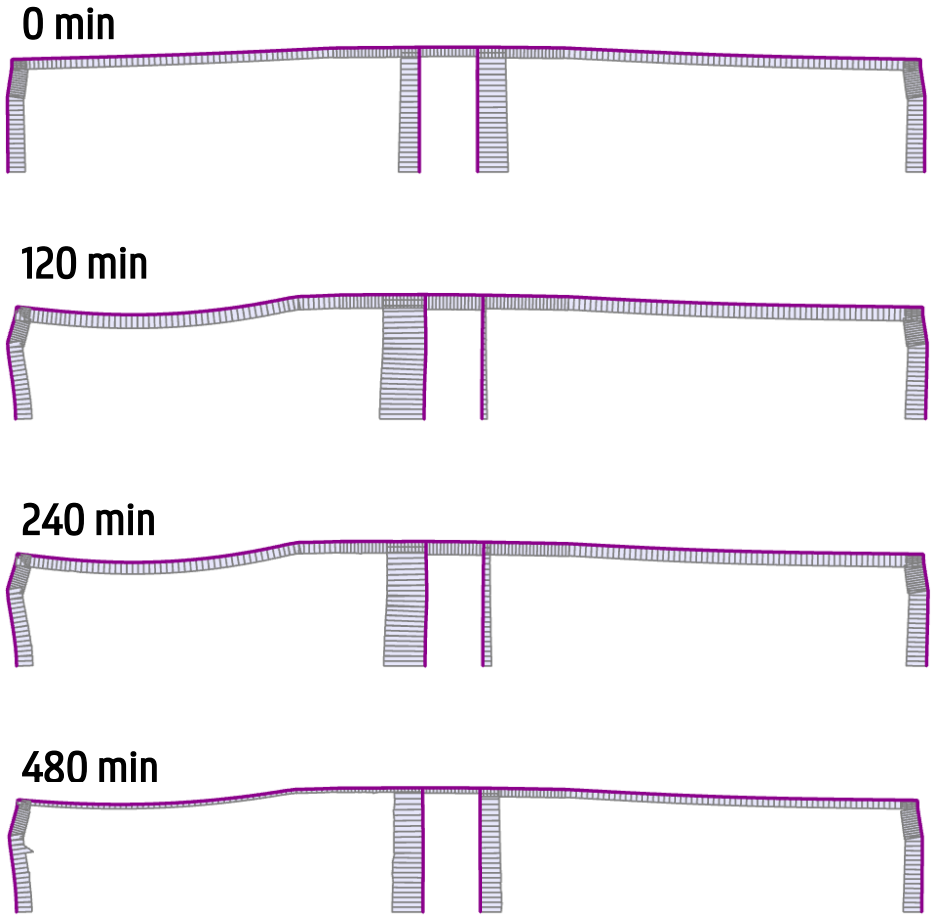


Mechanical analysis

Four-lane tunnel, 120 min RWS, no spalling

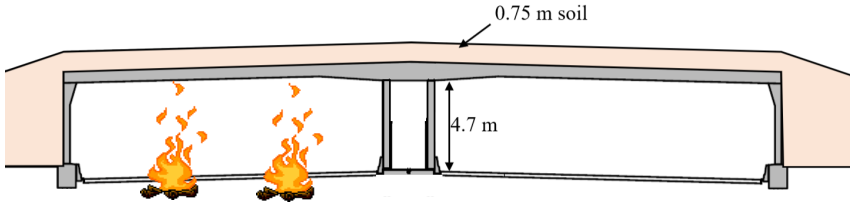


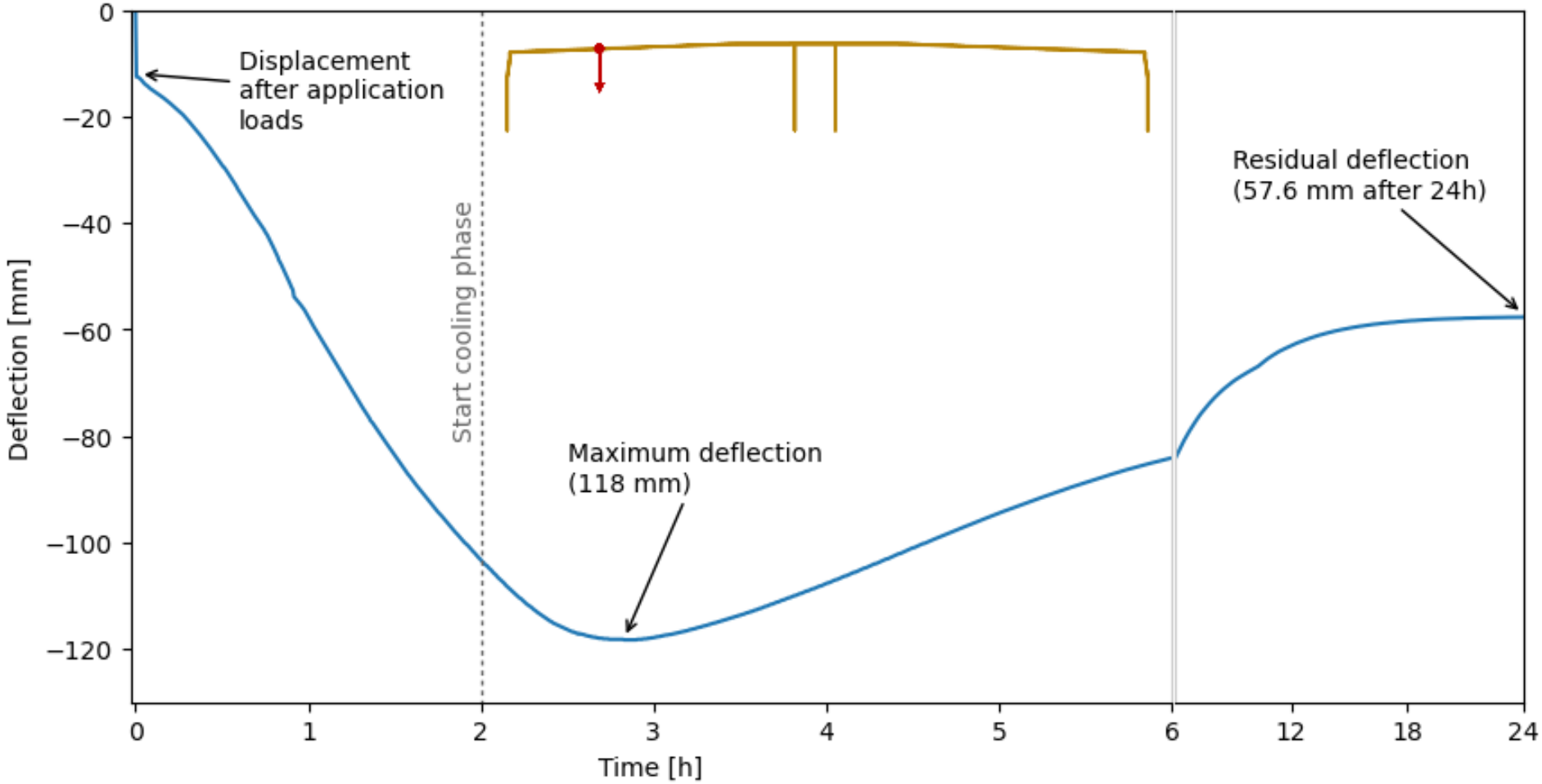




Mechanical analysis

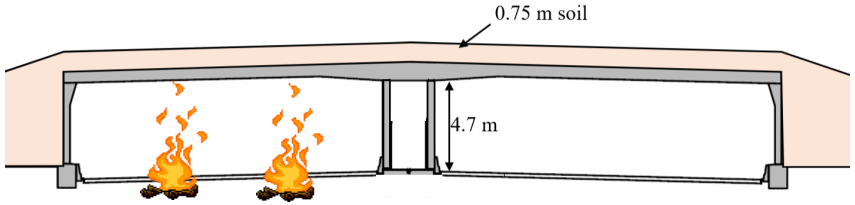
Four-lane tunnel, 120 min RWS, no spalling

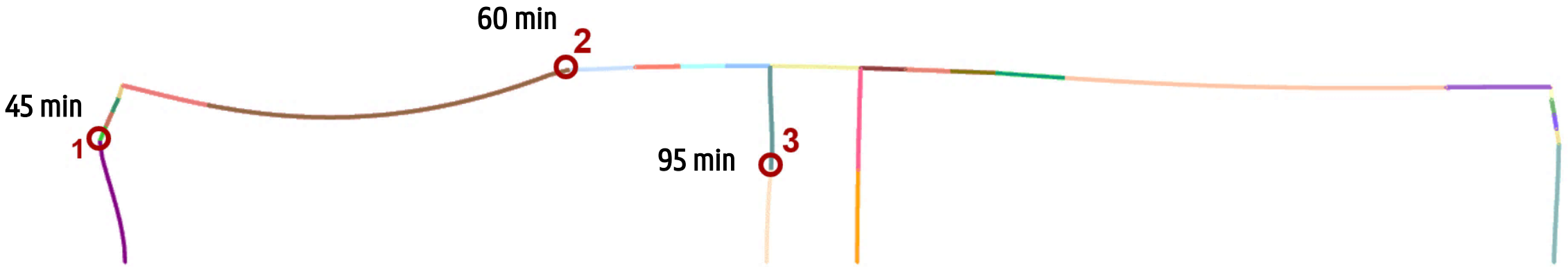




Mechanical analysis

