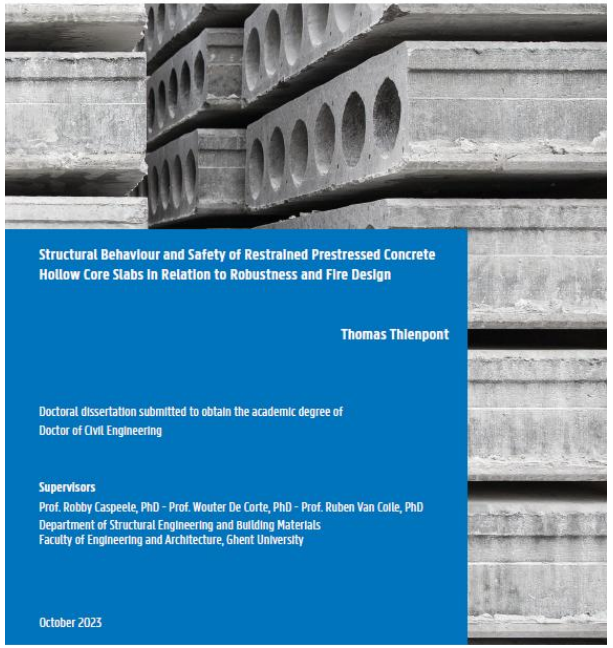
Post-fire damage quantification of concrete cut-and-cover tunnels

Thomas Thienpont
Ghent University
26.09.2025

About me

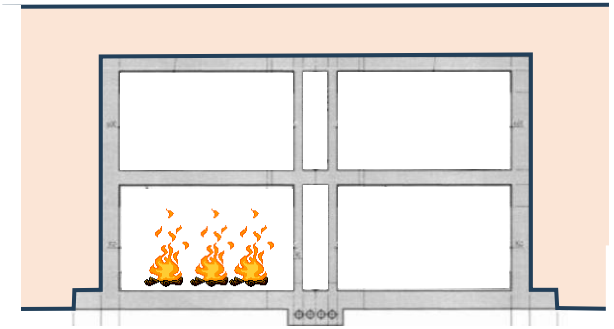
PhD (2018 - 2023)

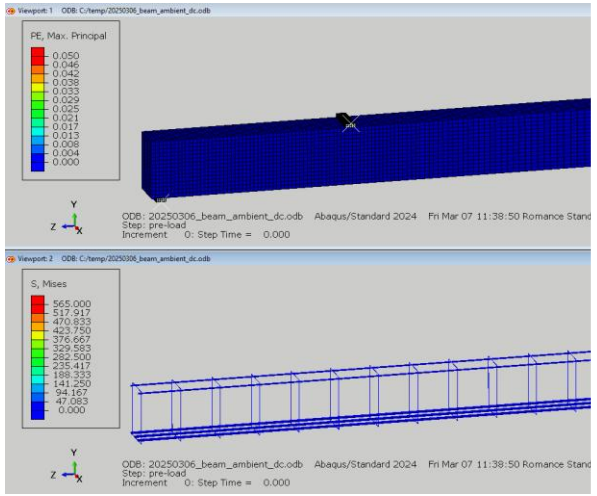
FACULTY OF ENGINEERING AND ARCHITECTURE



GHENT UNIVERSITY

Postdoc (2023 - 2025)





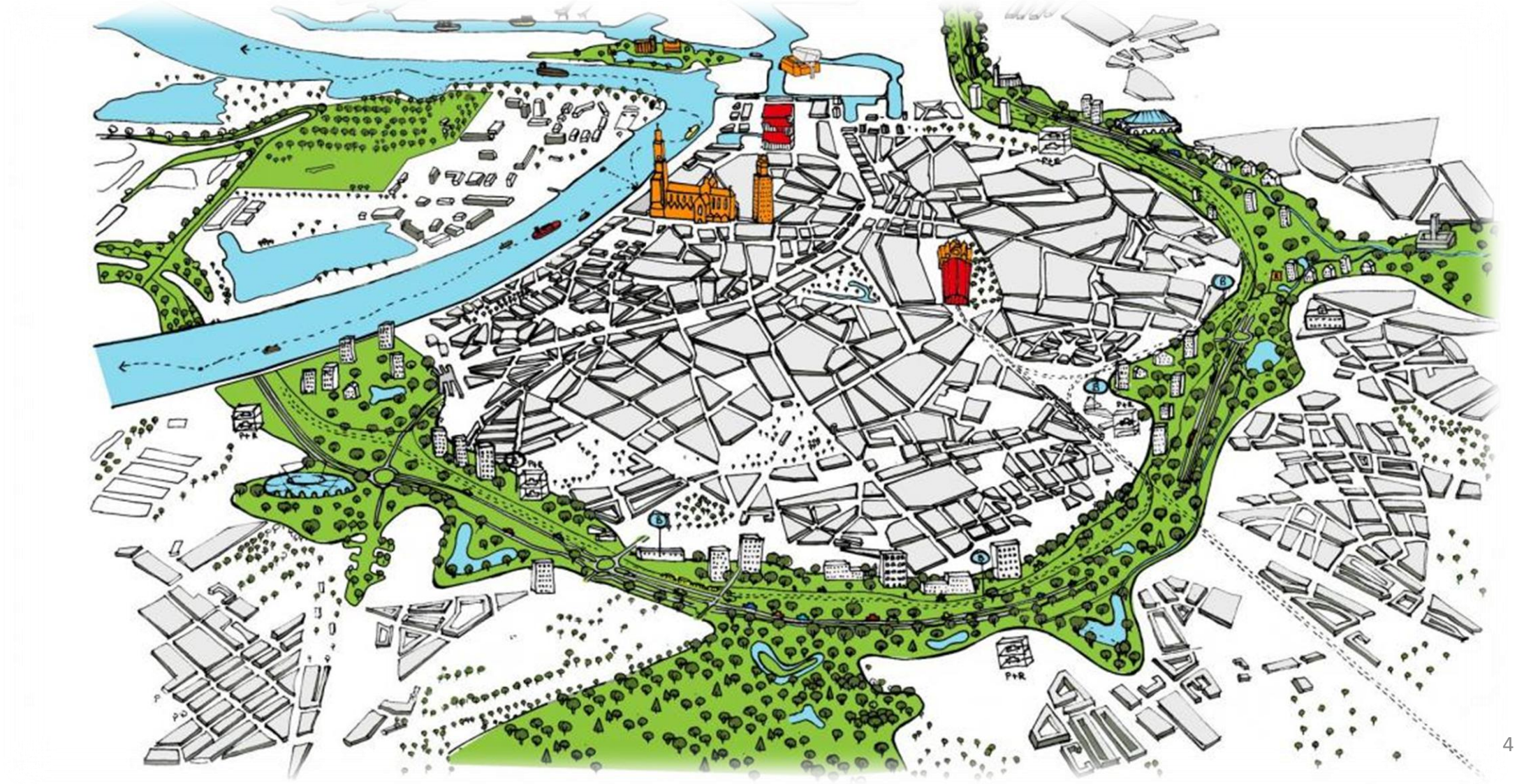
Pyro (2026 - ...)

PYRO Engineering

UNIVERSITEIT GENT SPIN-OFF

Introduction

Introduction



Introduction

BrandVeilig.com

Archief Magazine Nieuwsbrief Abonnement afsluiten Adverteren Contact

HOME ARTIKELEN VIDEO'S OPLEIDINGEN COLUMNS WEBINARS VACATURES PARTNERS Zoeken

NIEUWS

Beton vier wegtunnels mogelijk minder brandwerend

9 augustus 2017

Vier wegtunnels zijn mogelijk minder brandveilig dan werd aangenomen. Het betreft de Salland-Twentetunnel (N35), Ketheltunnel (A4), Tweede Coentunnel (A10) en Koning Willem Alexandertunnel (A2). Het beton is mogelijk minder brandwerend in het geval van een zeer grote brand.

Rijkswaterstaat liet onderzoek uitvoeren naar de brandveiligheid in tunnels. Hieruit blijkt dat deze veilig zijn voor gebruikers, maar dat de vier tunnels extra aandacht vereisen om te kunnen garanderen dat hulpdiensten hun werk veilig kunnen blijven doen.

Op maat gemaakte maatregelen

Zo zal de brandweer in de Salland-Twentetunnel per keer bekijken of zij bij een vrachtwagenbrand de tunnel in gaat om hulp te bieden, of dat dit te gevaarlijk is voor het eigen personeel. Voor de Ketheltunnel is afgesproken dat Rijkswaterstaat „met verhoogde aandacht" de tunnel in de gaten houdt en dat in geval van een vrachtwagenbrand het hele tunneldak direct wordt ontruimd.

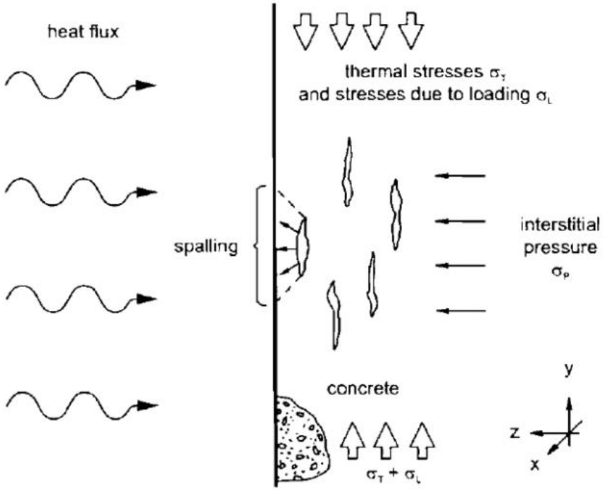
Brandproeven

In de vier tunnels, die zijn opgeleverd na 2008, werden diverse brandproeven uitgevoerd. Op basis hiervan kan niet met zekerheid worden gezegd of ze nog voldoen aan de brandwerendheidseisen. Volgens experts is een verandering in de samenstelling van het beton in 2008 waarschijnlijk de oorzaak. Minister Schultz van Haegen van Infrastructuur benadrukt dat het hier gaat om een scenario van een zeer grote brand, die zich in Nederland nog nooit eerder heeft voorgedaan. Zelfs bij de brand in de Mont Blanc-tunnel in 1999 was geen sprake van een dermate intense brand.

Komende tijd zal ook worden gekeken naar tunnels die tussen 2000 en 2008 zijn opgeleverd en naar nieuw te bouwen tunnels.

Bron: ANP

<<Lees ook: Speciaal team voorkomt grote vertragingen na brandalarm Schipholtunnel>>

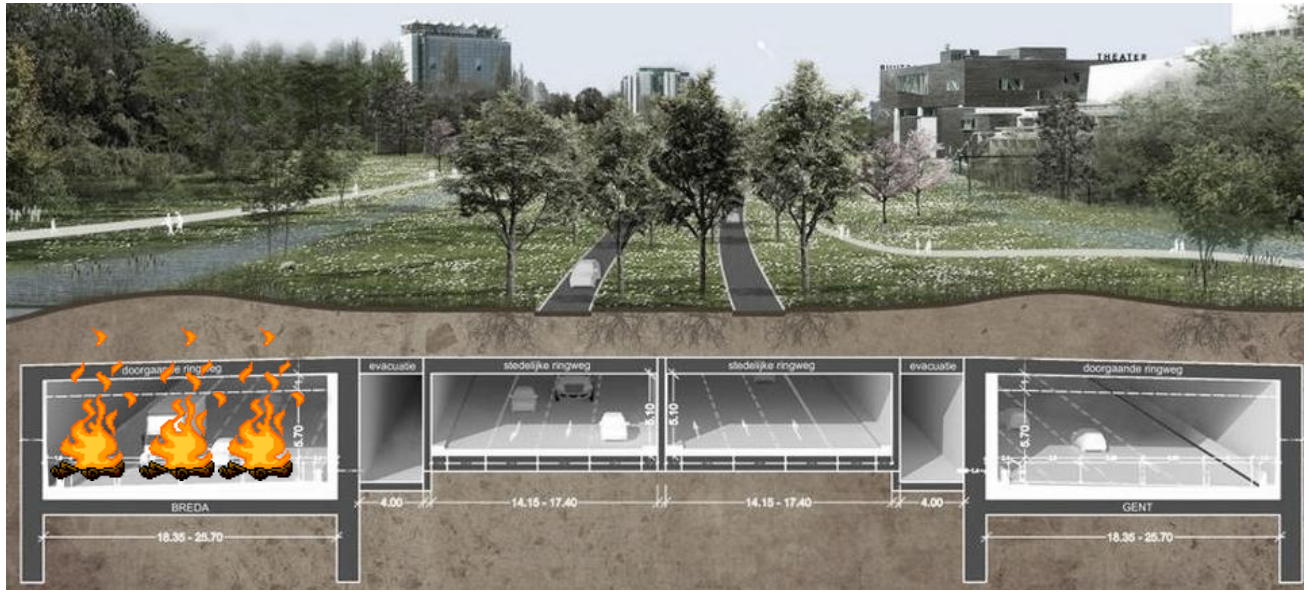


Maluk, C. (2017).

Jansson, R. (2013).

Introduction

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



Phase 1
Cost-benefit analysis

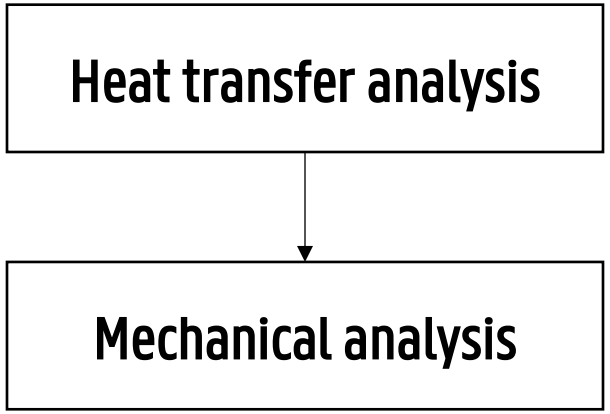
Phase 2
Analysis structural fire response

Phase 3
Post-fire damage (and repairability)

Phase 2

Structural fire response

Modeling approach

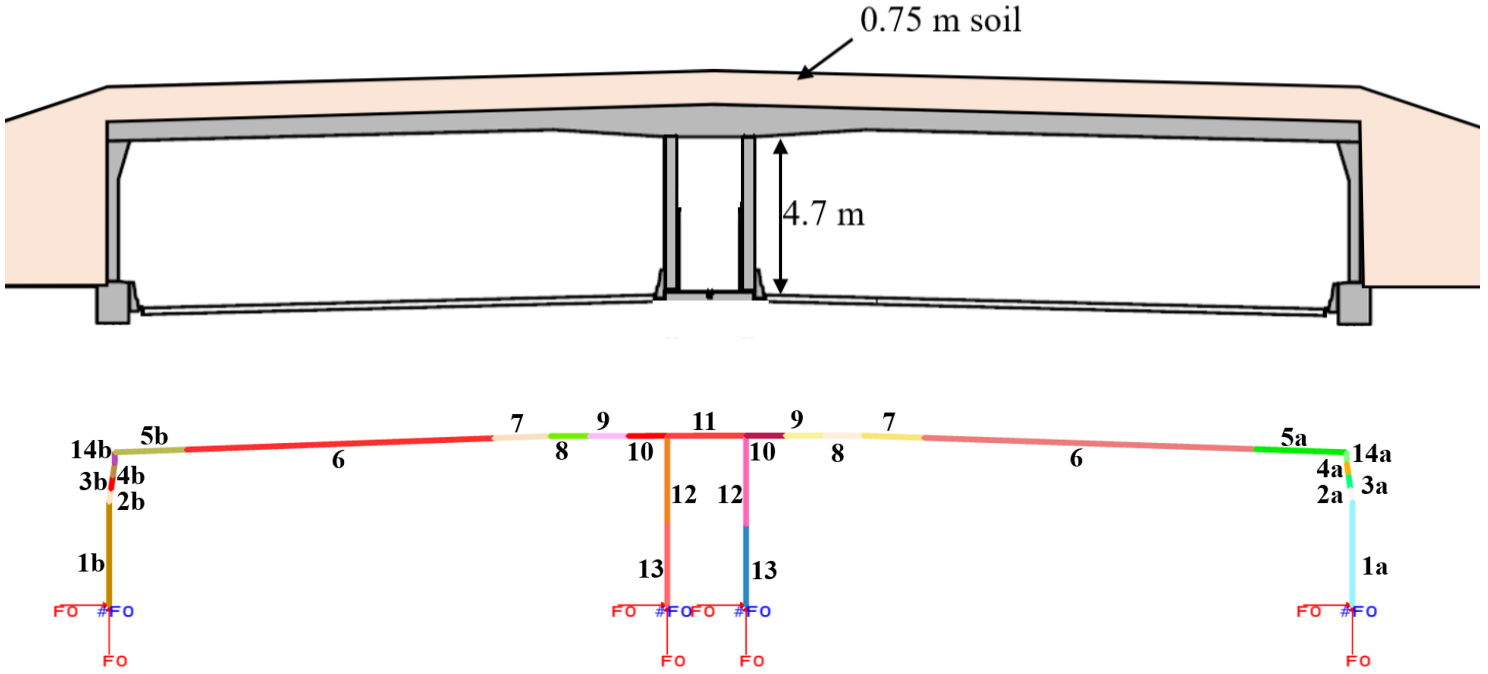


SAFIR + Python

SAFIR

Modeling approach

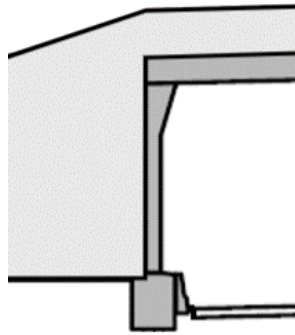
2D analysis

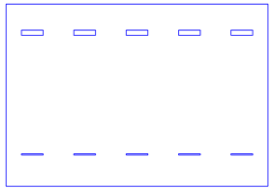
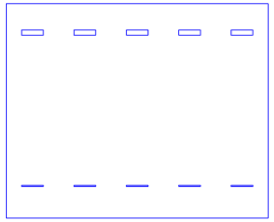
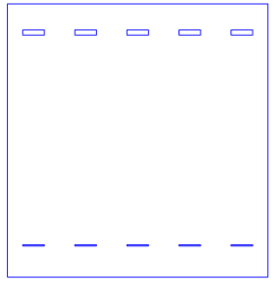


