Fire dynamics simulations in structural stability prediction and fire safety assessment

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Problem description

Tall buildings


Shopping mall


Airplane


Tunnel


Vehicles


Ships

How can we minimize the damage of the fire accident?

1. Structure: enough fire resistance capability; 2. Designer: Proper fire safety strategy

Content

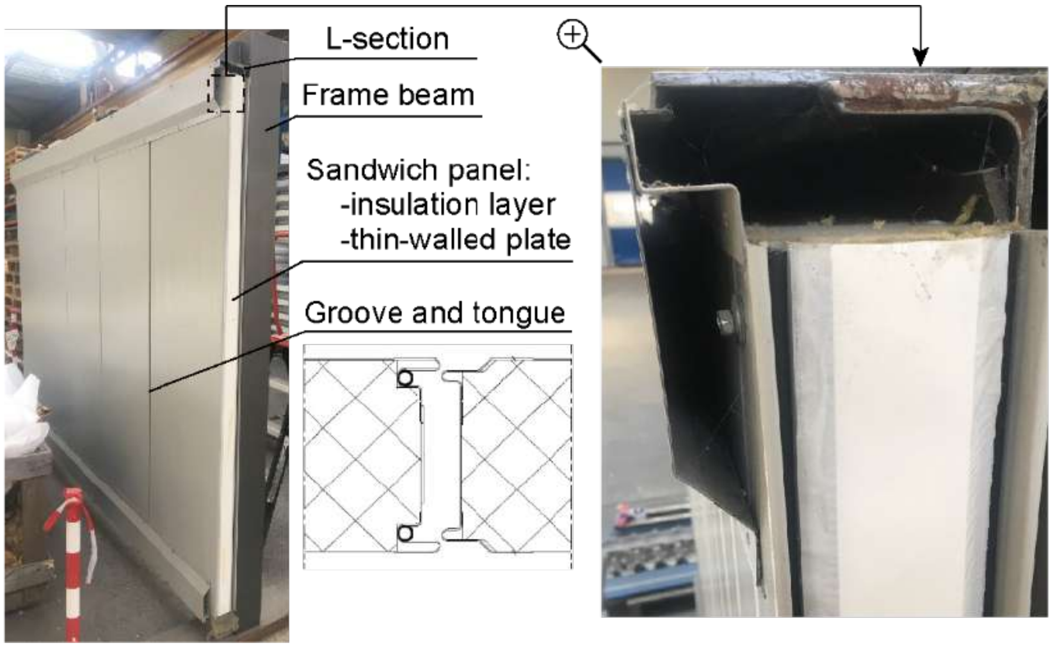
- Fire resistance capability of structures: Buildings with Connections + Insulation Systems
- Fire safety design and risk analyses in projects

Background

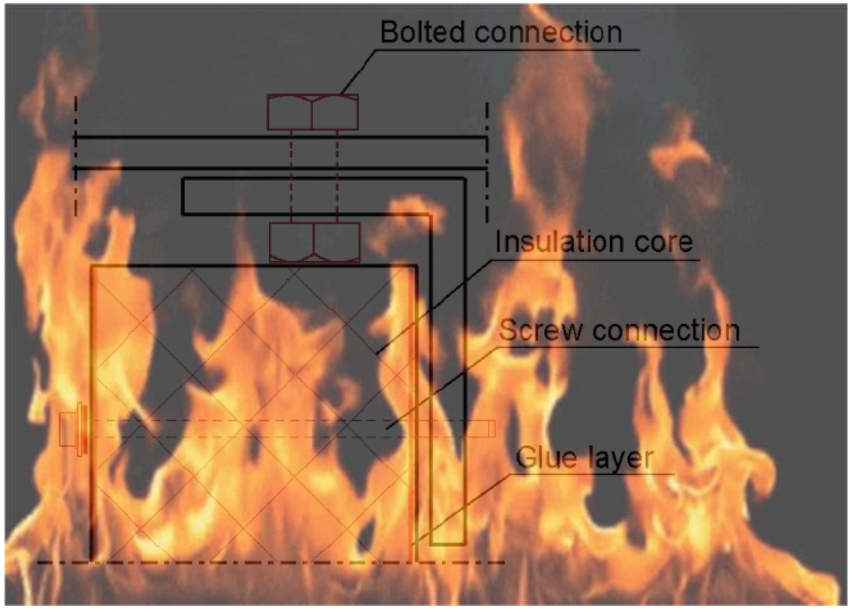
Fire ⇄ Structure

This video refers from the *Fire Safety Research Institute* on YouTube:
https://www.youtube.com/watch?v=tGTESi1ejA0&list=RDCMUCd36aiebKHk0EKmP7MTuuqw&index=8