Four-lane tunnel, 120 min RWS, no spalling



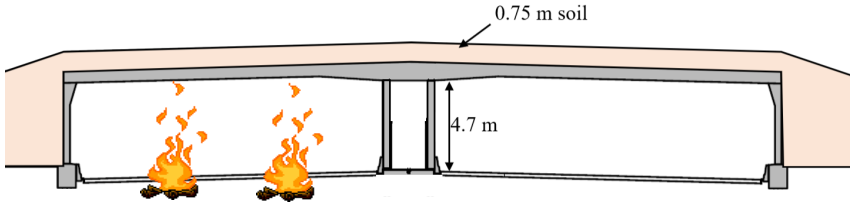


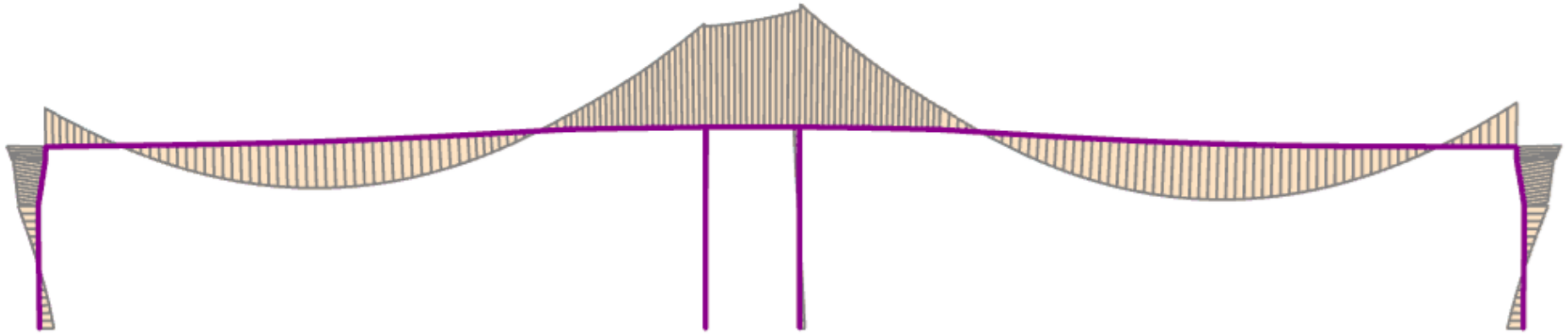
Summary

- Tunnel survives full duration of fire
- Moment line changes significantly during heating and cooling
- Large residual deformations
- Damage at unexposed sides
- Plastic hinges (locations where steel exceeds yield strain)