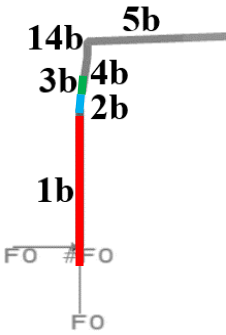
Modeling approach

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

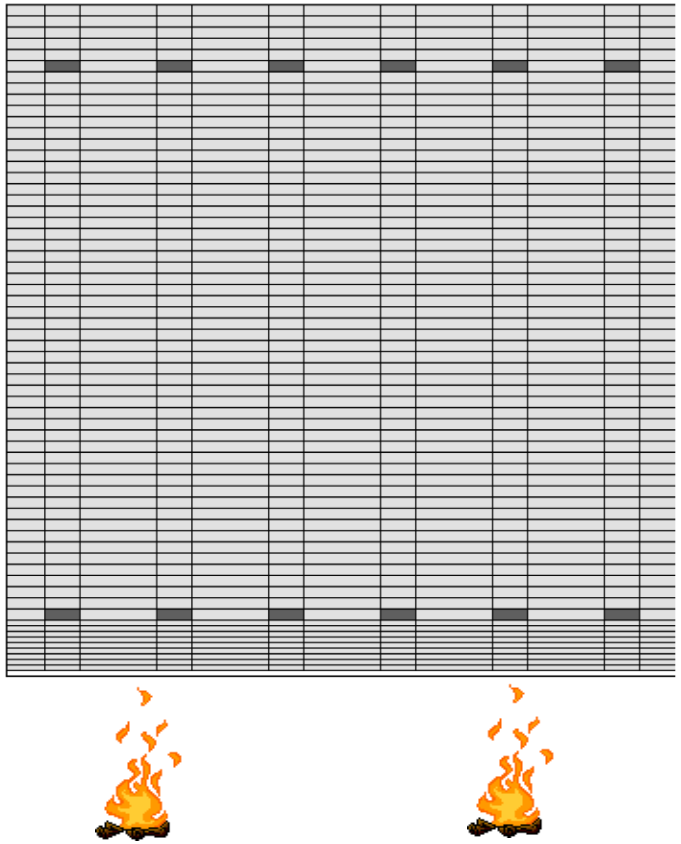


Heat transfer analysis

SAFIR + Python

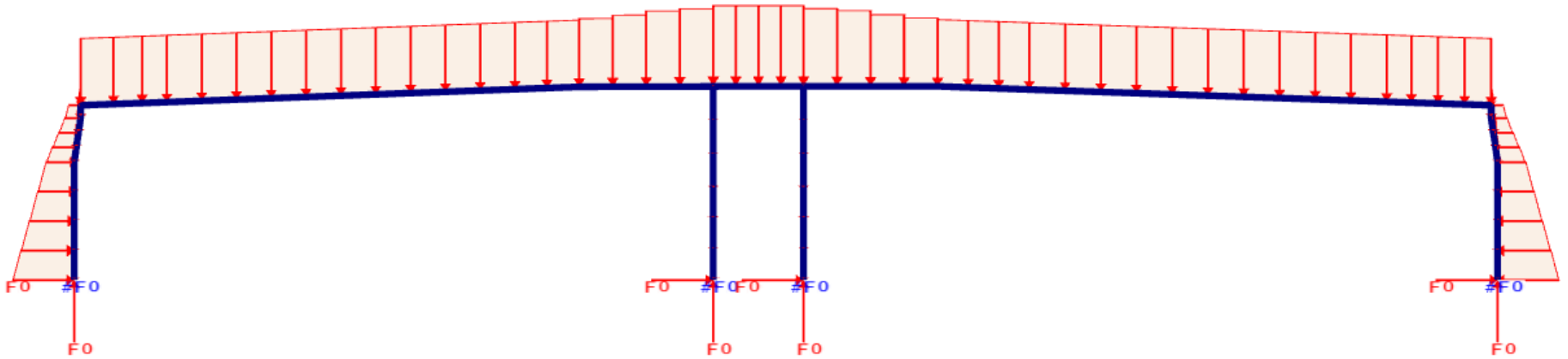
Spalling model

- 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



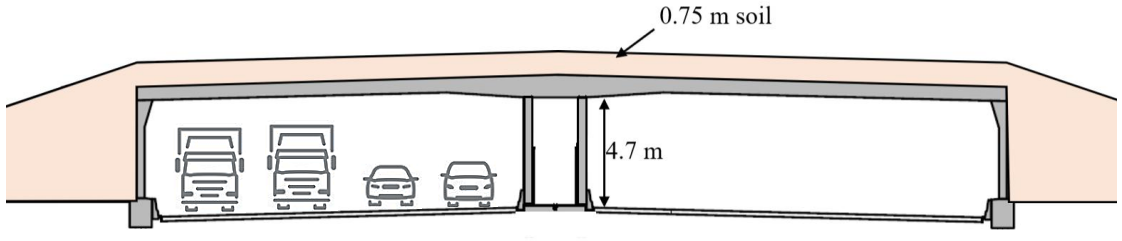
Mechanical analysis

SAFIR

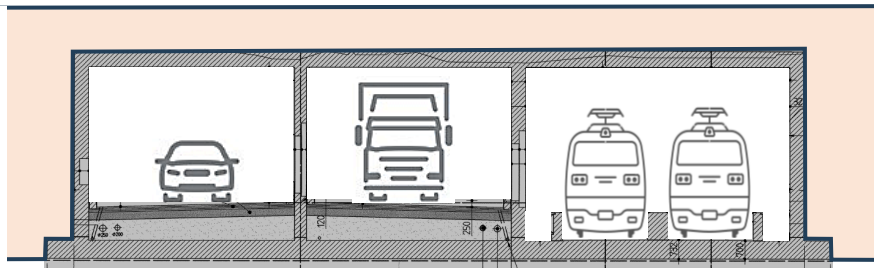


Results

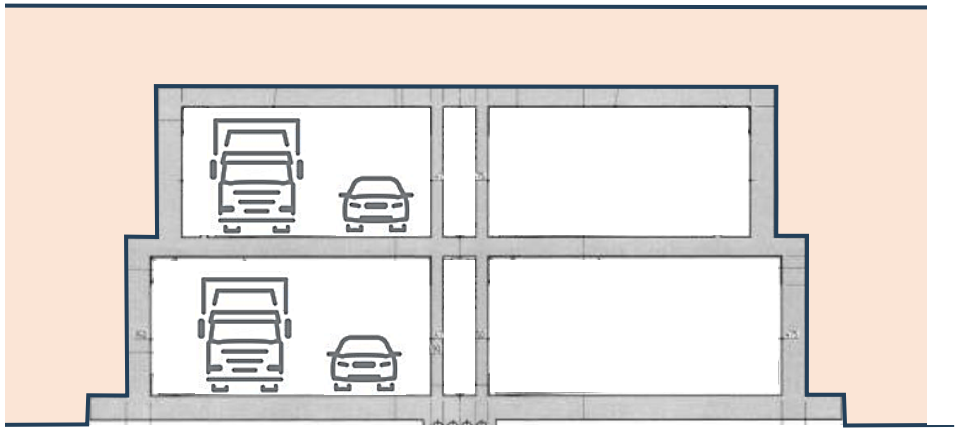
RWS120 – no spalling



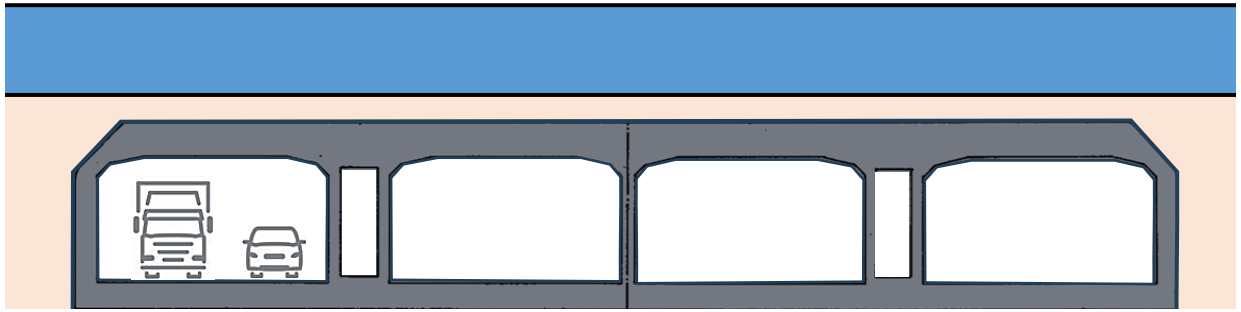
No collapse



No collapse



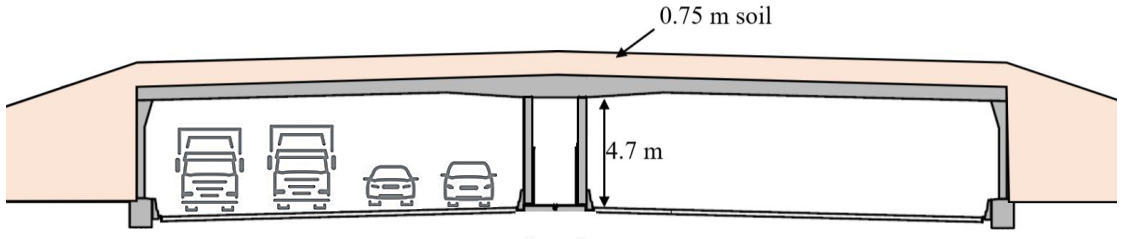
No collapse



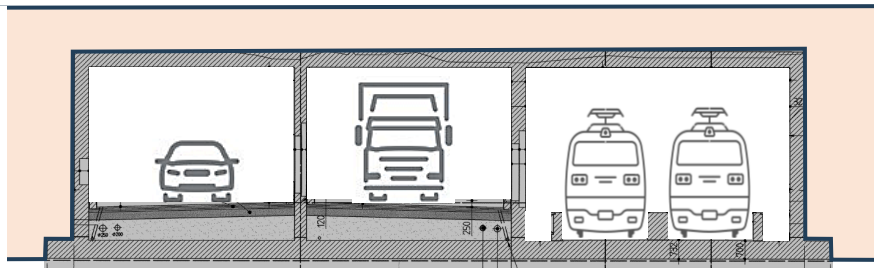
No collapse

Results

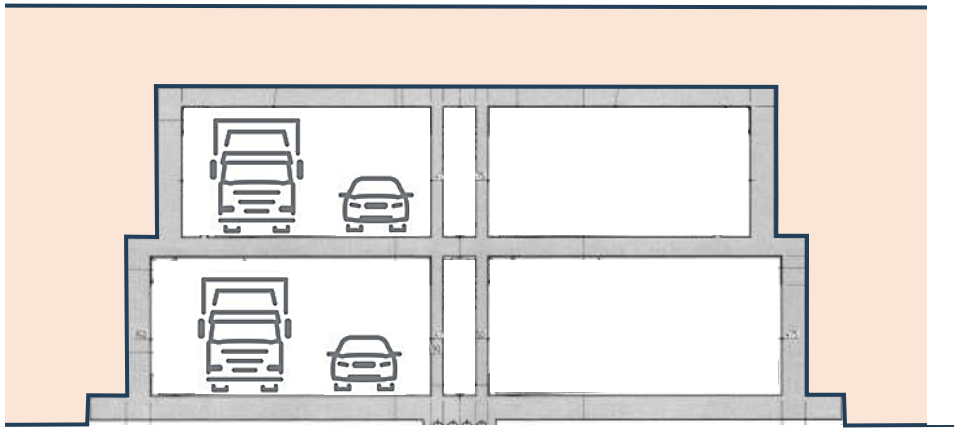
RWS120 – spalling 5mm/min (up to rebar)