Research target



Sandwich panel façade system with connections



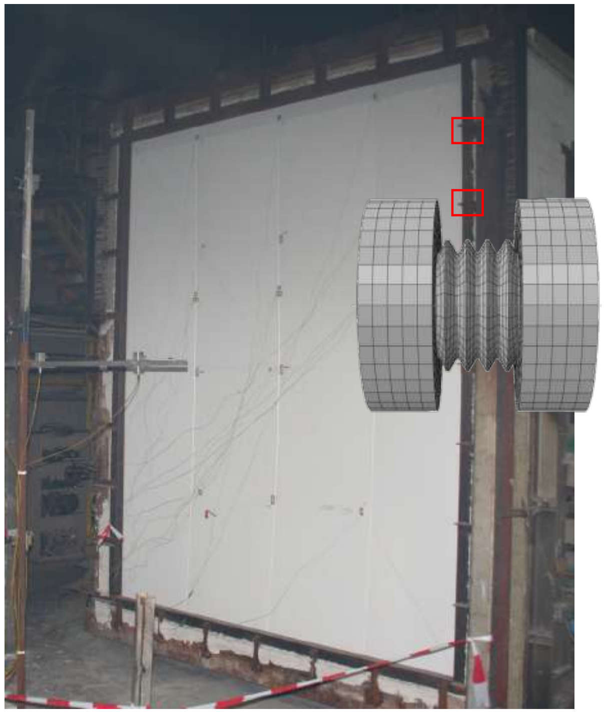
Connections

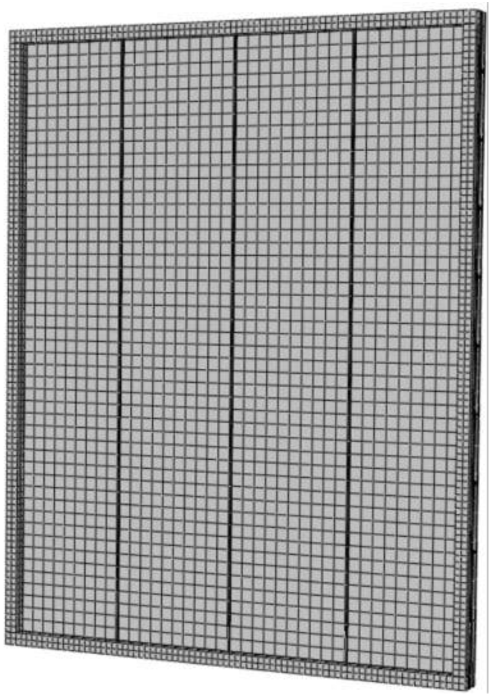
Insulation

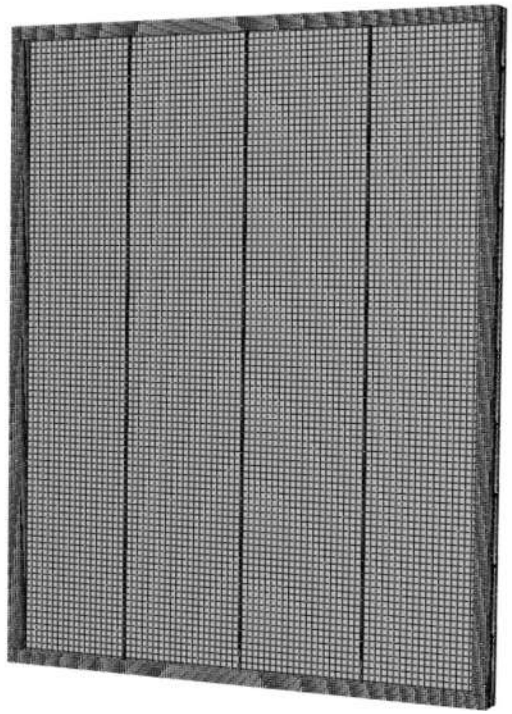
Fire Safe Buildings with Thin-Walled Steel + Insulation Systems

- Modelling the small-scale connections in the large-scale façade
- The modelling and its verification of sandwich panels including connections in fire resistance tests
- Pyrolysis modelling of composite materials in coupled fire-structure simulations