Mechanical analysis

4-lane tunnel, 120 min RWS, spalling 5 mm/min





Diamond 2016 for SAFIR

FILE : RWS_kethel_clamp
NODES : 301
BEAMS : 150

BEAMS PLOT
RESULTS ON DISPLACED CONF.
DISPLACED CONFIGURATION (x10)
BENDING MOMENT MZ PLOT

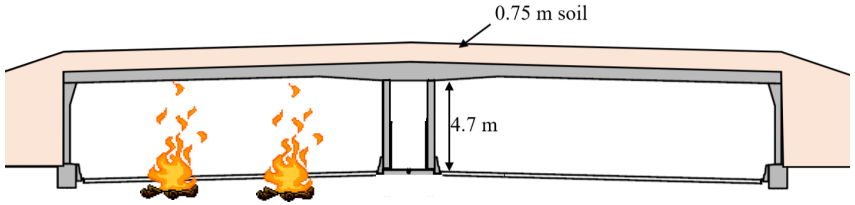
TIME : 20 sec

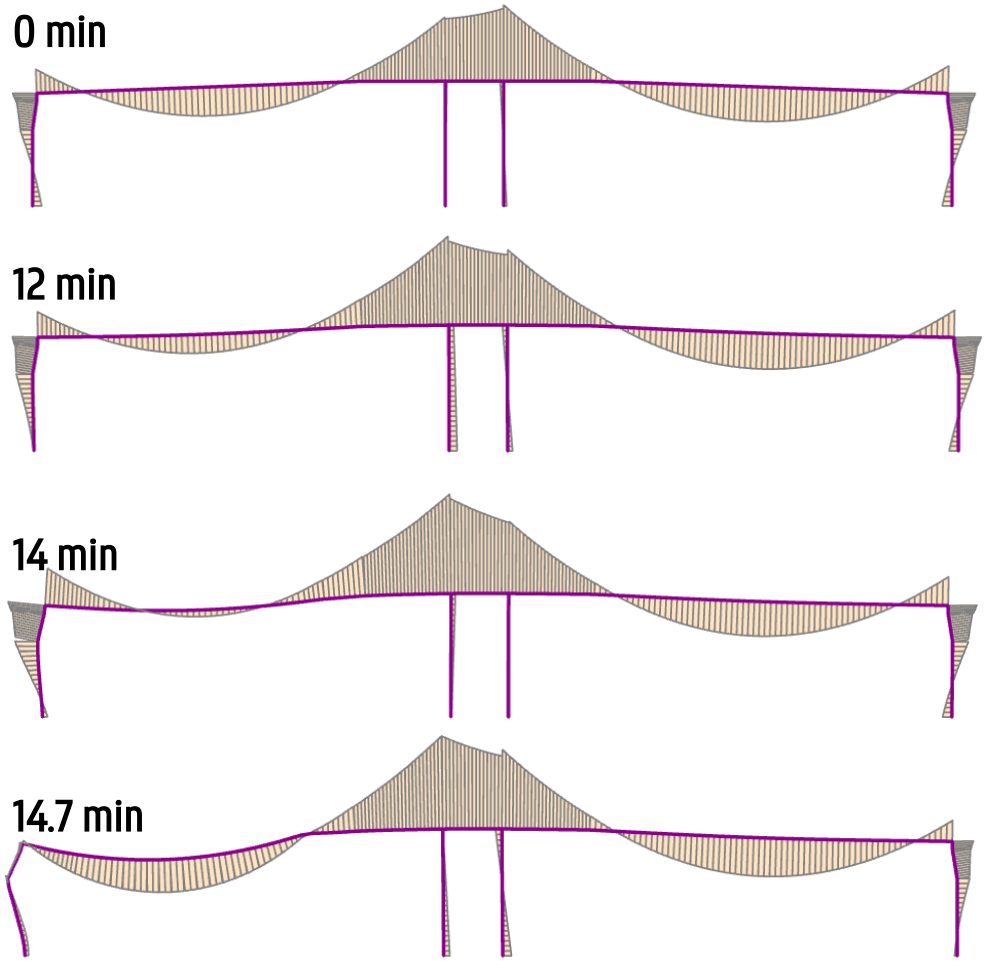
BEAMS :
Beam Element

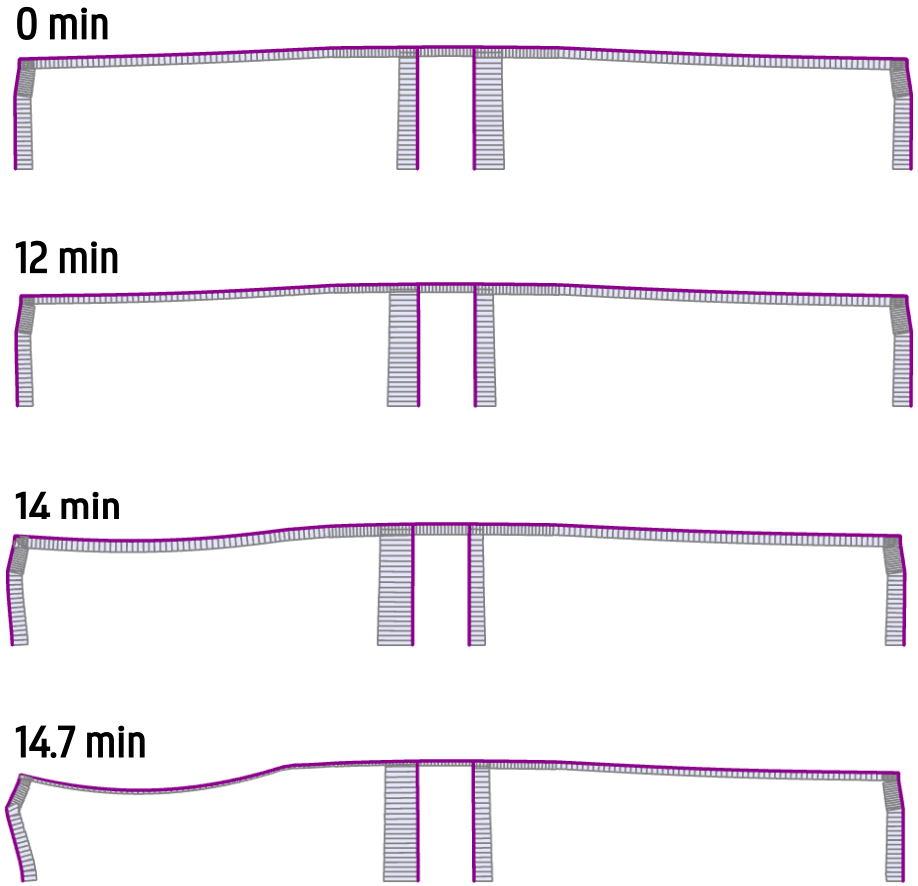