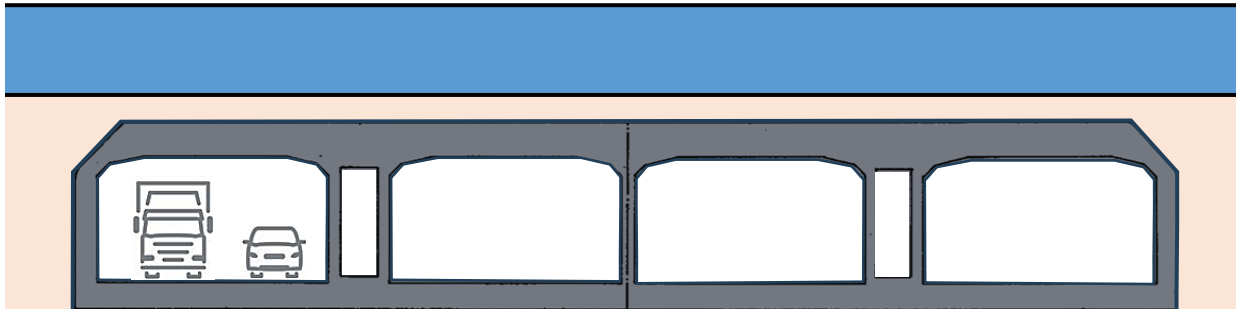
Collapse



Sometimes collapse

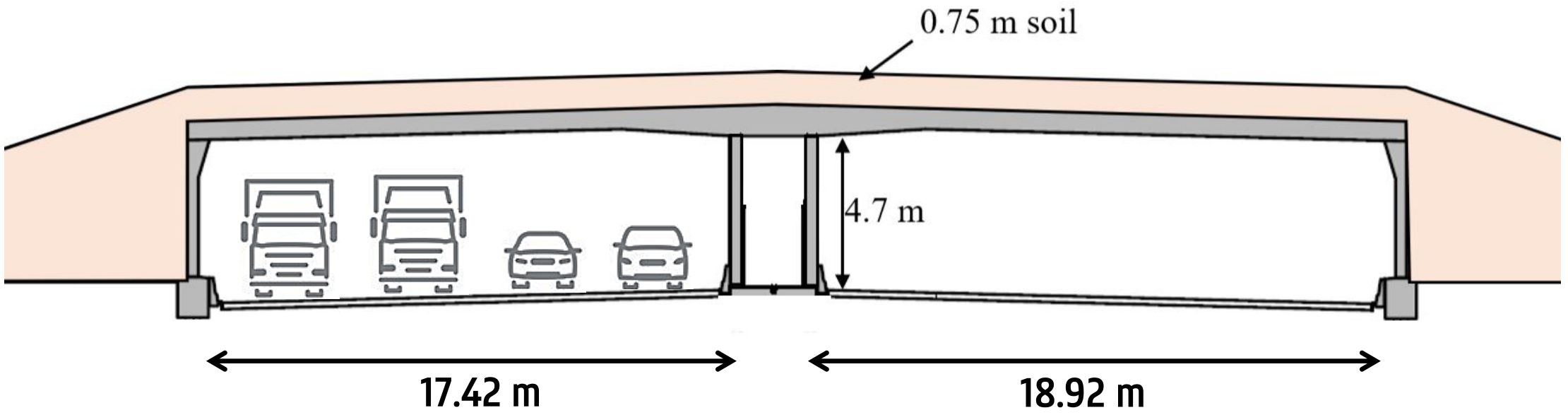


No collapse



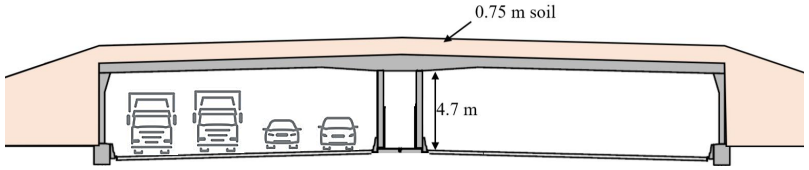
No collapse

2×4 lane tunnel

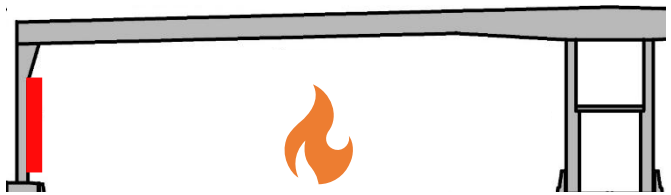


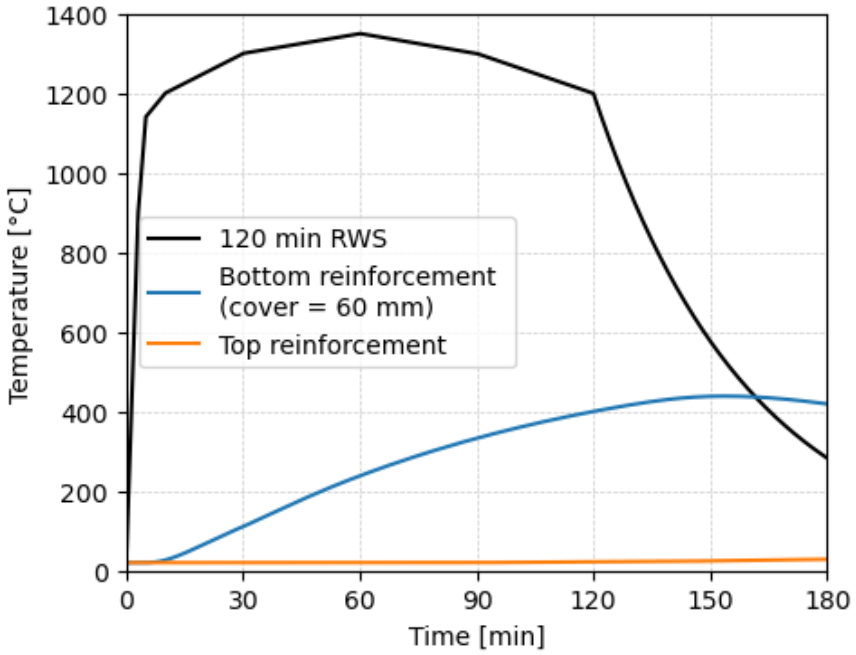
2×4 lane tunnel

RWS120 – no spalling

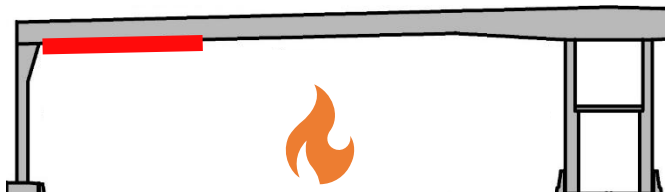


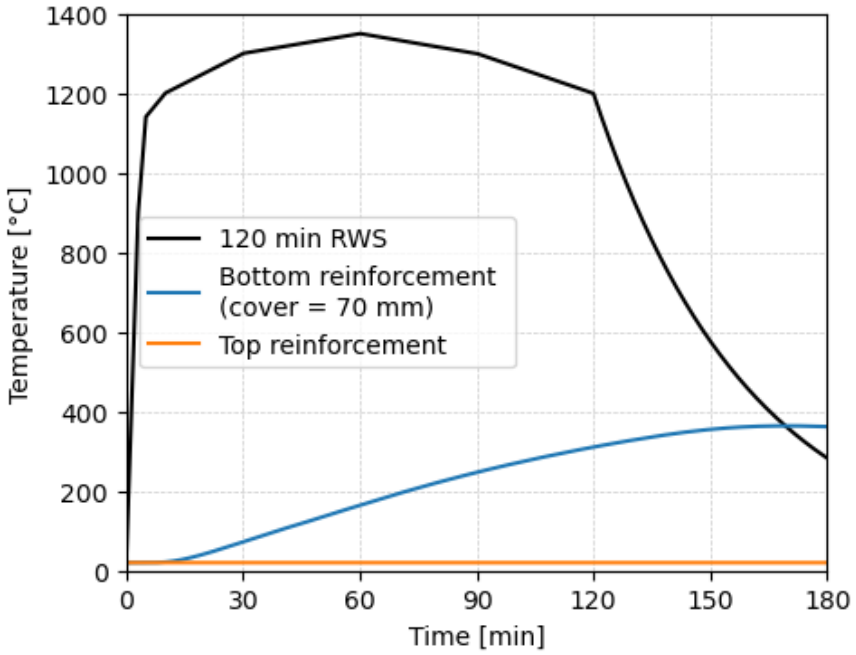
Outer wall





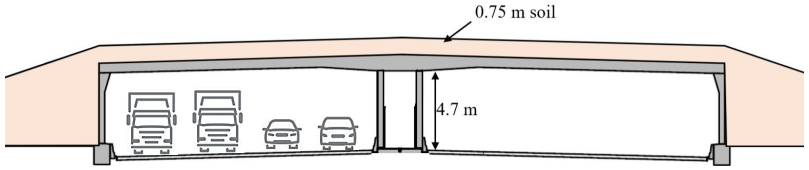
Roof slab

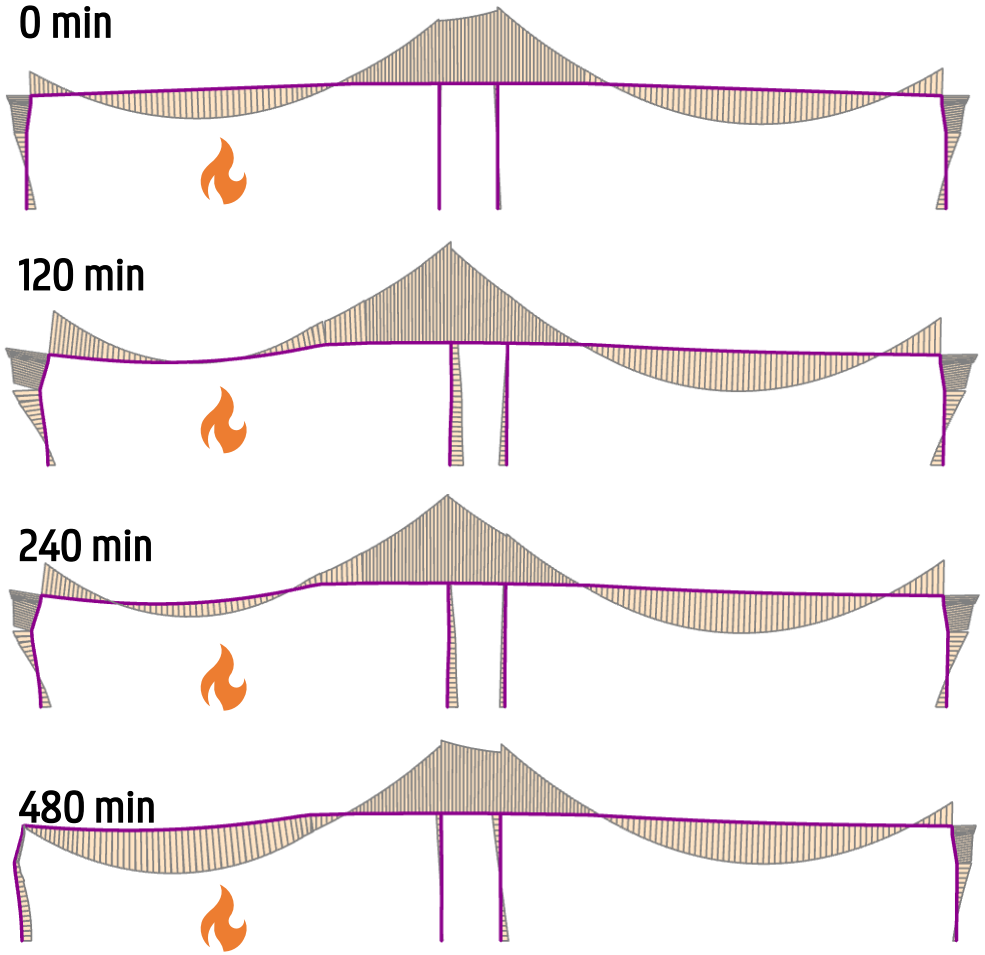


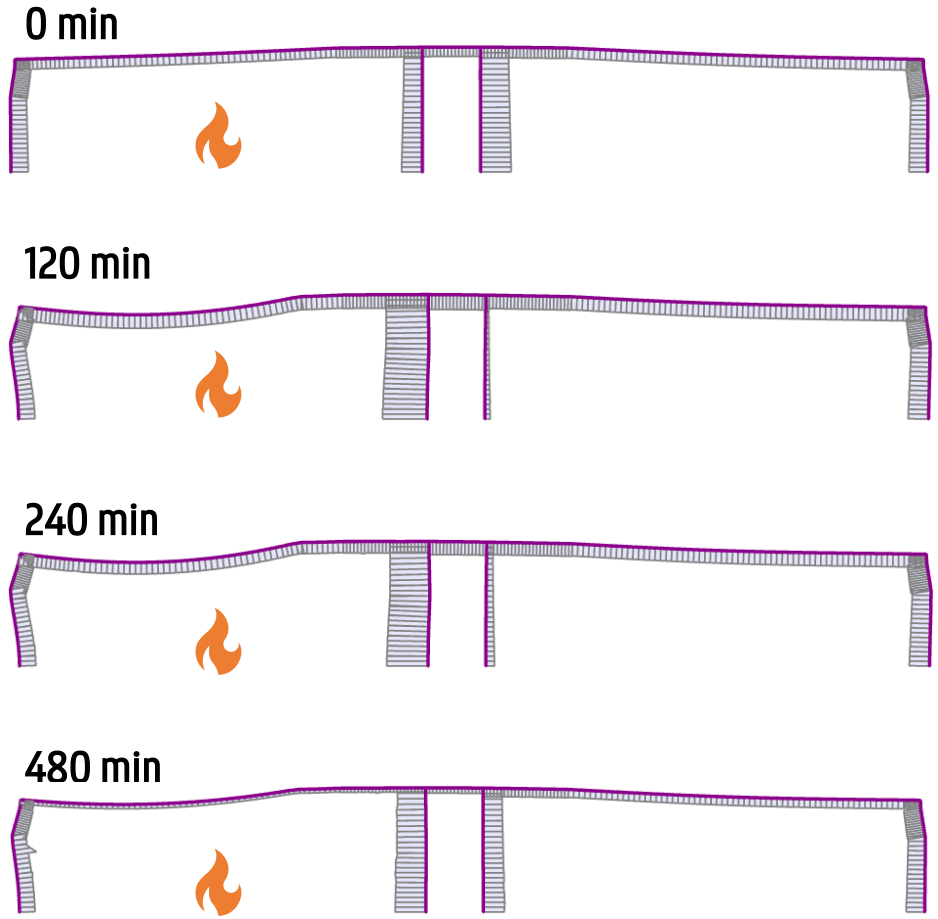


2×4 lane tunnel

RWS120 – no spalling

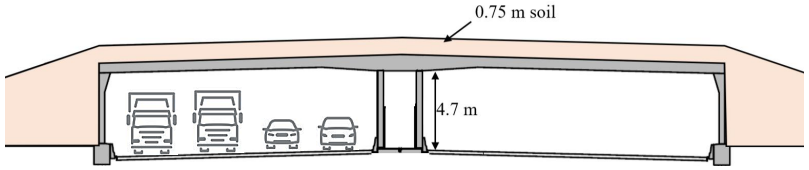






2×4 lane tunnel

RWS120 – no spalling



Heating phase (0 -> 7200 s)

Diamond 2016 for SAFIR

FILE : RWS_model3
NODES : 297
BEAMS : 148
SPRINGS : 24

BEAMS PLOT

DISPLACED CONFIGURATION (x5)
RESULTS ON DISPLACED CONF.
REACTIONS PLOT

BENDING MOMENT MZ PLOT

TIME : 39.5 sec

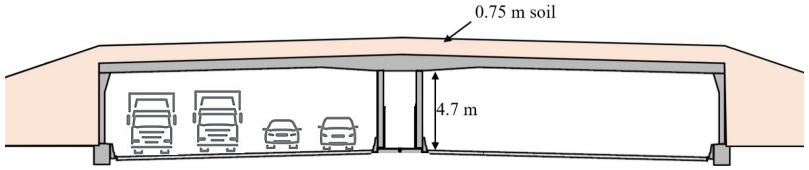
BEAMS :
Beam Element

Reactions in N

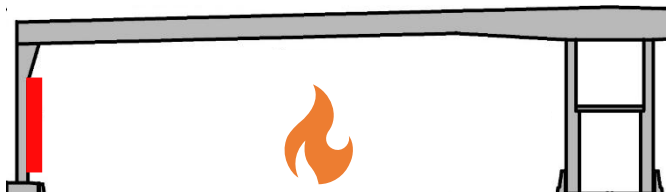
Bending moments in N.m

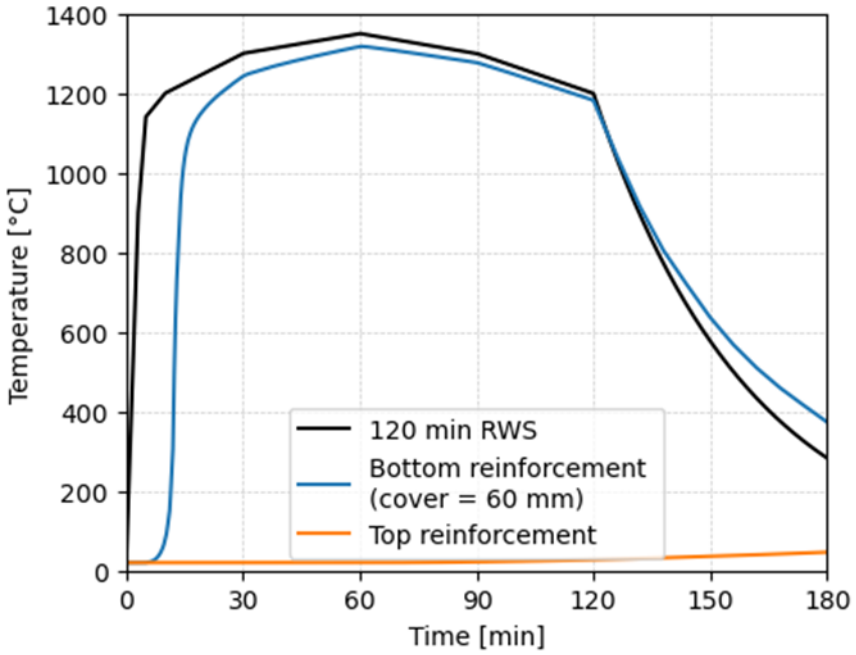
2×4 lane tunnel

RWS120 – spalling 5mm/min (up to rebar)