Problem description- different scales

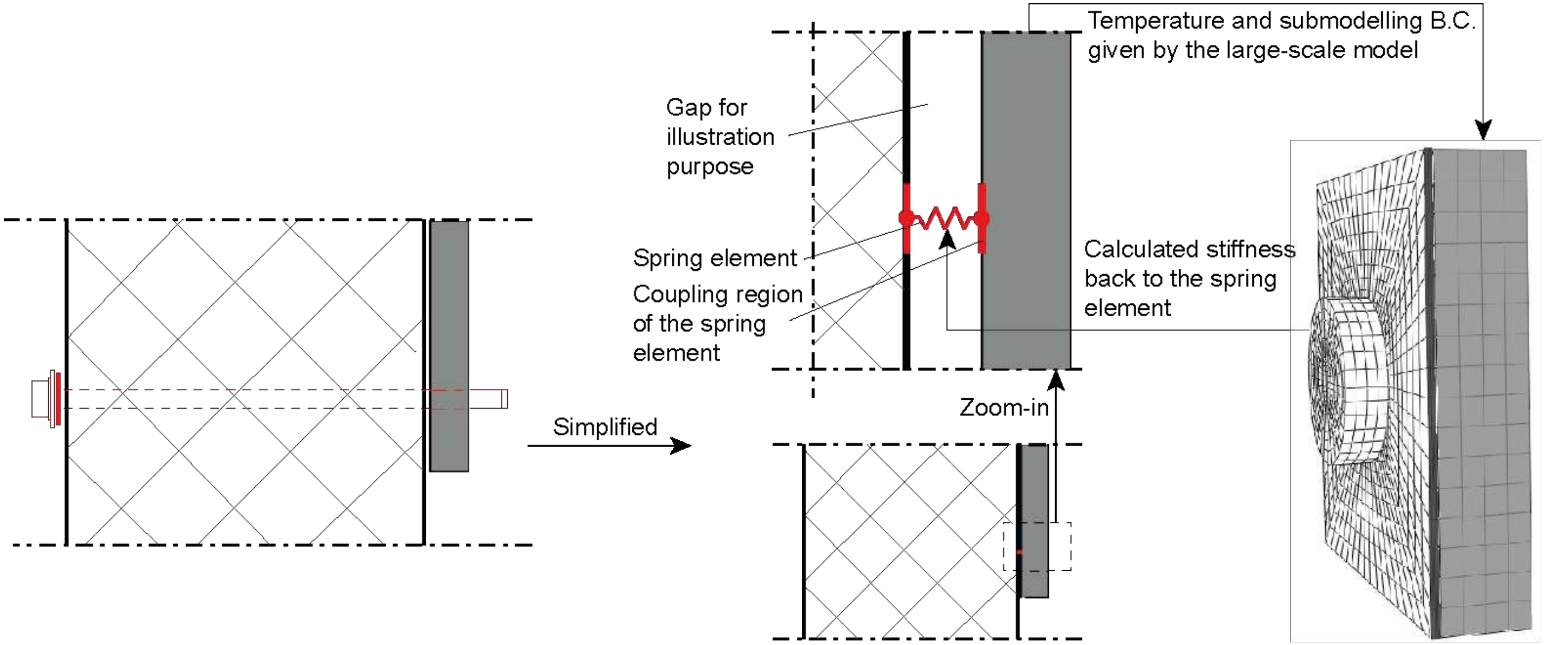






In finite element analysis, structures must be divided into small elements (meshes). The finer the mesh, the more accurate the results will be obtained. However, the computational costs will also be increased.