Bending moments in N.m

Mechanical analysis

4-lane tunnel, 120 min RWS, spalling 5 mm/min

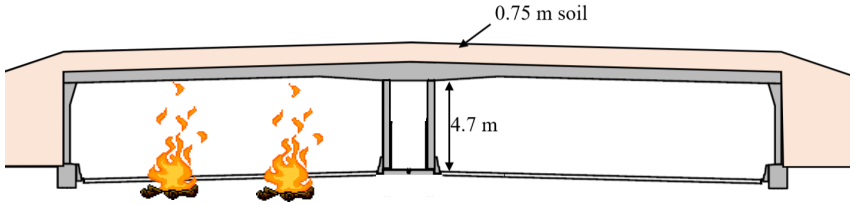


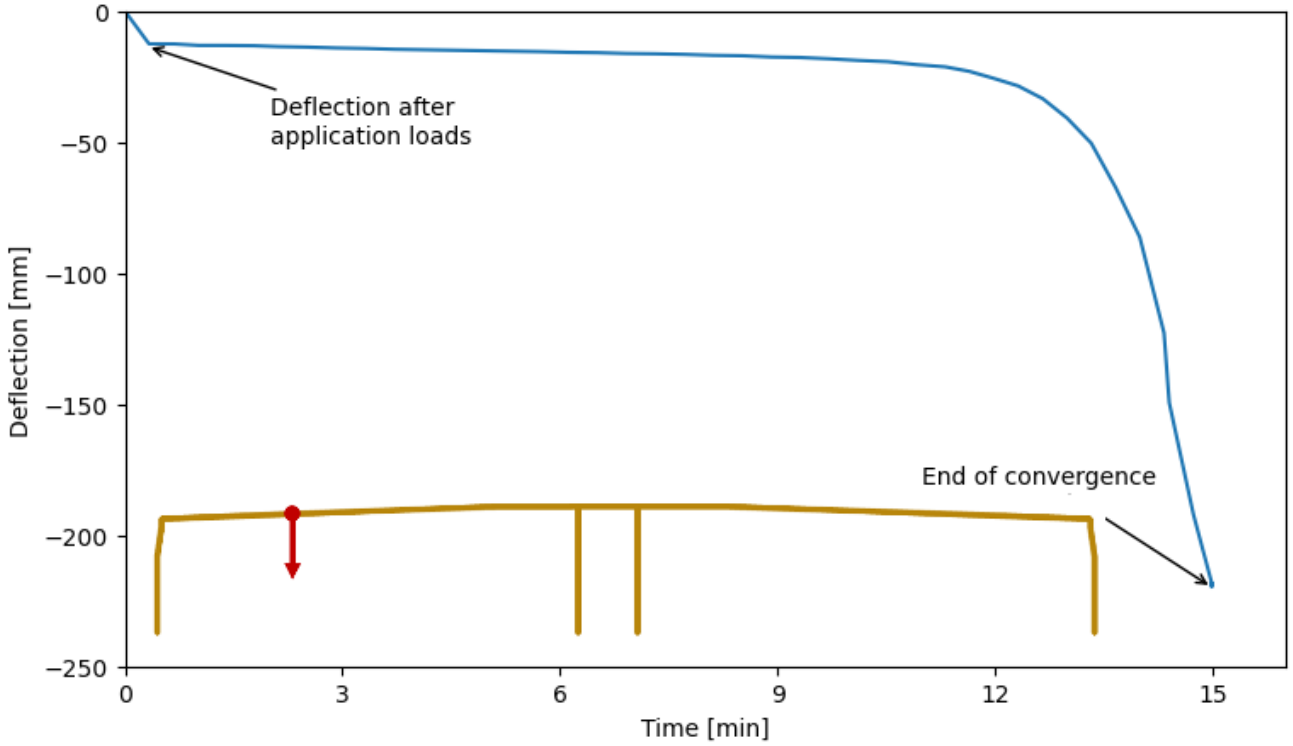




Mechanical analysis

4-lane tunnel, 120 min RWS, spalling 5 mm/min





Summary

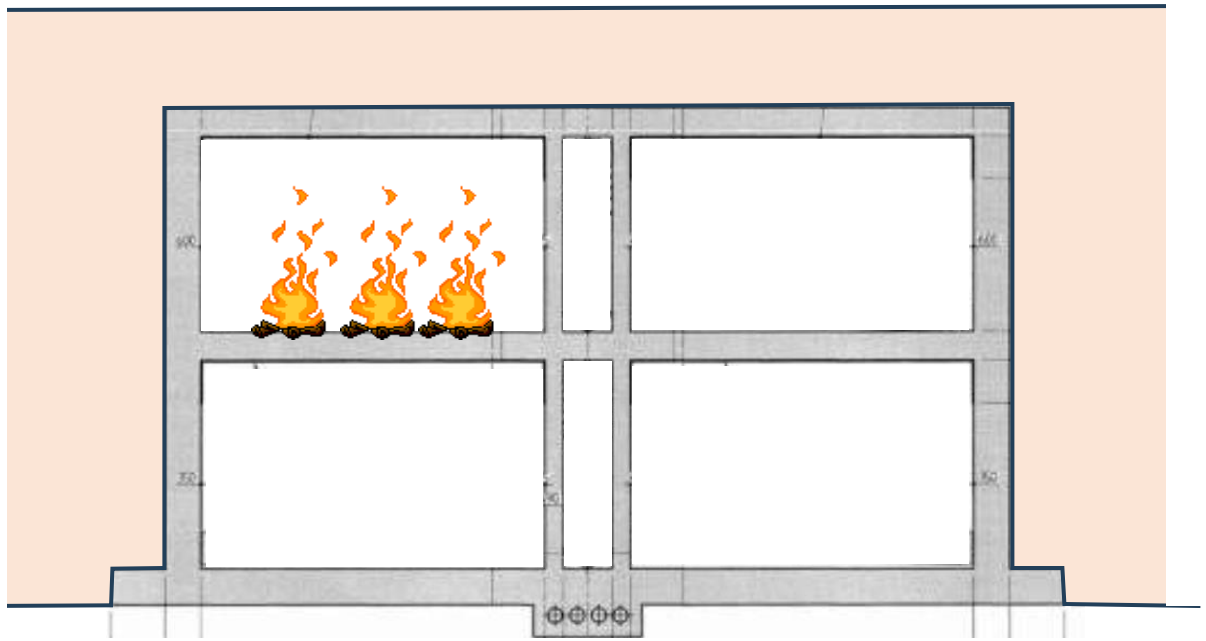
- Tunnel collapses after 15-20 minutes
- Collapse shortly after steel is directly exposed to fire