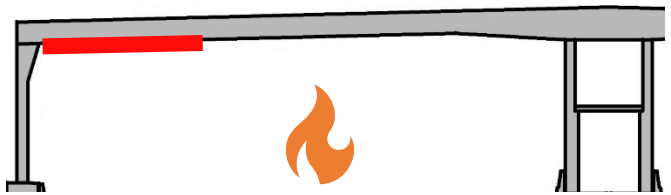


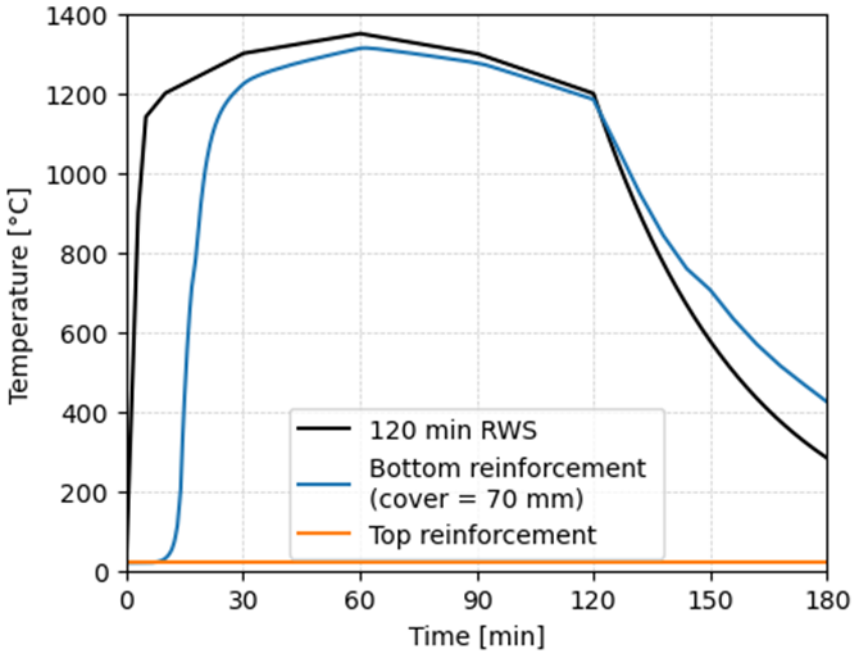
Outer wall





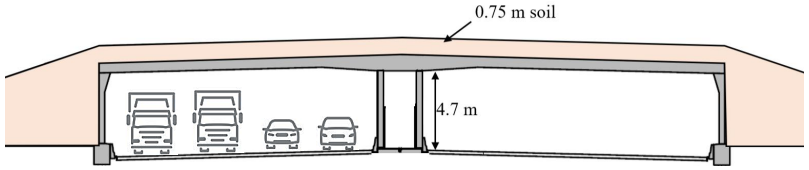
Roof slab

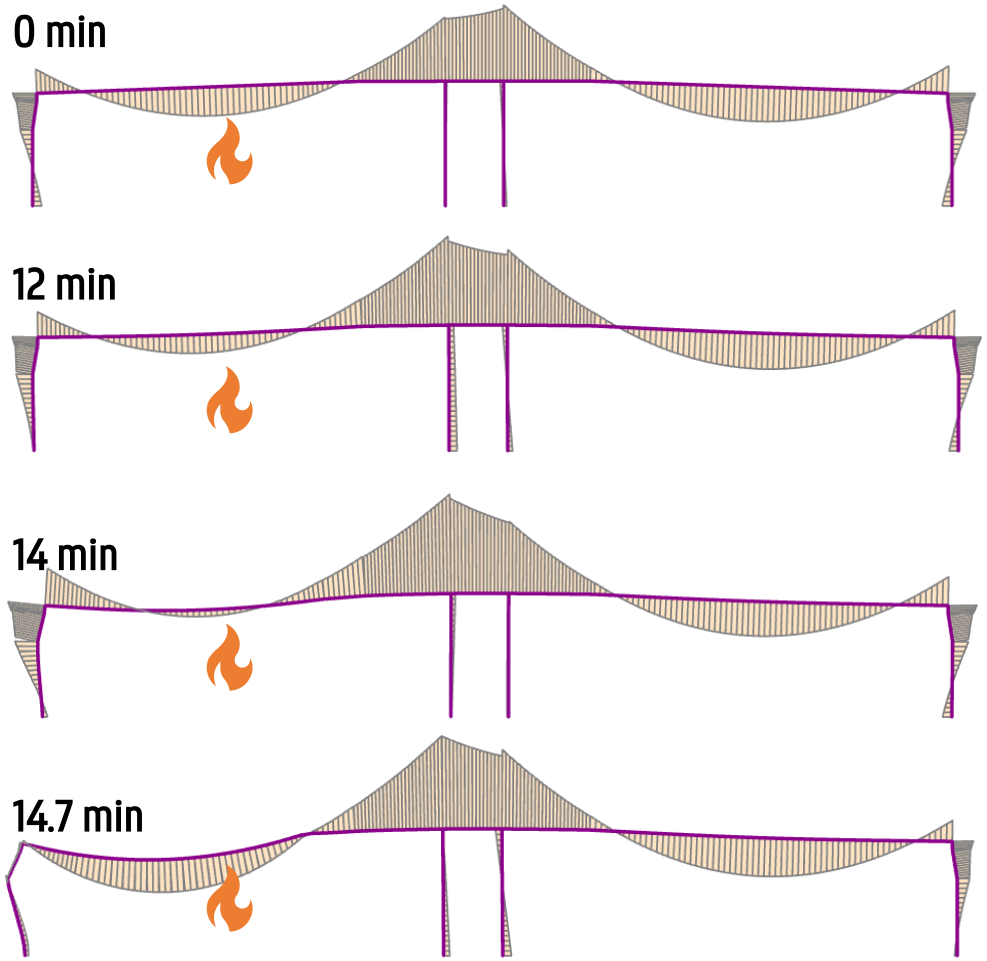


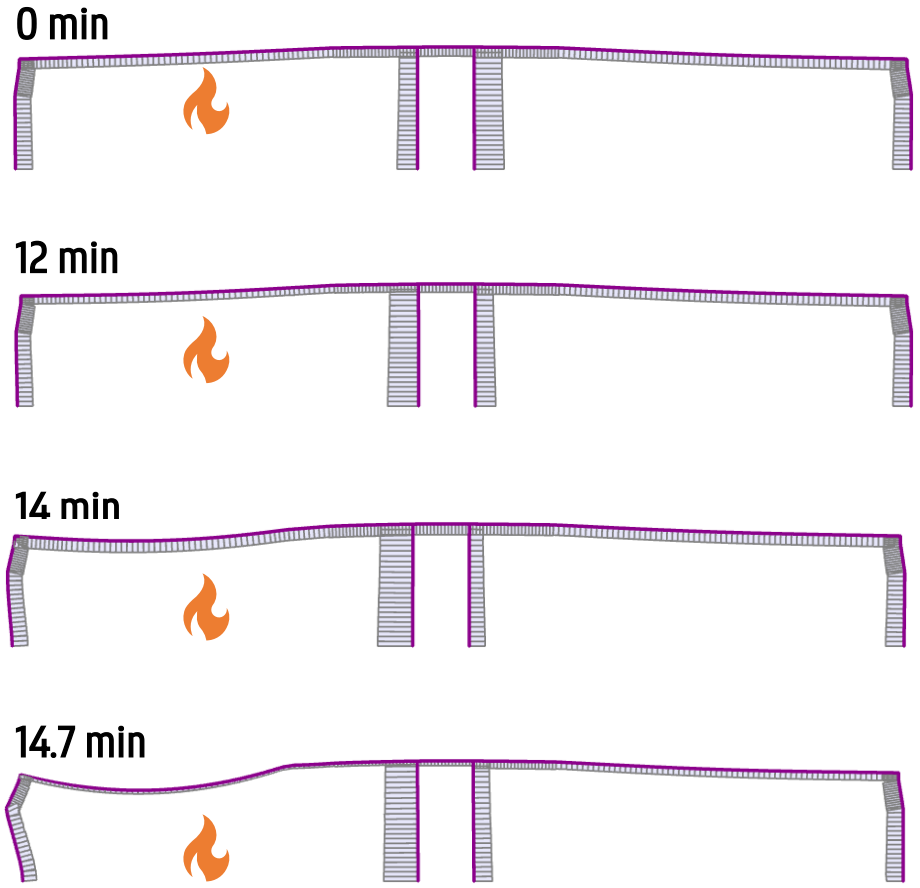


2×4 lane tunnel

RWS120 – spalling 5mm/min (up to rebar)

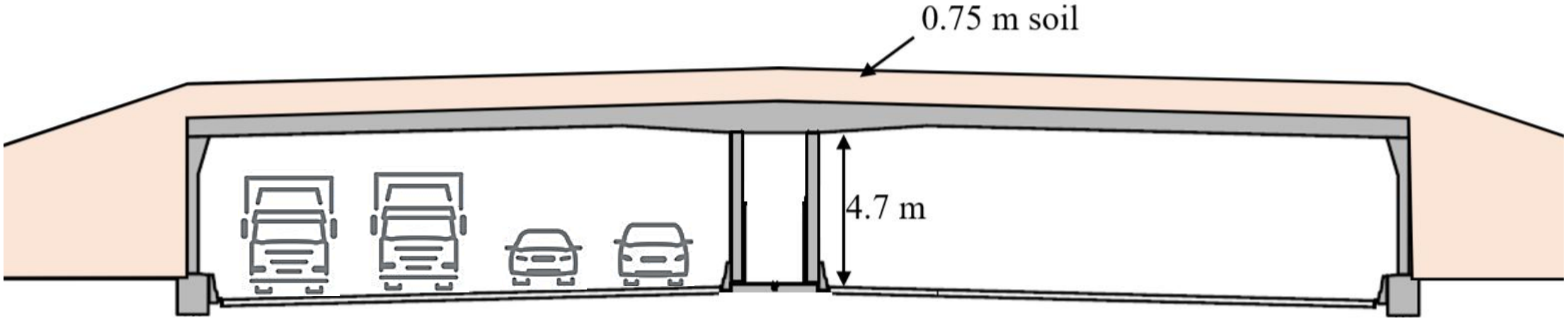






2×4 lane tunnel

Summary



No spalling case

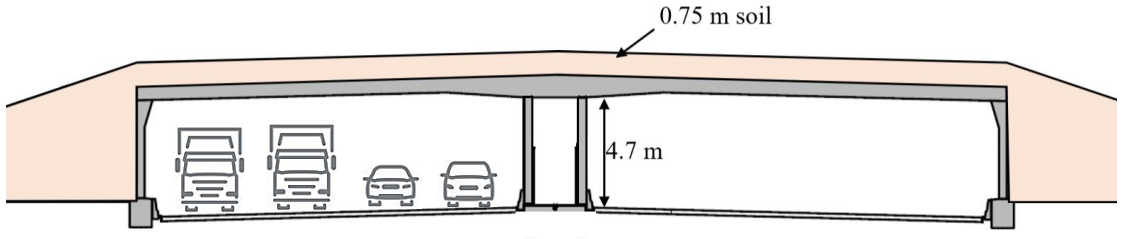
- Significant force redistributions
- Permanent deformations

Spalling case (5 mm/min)

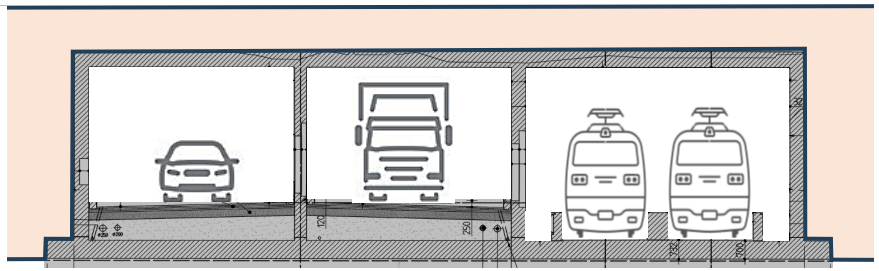
- Premature collapse → longer span collapses faster!
- Collapse soon after rebars are directly exposed to fire

Results

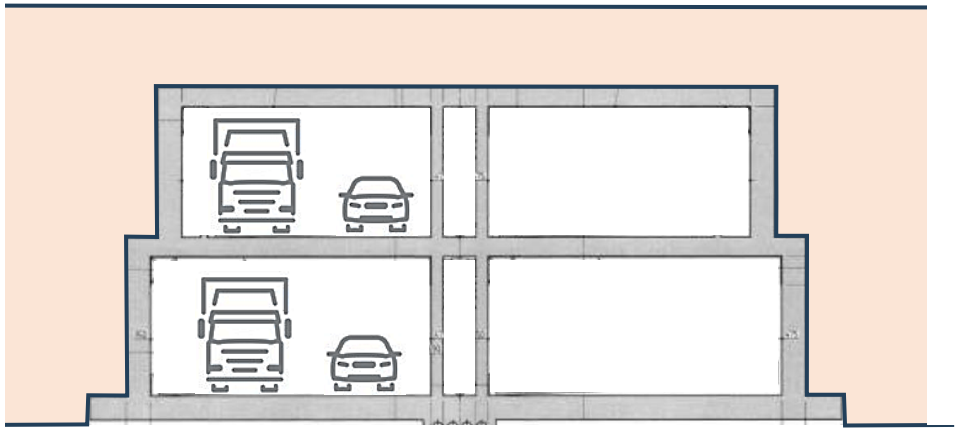
RWS120 – spalling 5mm/min (up to rebar)



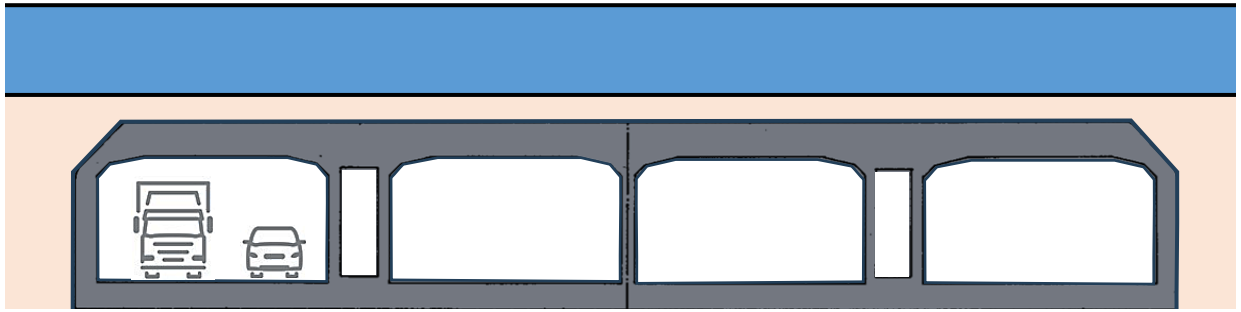
Collapse



Sometimes collapse

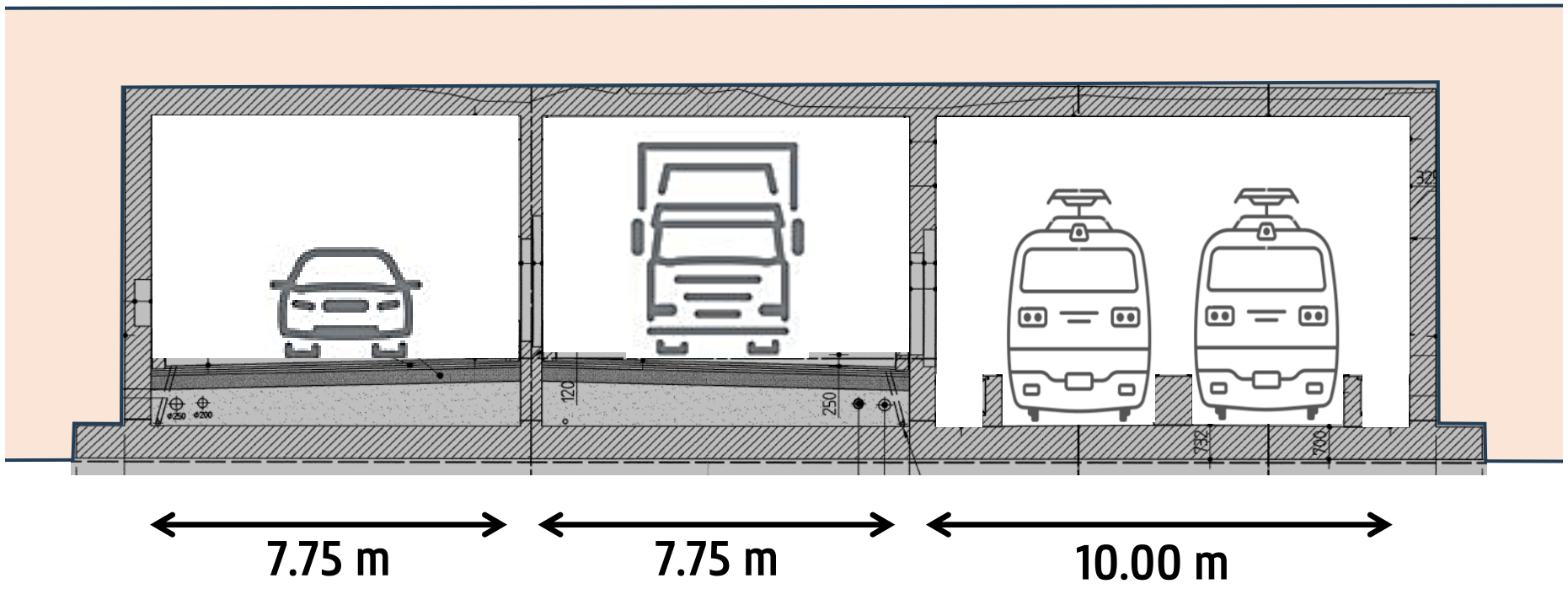


No collapse



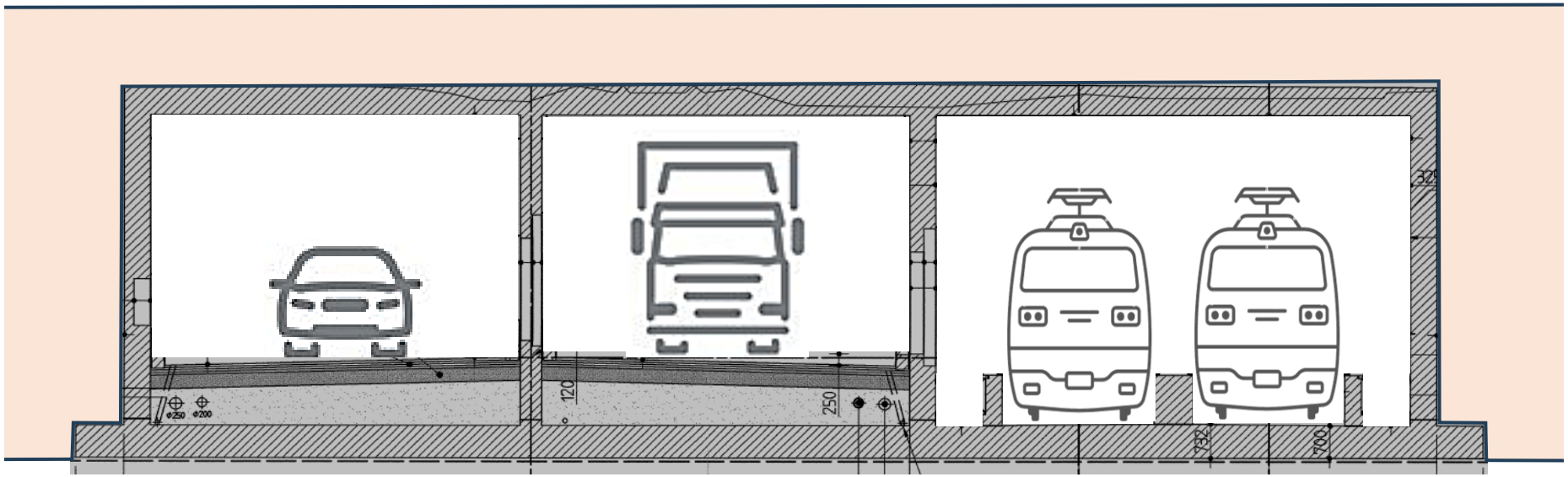
No collapse

2×1 lane + train tunnel



Sometimes collapse

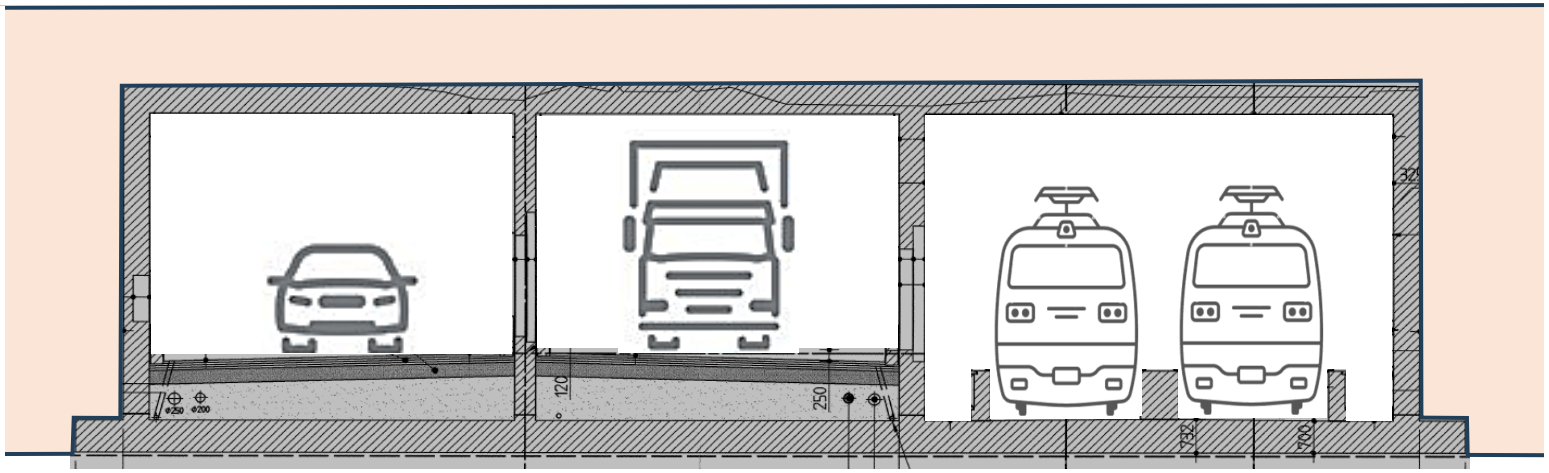
2×1 lane + train tunnel



	Left tube	Centre tube	Train tube
No spalling	No collapse	No collapse	No collapse
Spalling 5mm/min, up to rebar	Collapse (20.2 min)	No collapse	Collapse (65.4 min)

2×1 lane + train tunnel

Summary



No spalling case

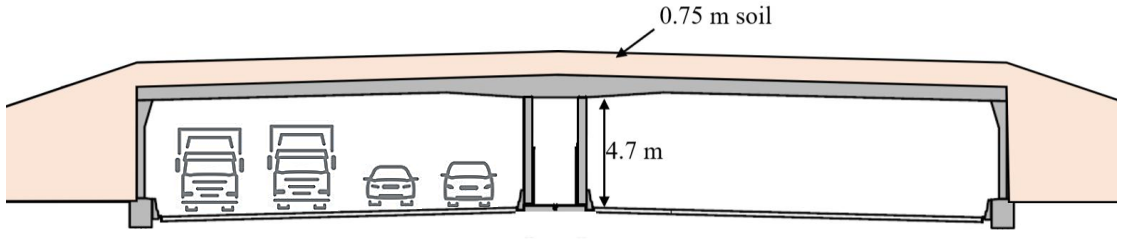
- No collapse, but significant force redistributions
- Permanent deformations

Spalling case (5 mm/min)

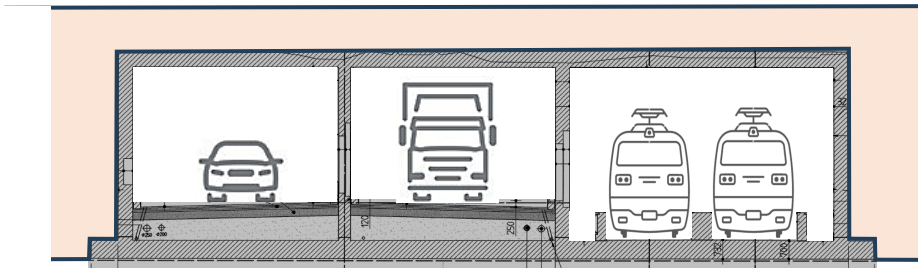
- Premature collapse in outer tubes

Results

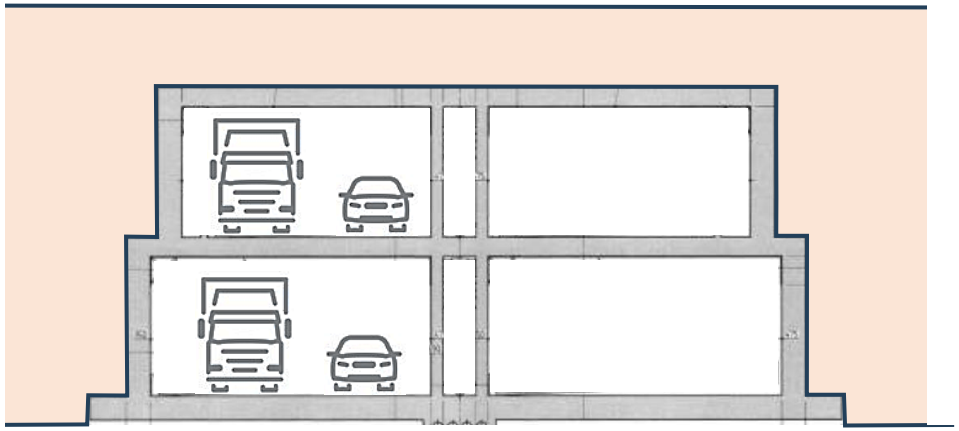
RWS120 – spalling 5mm/min (up to rebar)



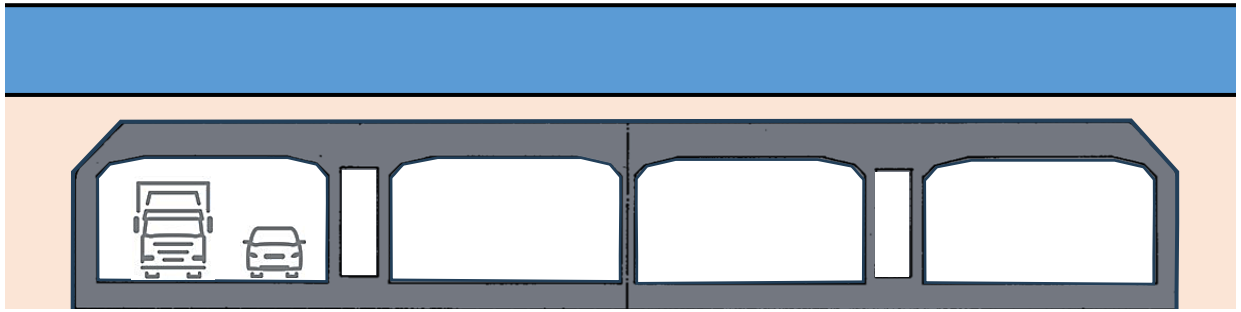
Collapse



Sometimes collapse

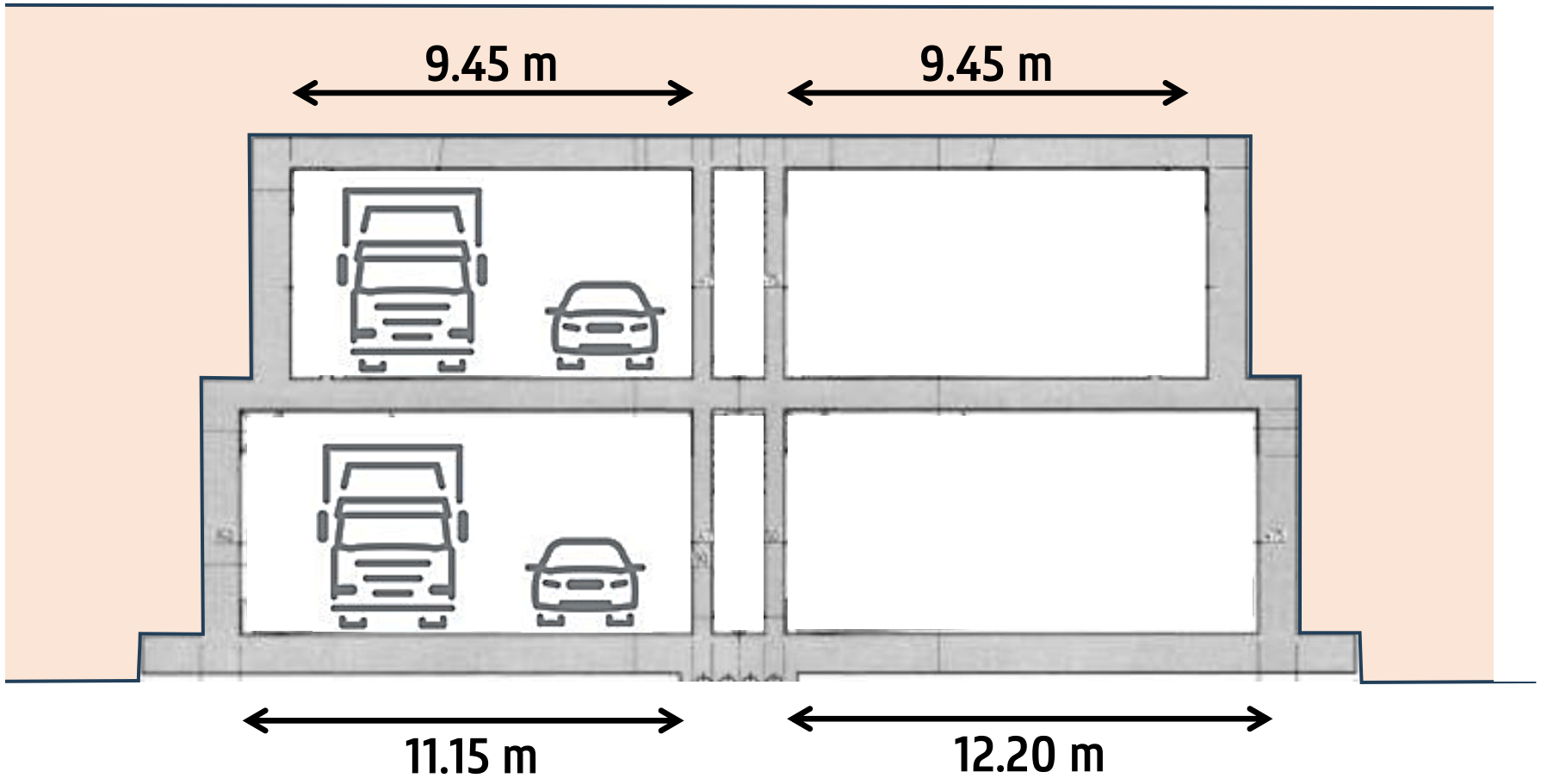


No collapse



No collapse

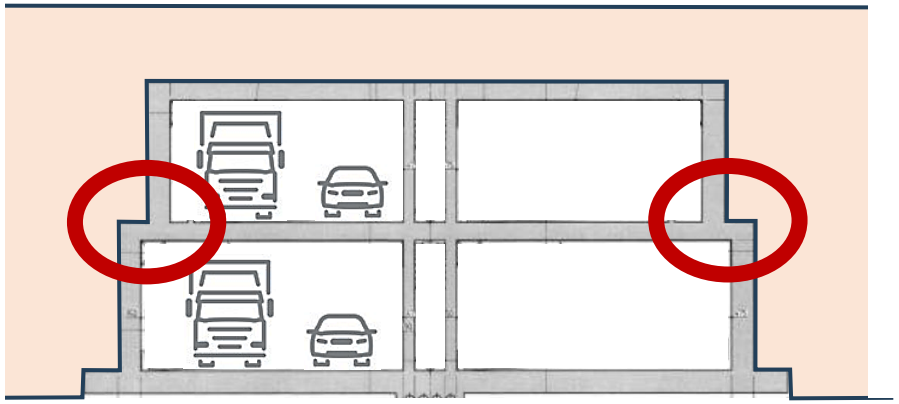
4×2 lane tunnel



No collapse, due to passive fire protection and highly reinforced roof

4×2 lane tunnel

Open issue: shear capacity in case of spalling



High shear + bending + spalling = ???