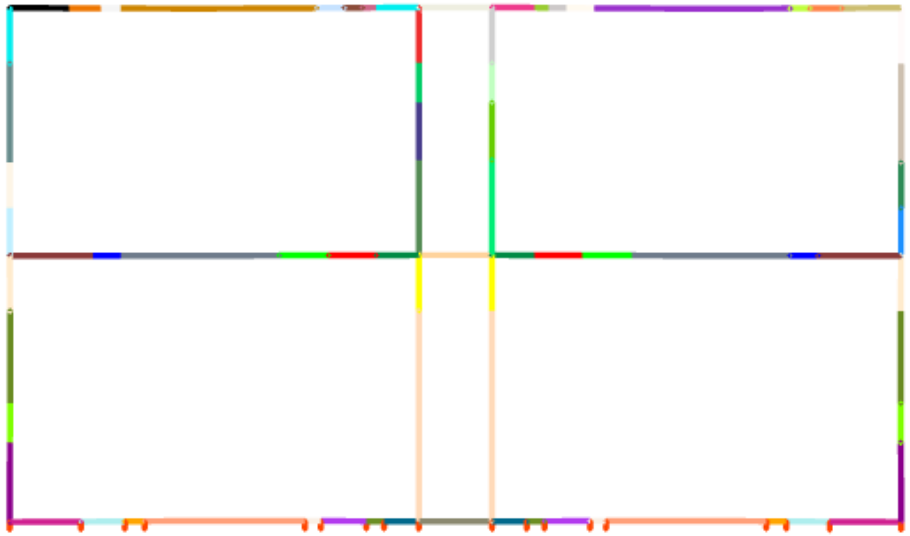
Part 4

Double layer tunnel

CASE 2

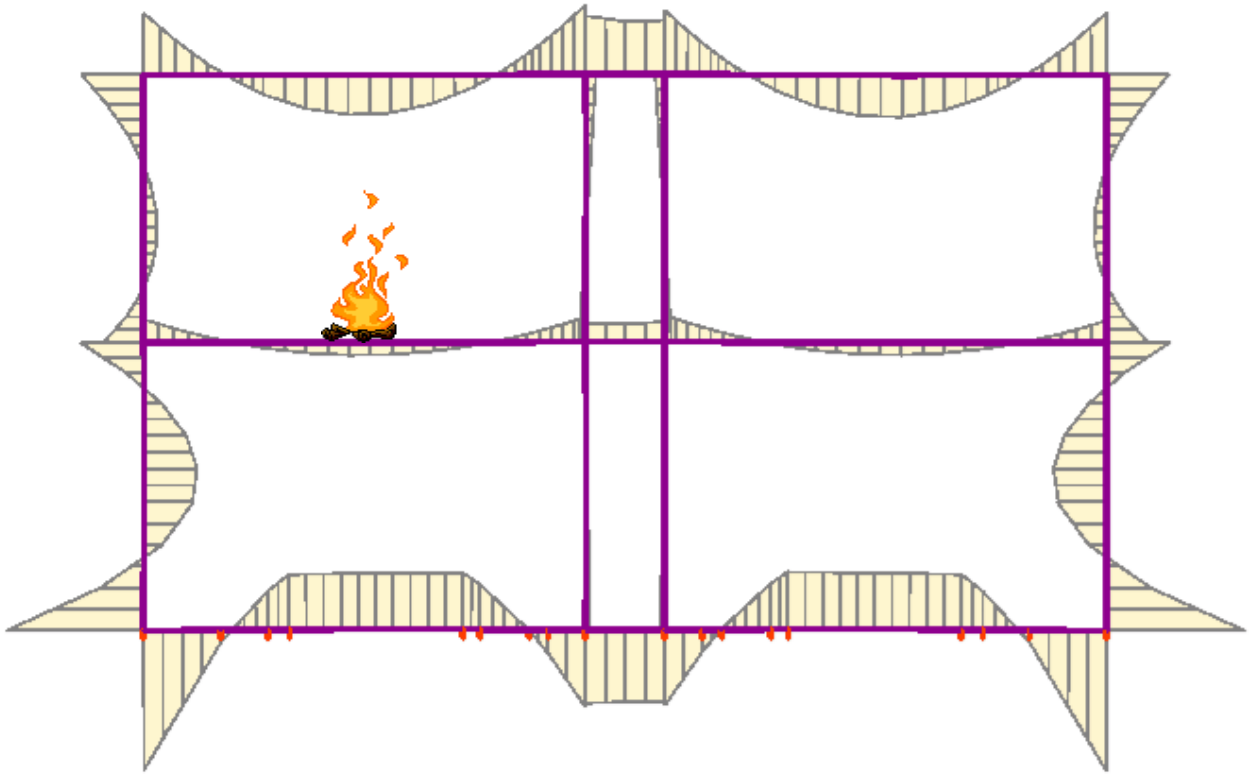
Double layer tunnel





CASE 2

Double layer tunnel, 120 min RWS, no spalling



Diamond 2016 for SAFIR

FILE : KWA
NODES : 315
BEAMS : 160
SPRINGS : 18

BEAMS PLOT
SPRINGS PLOT
DISPLACED CONFIGURATION (x10)
RESULTS ON DISPLACED CONF.
BENDING MOMENT MZ PLOT

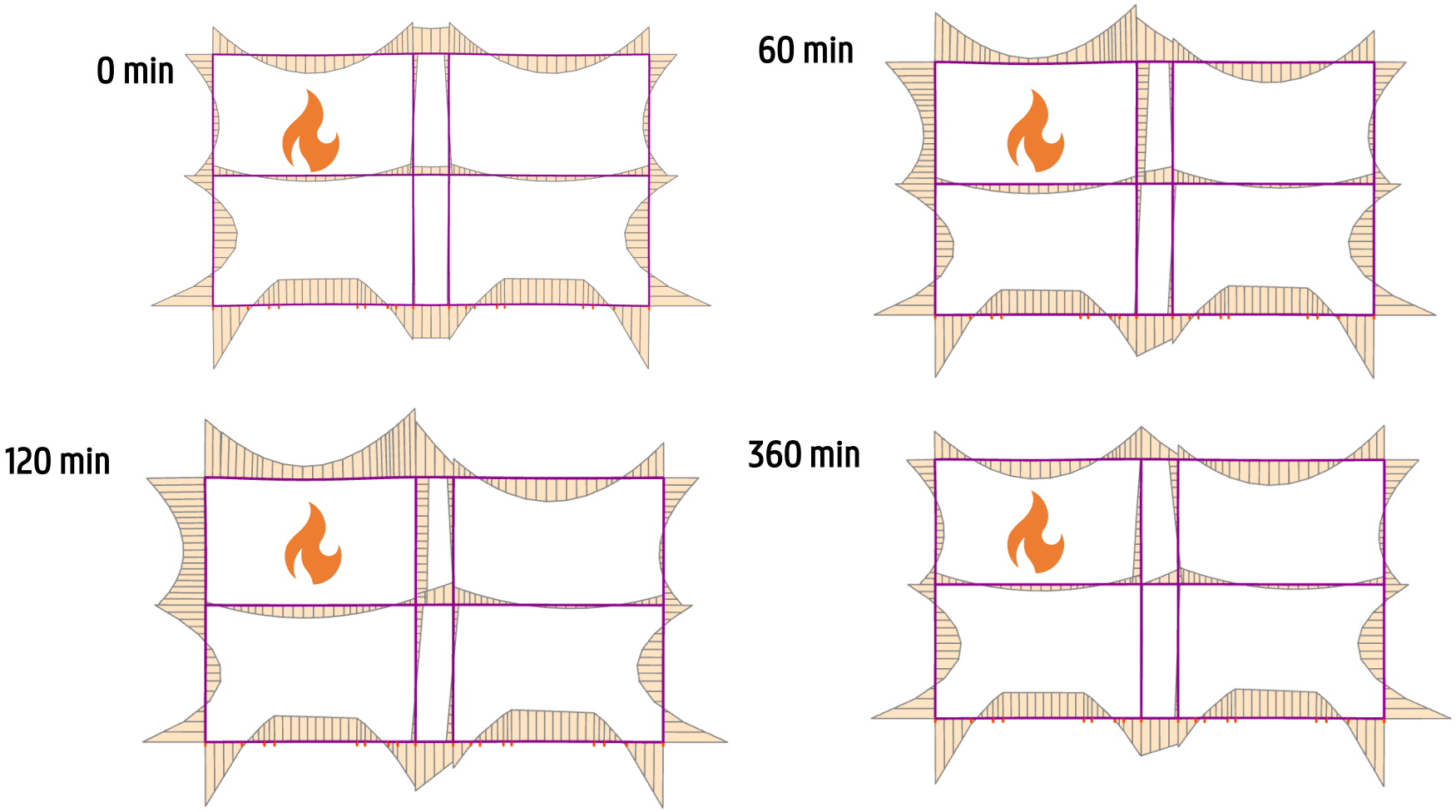
TIME : 20 sec

BEAMS :
Beam Element
SPRINGS :
Spring Element