EN 1992-1-1:2004 + EN 1992-1-2:2004 (annex D)

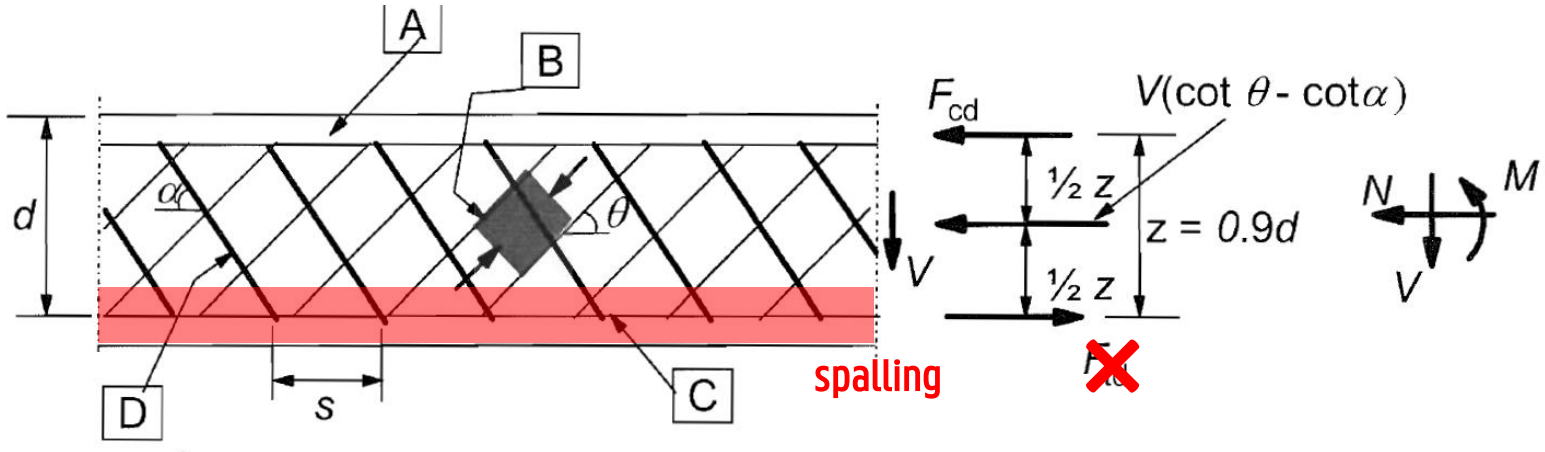
(3) For members with vertical shear reinforcement, the shear resistance, V_{Rd} is the smaller value of:

$$V_{Rd,s} = \frac{A_{sw}}{s} z\, f_{ywd} \cot\theta \qquad (6.8)$$

Note: If Expression (6.10) is used the value of f_{ywd} should be reduced to 0,8 f_{ywk} in Expression (6.8)

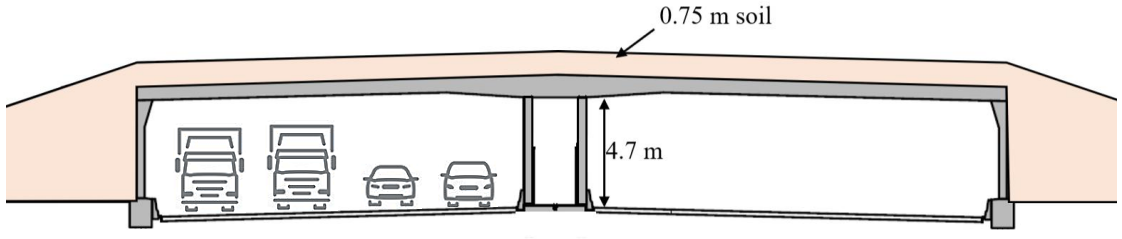
and

$$V_{Rd,max} = \alpha_{cw}\, b_w\, z\, \nu_1\, f_{cd}/(\cot\theta + \tan\theta) \qquad (6.9)$$

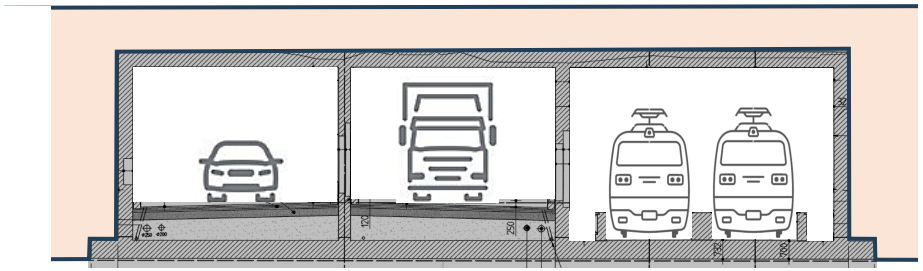


Results

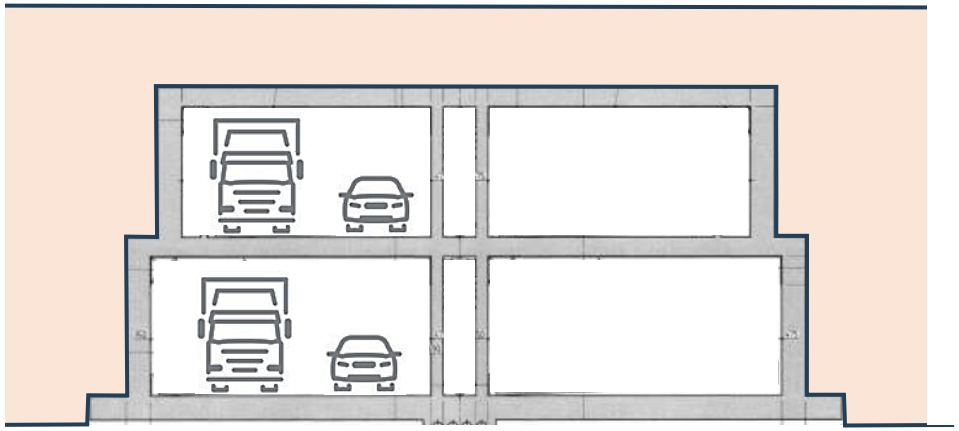
RWS120 – spalling 5mm/min (up to rebar)



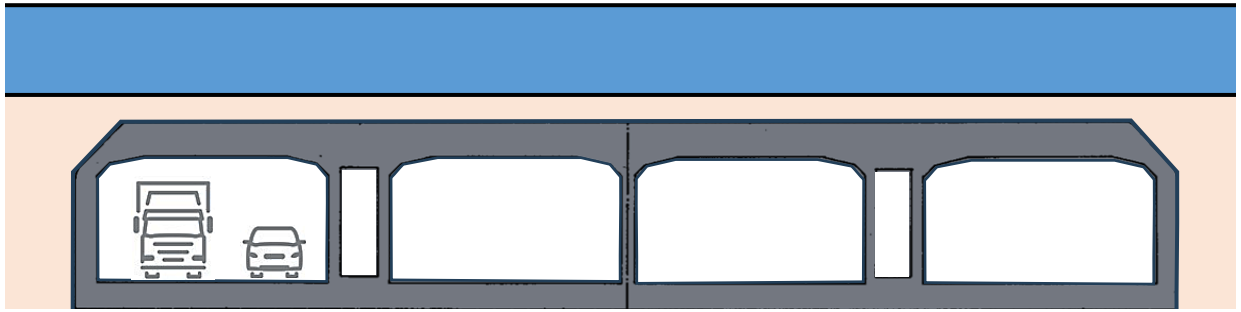
Collapse



Sometimes collapse



Possible collapse

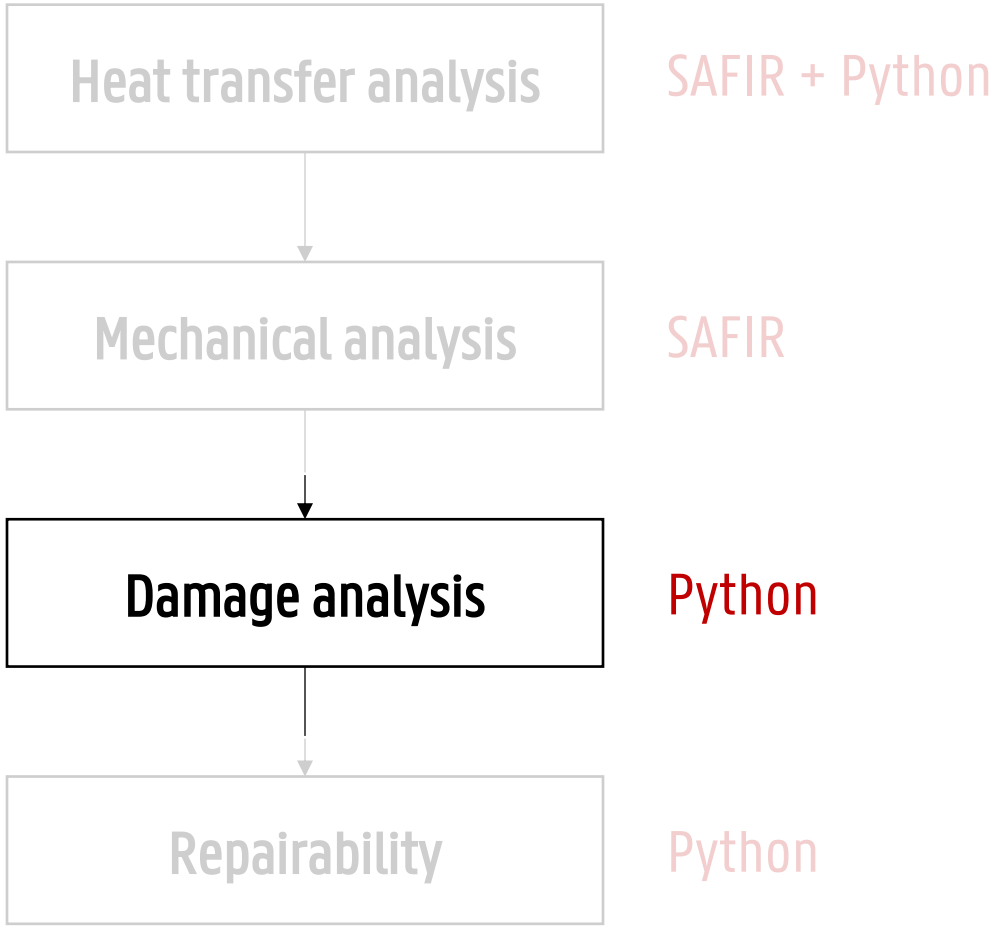


No collapse

Phase 3

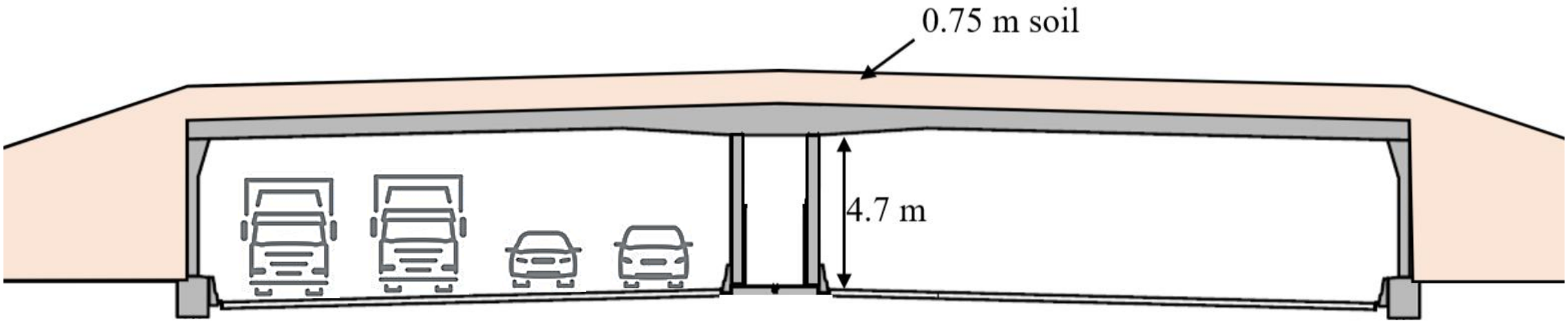
Post-fire damage

Modeling approach



2×4 lane tunnel

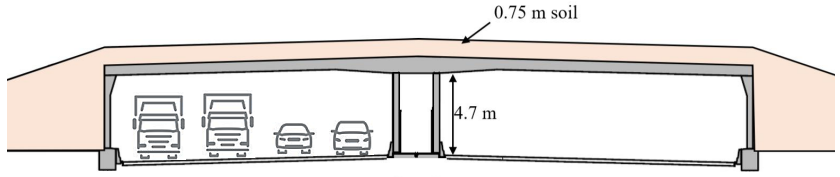
Damage during and after fire



RWS120 – No spalling

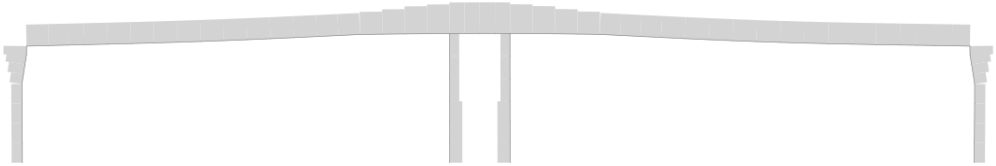
2×4 lane tunnel

Damage during and after fire (RWS120 – no spalling)



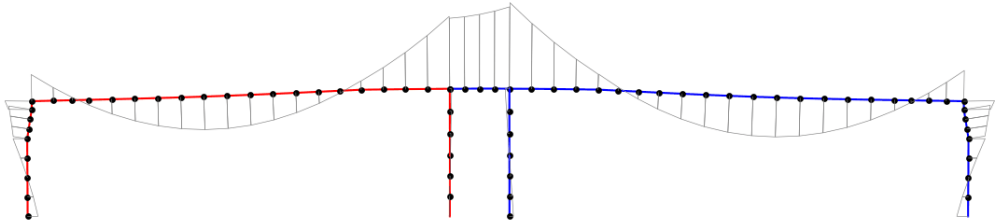
Damage analysis after 0.33mins (0.01h)

300 °C isotherm



Volume of concrete that experienced 300 °C or more: 0.000 m^3/m

Bending moments (deformations scaled 5x)

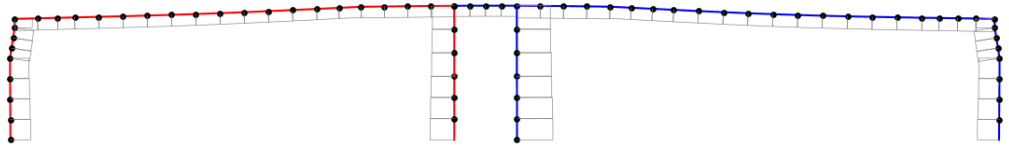


Cracks and plastic hinges

Severely cracked sections: 0m
Plastic steel strain at 0 sections

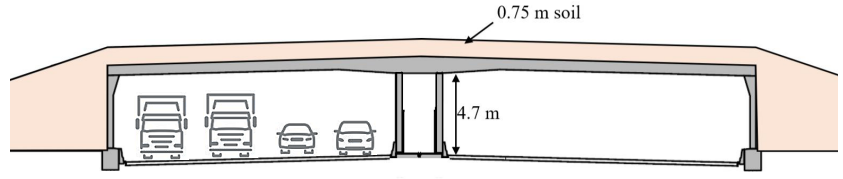
Fully cracked Lightly cracked Not cracked

Axial forces (deformations scaled 5x)



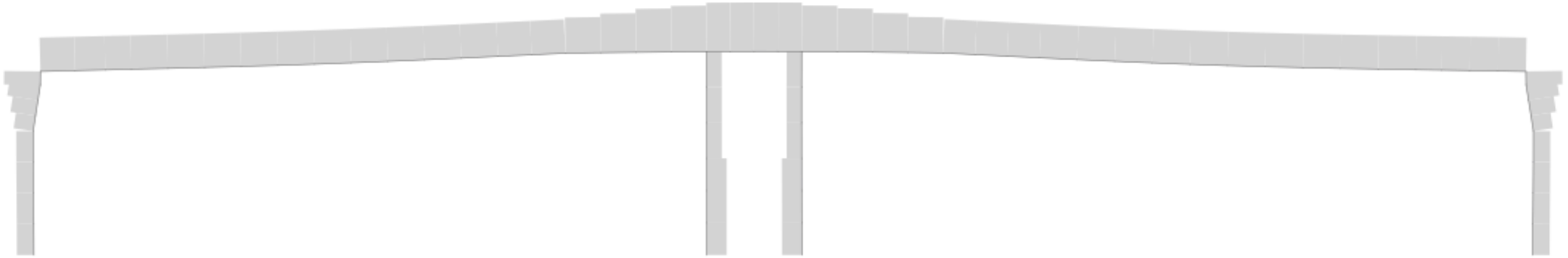
2×4 lane tunnel

Thermal damage (RWS120 – no spalling)



Damage analysis after 0.33mins (0.01h)

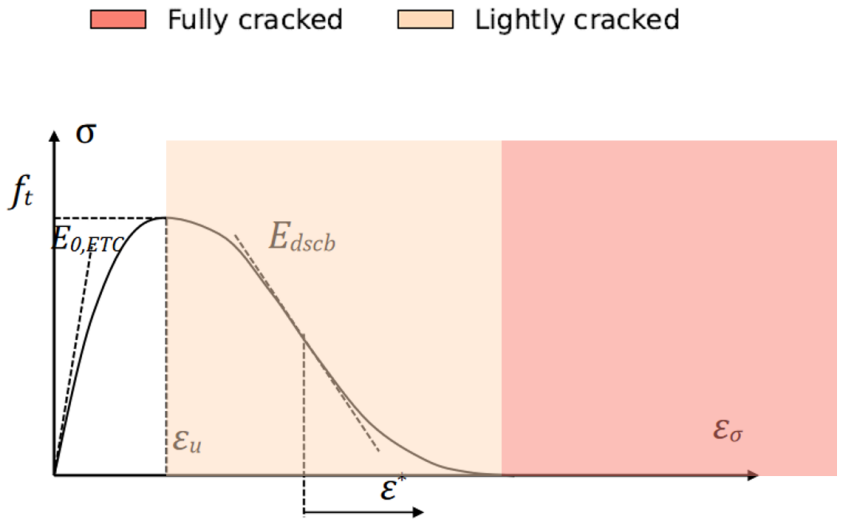
300 °C isotherm



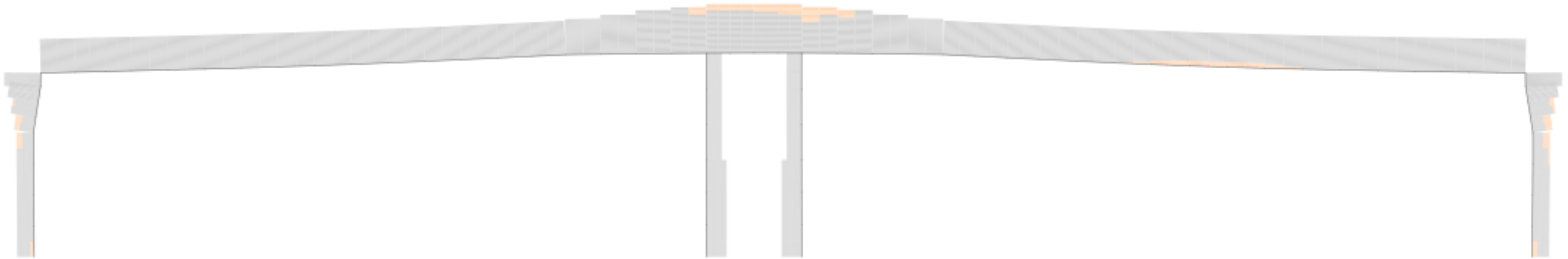
Volume of concrete that experienced 300 °C or more: 0.000 m^3/m

2×4 lane tunnel

Mechanical damage (RWS120 – no spalling)



Damage analysis after 0.33mins (0.01h)



Severely cracked sections: 0m
Plastic steel strain at 0 sections

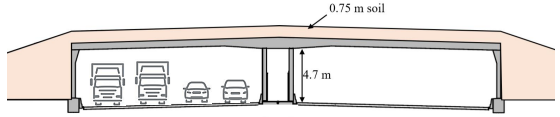
Fully cracked Lightly cracked Not cracked

Plastic hinge

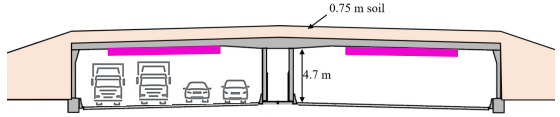
2×4 lane tunnel

Effect of passive fire protection (RWS120 – no spalling)

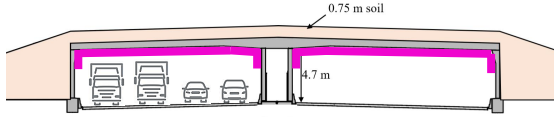
Unprotected



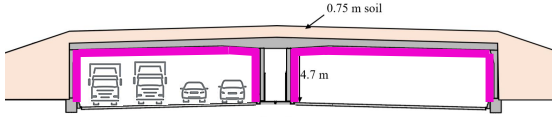
Roof protected (partially)

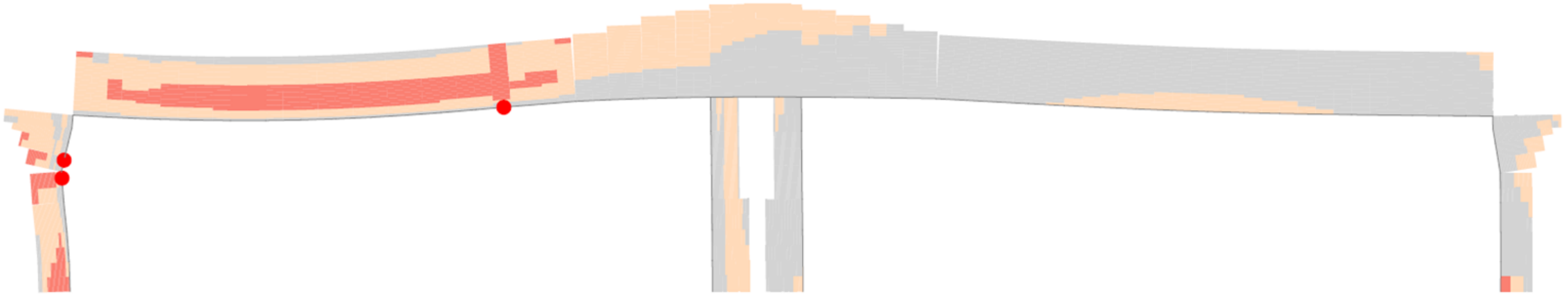


Roof protected (full)



Full protection





Severely cracked sections: 16.77m
Plastic steel strain at 3 sections

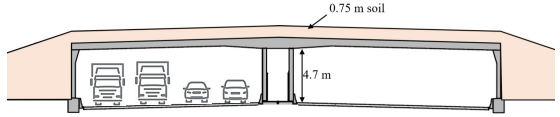
Fully cracked Lightly cracked Not cracked

Plastic hinge

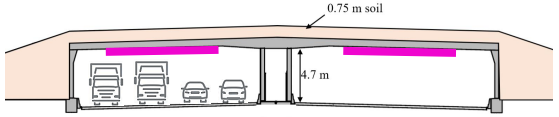
2×4 lane tunnel

Effect of passive fire protection (RWS120 – no spalling)

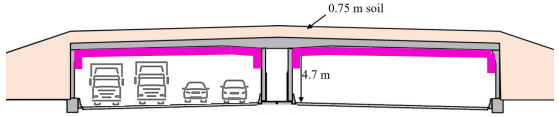
Unprotected



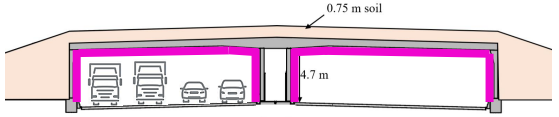
Roof protected (partially)

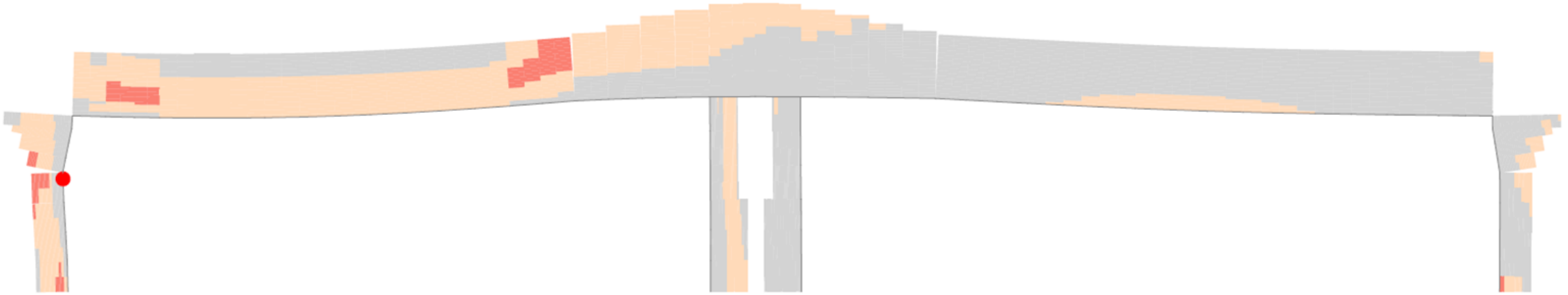


Roof protected (full)



Full protection





Severely cracked sections: 6.22m
Plastic steel strain at 1 sections

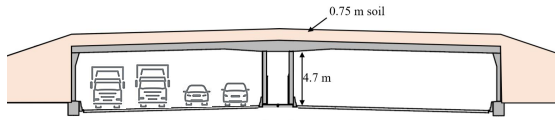
Fully cracked Lightly cracked Not cracked

Plastic hinge

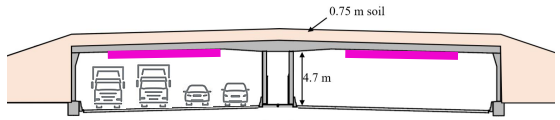
2×4 lane tunnel

Effect of passive fire protection (RWS120 – no spalling)

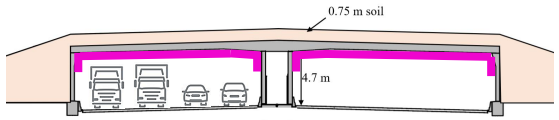
Unprotected



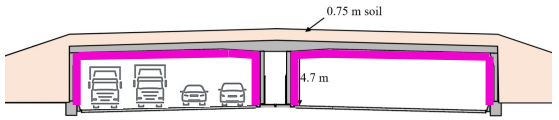
Roof protected (partially)

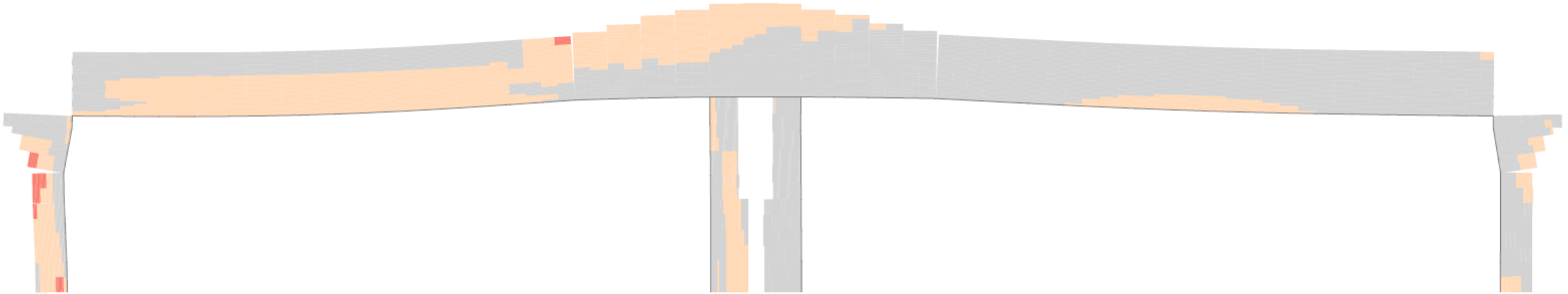


Roof protected (full)



Full protection





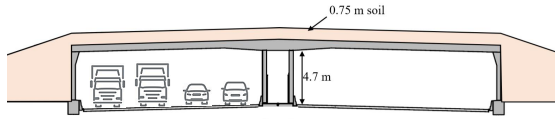
Severely cracked sections: 2.77m
Plastic steel strain at 0 sections

Fully cracked Lightly cracked Not cracked

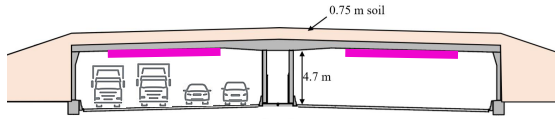
2×4 lane tunnel

Effect of passive fire protection (RWS120 – no spalling)

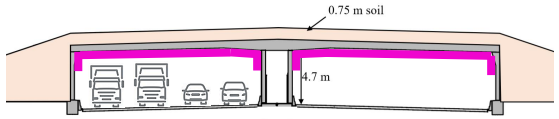
Unprotected



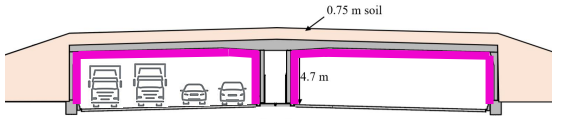
Roof protected (partially)

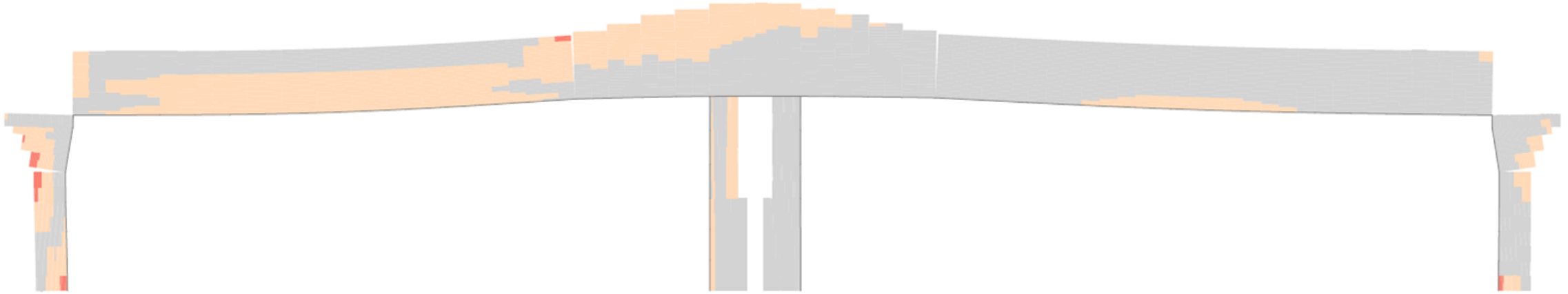


Roof protected (full)



Full protection



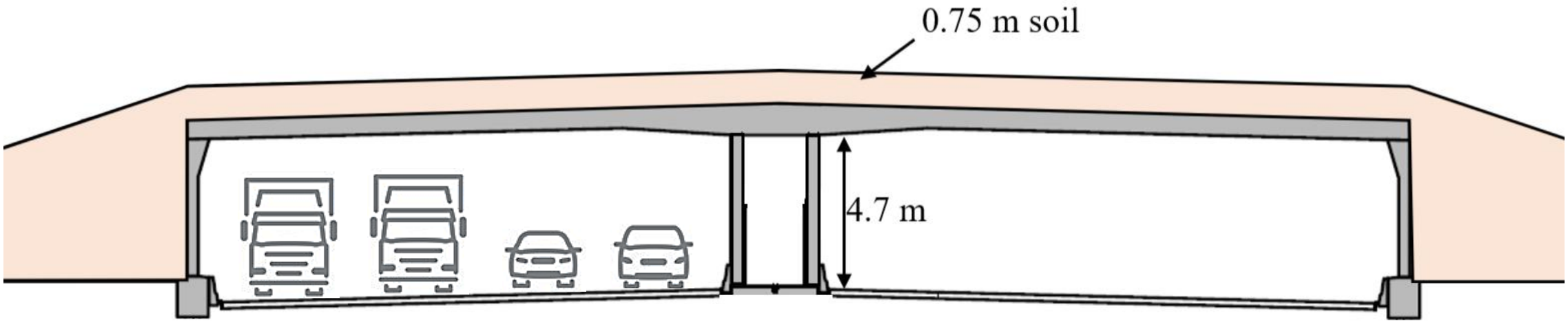


Severely cracked sections: 2.65m
Plastic steel strain at 0 sections

Fully cracked Lightly cracked Not cracked

2×4 lane tunnel

Damage during and after fire

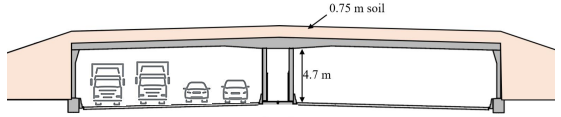


RWS120 – spalling 5 mm/min

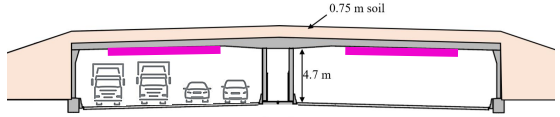
2×4 lane tunnel

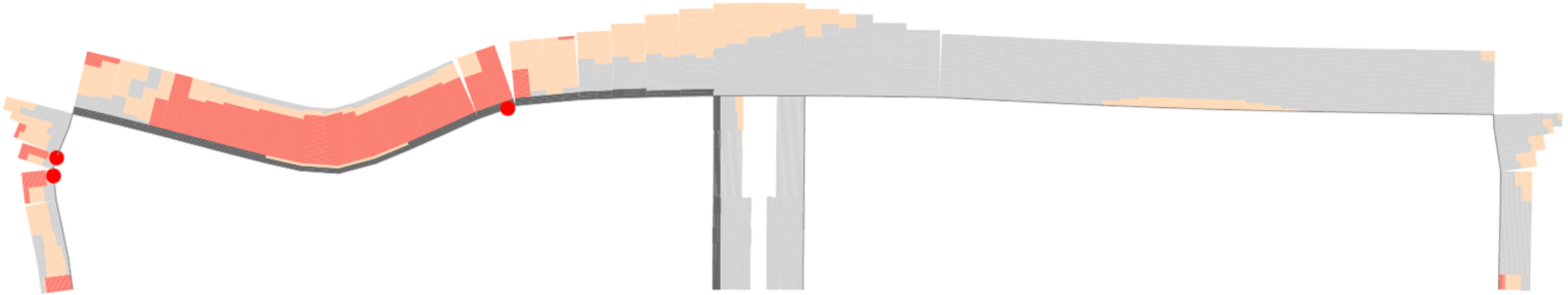
Effect of passive fire protection (RWS120 – spalling 5 mm/min)