Bending moments in N.m

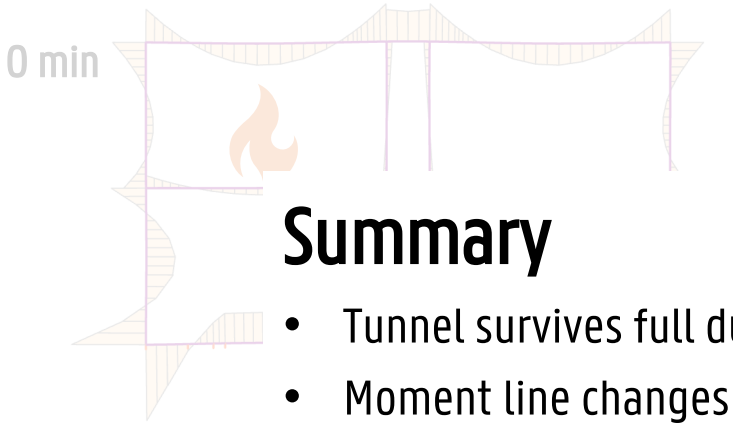
CASE 2

Double layer tunnel, 120 min RWS, no spalling



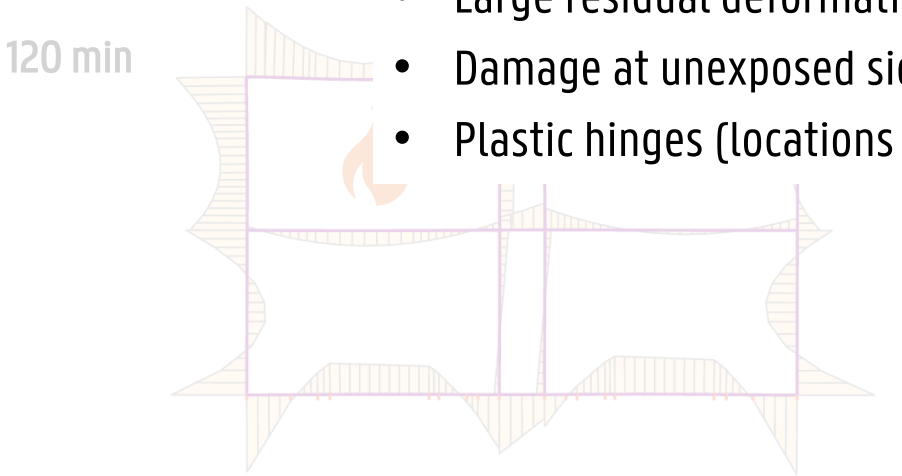
CASE 2

Double layer tunnel, 120 min RWS, no palling



Summary

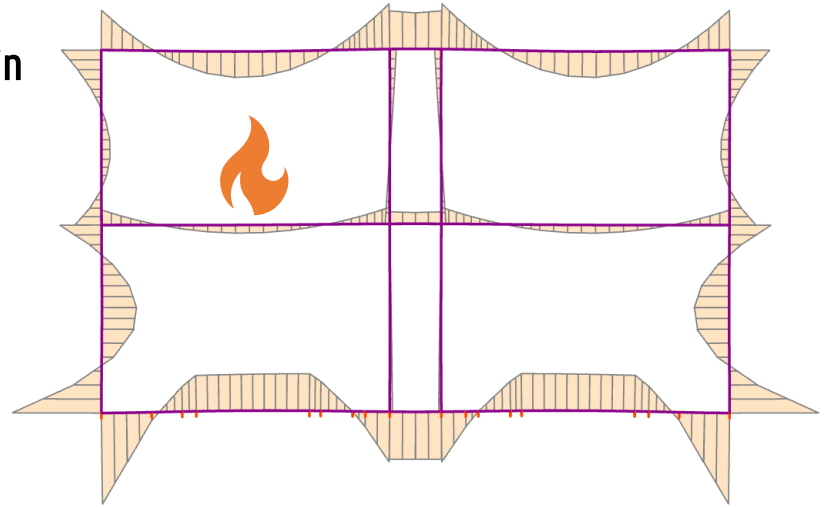
- Tunnel survives full duration of fire
- Moment line changes significantly during heating and cooling
- Large residual deformations
- Damage at unexposed sides
- Plastic hinges (locations where steel exceeds yield strain