Unprotected



Roof protected (partially)





Severely cracked sections: 14.02m
Plastic steel strain at 3 sections

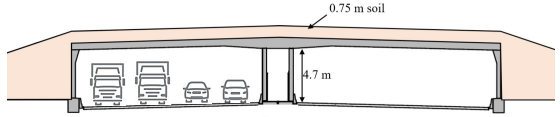
Fully cracked Lightly cracked Not cracked

Plastic hinge

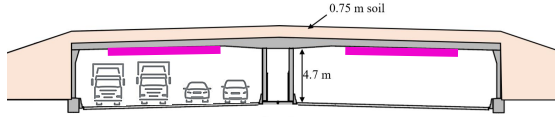
2×4 lane tunnel

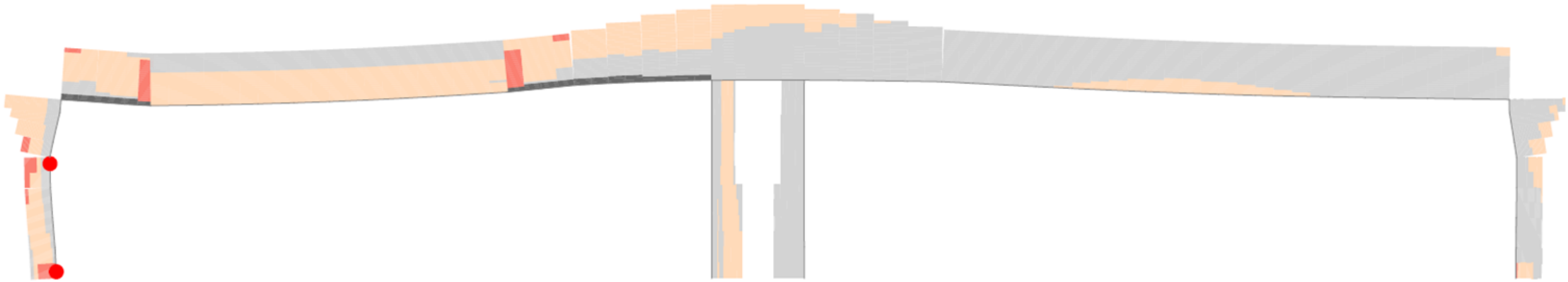
Effect of passive fire protection (RWS120 – spalling 5 mm/min)

Unprotected



Roof protected (partially)





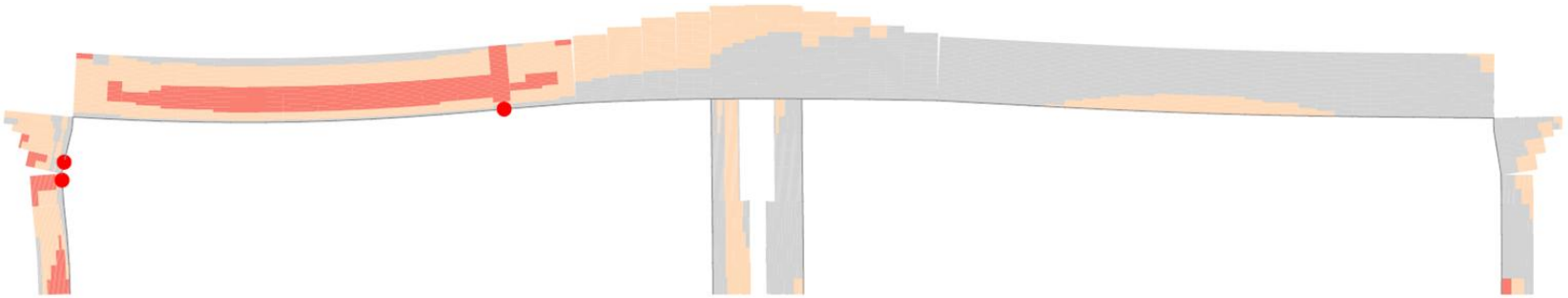
Severely cracked sections: 4.53m
Plastic steel strain at 2 sections

Fully cracked Lightly cracked Not cracked

Plastic hinge

2×4 lane tunnel

Damage during and after fire



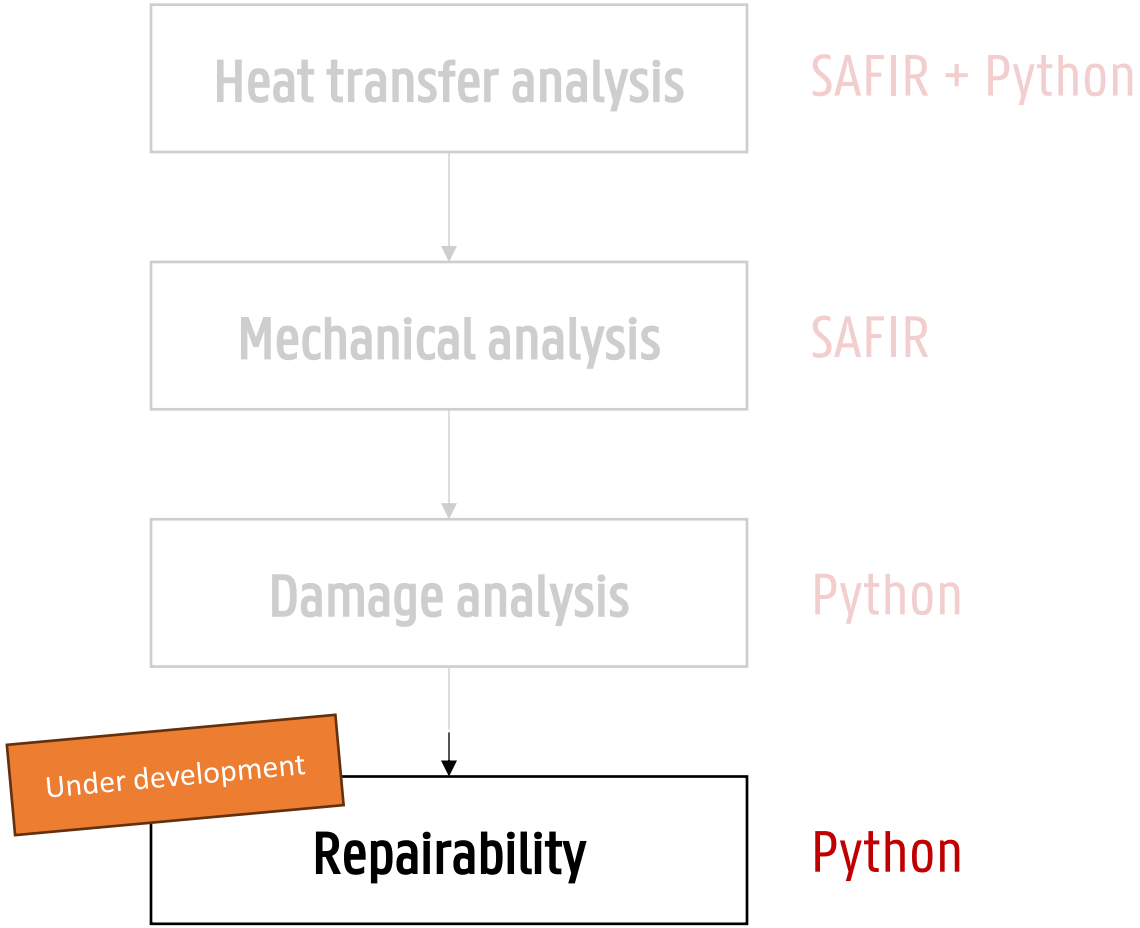
No spalling case

- No protection: plastic hinges
- Roof and 1m walls protected: no plastic hinges, but some cracks

Spalling case (5 mm/min)

- No protection: premature collapse
- Protection roof: no collapse, but severe damage

Modeling approach



Under development

Repairability

Literature: Repairability linked to damage states

- Thermal damage
  - 300°C isotherm

Table 1
Fire damage states for the EDP of the penetration depth of the 300 °C isotherm in the sections of the RC members [41,46,47].

Damage states	EDP: Penetration depth of the 300 °C isotherm (d300)	Repair actions
DS0	Temperature did not exceed 300 °C in concrete	• No repair is required; redecoration if required
DS1	0 < d300 < c/10	• Chip, clean and patch the damaged region
DS2	c/10 ≤ d300 < c	• Remove damaged concrete in repair area to fully expose rebar • Clean by high water pressure • Blow off dust/debris with oil-free dry compressed air • Place repair material by wet shotcrete process to full depth of repair • Carefully trim excess material and steel trowel finish without overworking • Cure with sprayed membrane curing compound
DS3	c ≤ d300 < d/4 (d is the side dimension of the cross section)	• Remove concrete in repair area to fully expose reinforcing bars and to the depth of 300 °C • Final clean by high water pressure • Blow off dust/debris with oil-free dry compressed air • Placement of supplemental rebar • Place repair material by wet shotcrete process to full depth of repair • Carefully trim excess material and steel trowel finish without overworking • Cure with sprayed membrane curing compound
DS4	d/4 ≤ d300 ≤ d/2	• Demolish and reconstruct

* c = concrete cover to the edge of the rebar.

Ni & Gernay (2021)

Under development

Repairability

Literature: Repairability linked to damage states

- Thermal damage
  - 300°C isotherm

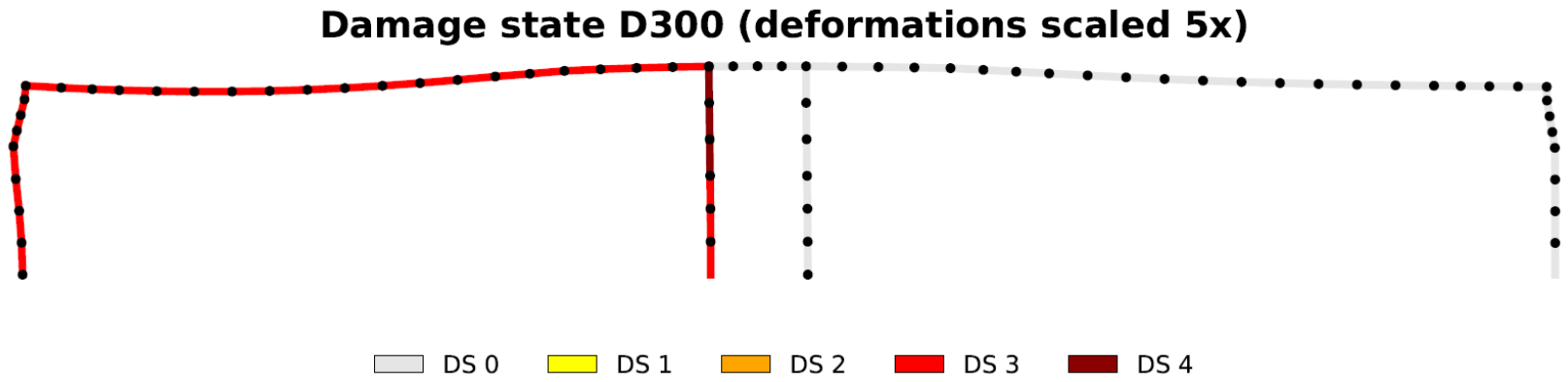


Table 1
Fire damage states for the EDP of the penetration depth of the 300 °C isotherm in the sections of the RC members [41,46,47].

Damage states	EDP: Penetration depth of the 300 °C isotherm (d300)	Repair actions
DS0	Temperature did not exceed 300 °C in concrete	• No repair is required; redecoration if required
DS1	$0 < d300 < c/10$	• Chip, clean and patch the damaged region
DS2	$c/10 \leq d300 < c$	• Remove damaged concrete in repair area to fully expose rebar • Clean by high water pressure • Blow off dust/debris with oil-free dry compressed air • Place repair material by wet shotcrete process to full depth of repair • Carefully trim excess material and steel trowel finish without overworking • Cure with sprayed membrane curing compound
DS3	$c \leq d300 < d/4$ (d is the side dimension of the cross section)	• Remove concrete in repair area to fully expose reinforcing bars and to the depth of 300 °C • Final clean by high water pressure • Blow off dust/debris with oil-free dry compressed air • Placement of supplemental rebar • Place repair material by wet shotcrete process to full depth of repair • Carefully trim excess material and steel trowel finish without overworking • Cure with sprayed membrane curing compound
DS4	$d/4 \leq d300 \leq d/2$	• Demolish and reconstruct

* c = concrete cover to the edge of the rebar.

Under development

Repairability

Literature: Repairability linked to damage states

- Thermal damage
  - 300°C isotherm
- Mechanical damage
  - Residual deflections

Table 3
Damage states based on residual vertical deflection of RC slabs [46,49,50].

Damage state	EDP: Residual vertical deflection (RDR)	Repair method
DS0	$\Delta_s/l < 1/240$	• No repair is required
DS1	$1/240 \leq \Delta_s/l < 1/120$	• Clean the surface by high-pressure water • Blow off dust/debris with oil-free dry compressed air • Place repair material • Cure with sprayed membrane curing compound
DS2	$1/120 \leq \Delta_s/l < 1/60$	• The slab should be demolished and reconstructed, while beams can be reused
DS3	$1/60 \leq \Delta_s/l$	• The whole floor system, including slabs and beams, should be demolished and reconstructed

Ni & Gernay (2021)

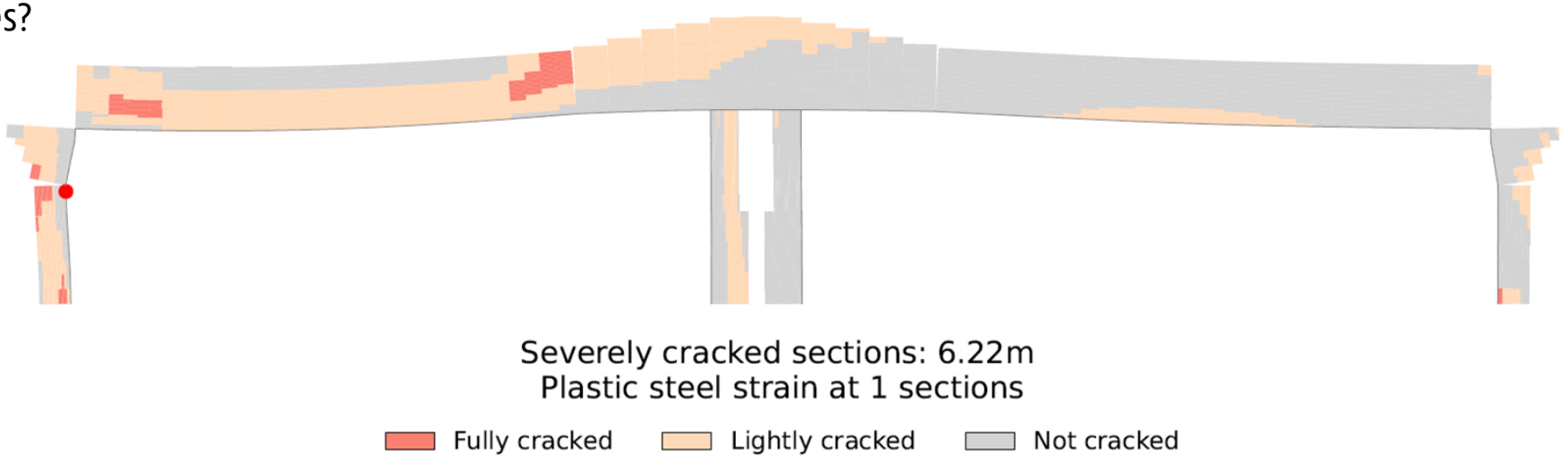
Under development

Repairability

Literature: Repairability linked to damage states

- Thermal damage
  - 300°C isotherm

- Mechanical damage
  - Residual deflections
  - Cracks and plastic hinges?



Conclusions

Conclusions

Structural fire analysis concrete tunnels (Phase 2)

- Fire performance in case of spalling highly depends on shape, reinforcement, passive fire protection

Damage analysis tool (Phase 3)

- Quantify damage during heating and cooling phases
- Can aid design (prevent collapse ↔ prevent severe damage)
- Informs repairability analysis

Open research questions

- How to deal with shear in case of spalling?
- Need for tunnel specific repairability metrics?
- What level of damage is acceptable (land tunnel ↔ underwater tunnel)

Questions

Thomas Thienpont

UNIVERSITEIT GENT

PYRO Engineering