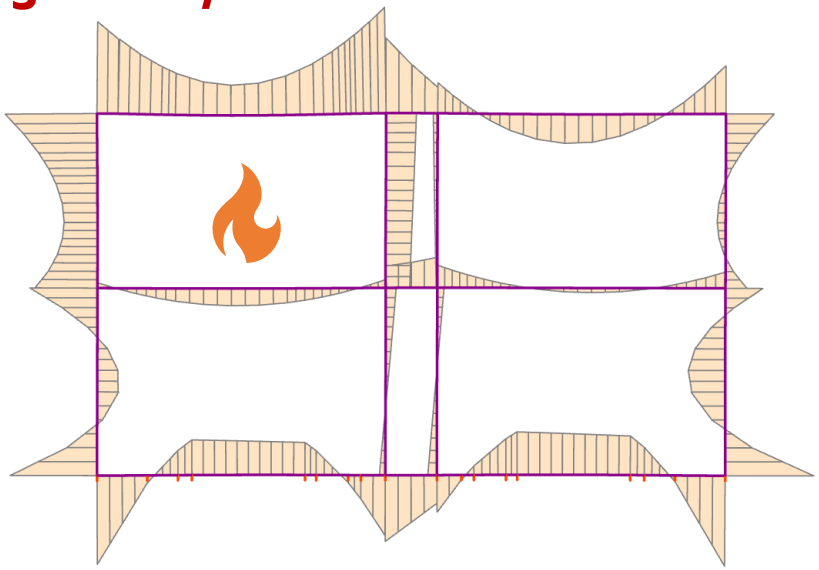
CASE 2

Double layer tunnel, 120 min RWS, spalling 5 mm/min

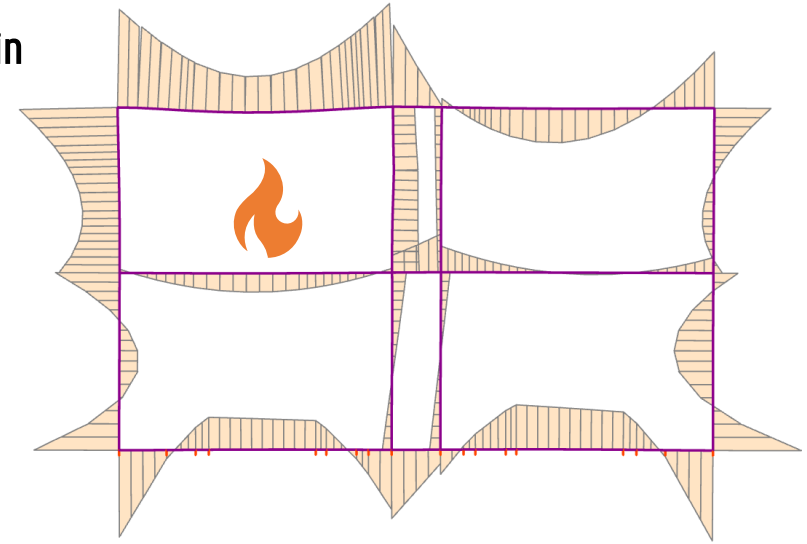
0 min



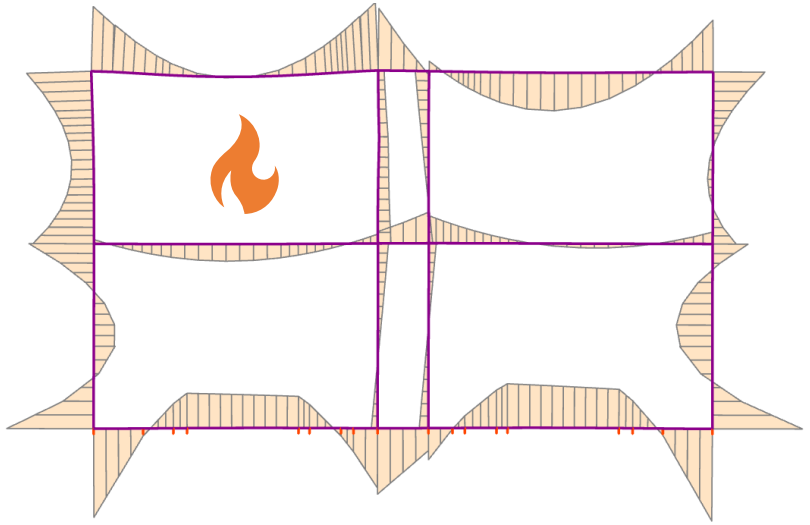
60 min



120 min

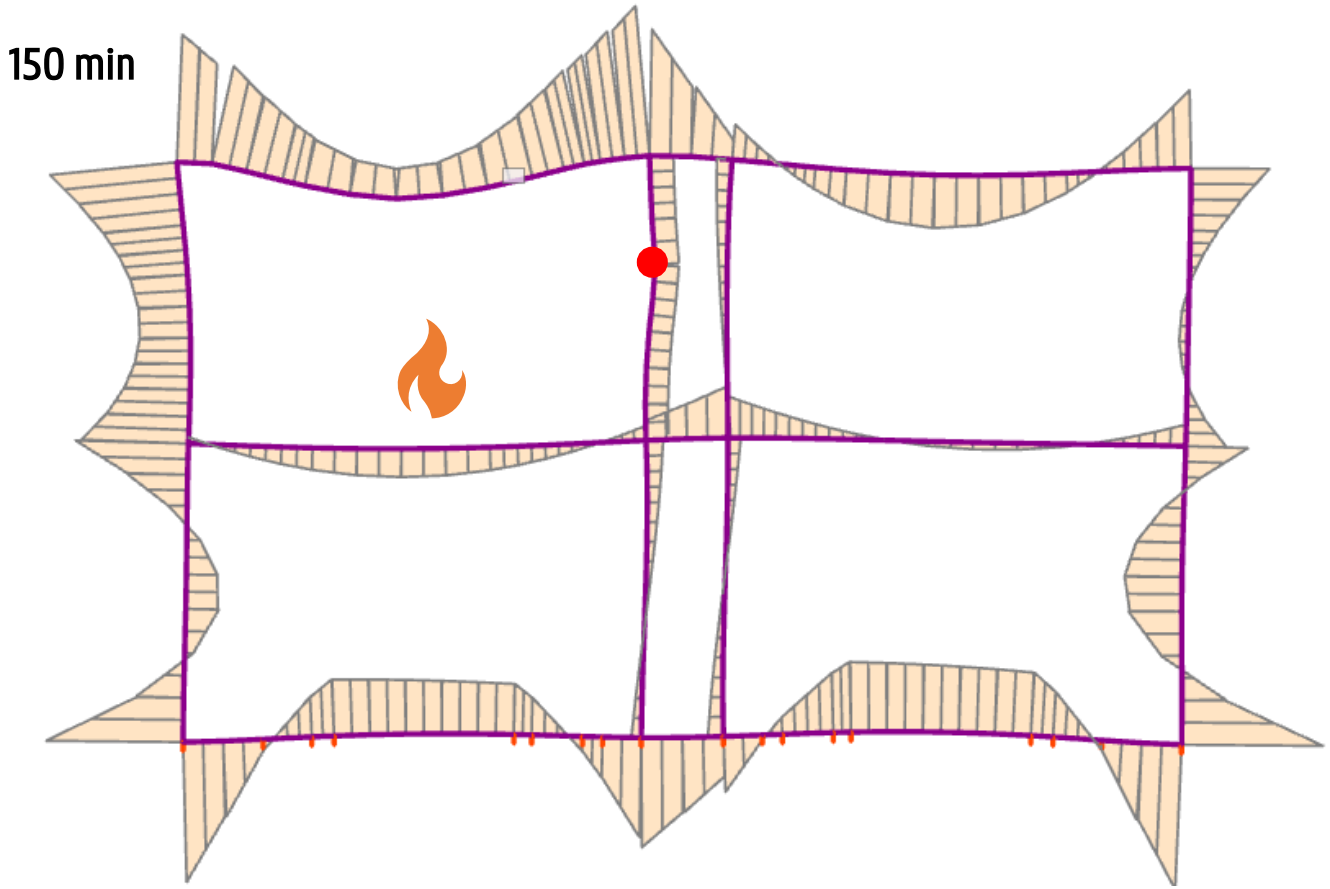


360 min



CASE 2

Double layer tunnel, 120 min RWS, spalling 5 mm/min



Summary

- Similar to case without spalling
- Larger deflections
- Plastic hinge in the cooling phase

Part 5
Conclusions

Conclusions

2D Finite Element Model

- Versatile and quick model evaluations
- Accounts for complex stress state and irreversible non-linear material properties
- Assessment of damage and residual deformation after fire (in case of no collapse)

CASE 1: four-lane tunnel

- No spalling: no collapse, damage unexposed side (plastic hinges) and permanent deflections
- Spalling: collapse fire exposed tube

CASE 2: Double layer

- No spalling: no collapse, limited deflections
- Spalling: no collapse, more severe deflections and plastic hinges

Key messages and discussion points

- Structural fire performance of concrete tunnels is **severely affected by spalling**
- Behaviour depends on tunnel geometry
- **Significant post-fire damage**, also in cases without spalling,
- **Cooling phase** behaviour important

- How to link fire scenario and spalling assumptions?
- How to deal with **shear**?

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10.05.2024

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