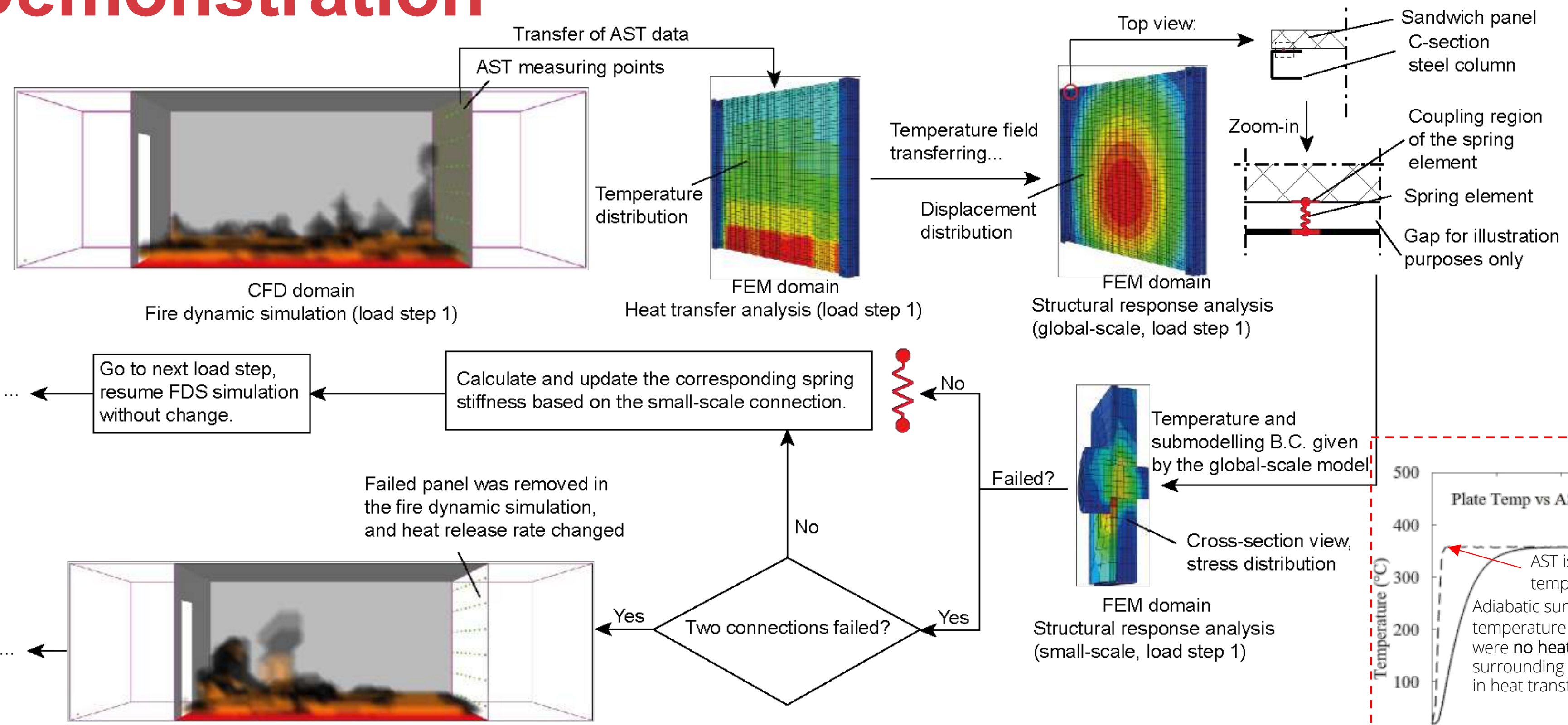
Two-scale model

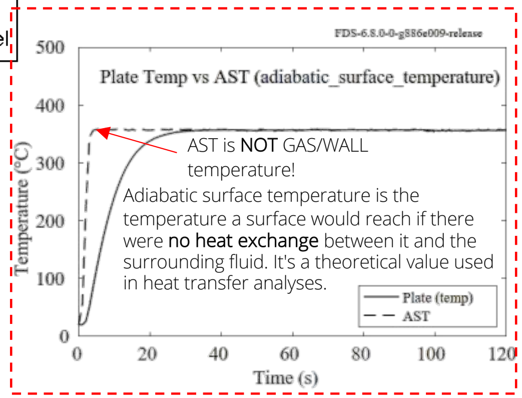


a) Sandwich panel with a screw connection b) Finite element modeling (large-scale) c) Two-scale model (small-scale model)

Overview of the two-scale model: the behaviour of the spring element comes from the detailed screw connection model (we do not need to model the screw in detail, so the computational cost is reduced).

Demonstration





Implementation of the **two-scale** model in a **two-way** coupled fire-structure simulation

Xu Q, Hofmeyer H, Maljaars J. A two-scale method to include essential screw connection behaviour in two-way coupled fire-structure simulations. *Journal of Structural Fire Engineering*. 2023 Aug 29. https:// 10.1108/JSFE-01-2023-0005

Xu Q, Hofmeyer H, Maljaars J. Multi-scale bolt connection model for thermomechanical simulations. *ce/papers*. 2021 Sep;4(2-4):1297-303. https://doi.org/10.1002/cepa.1424

Fire Safe Buildings with Thin-Walled Steel + Insulation Systems

- Modelling the **small-scale connections** in the large-scale façade
- The modelling and its verification of sandwich panels including connections in fire resistance tests
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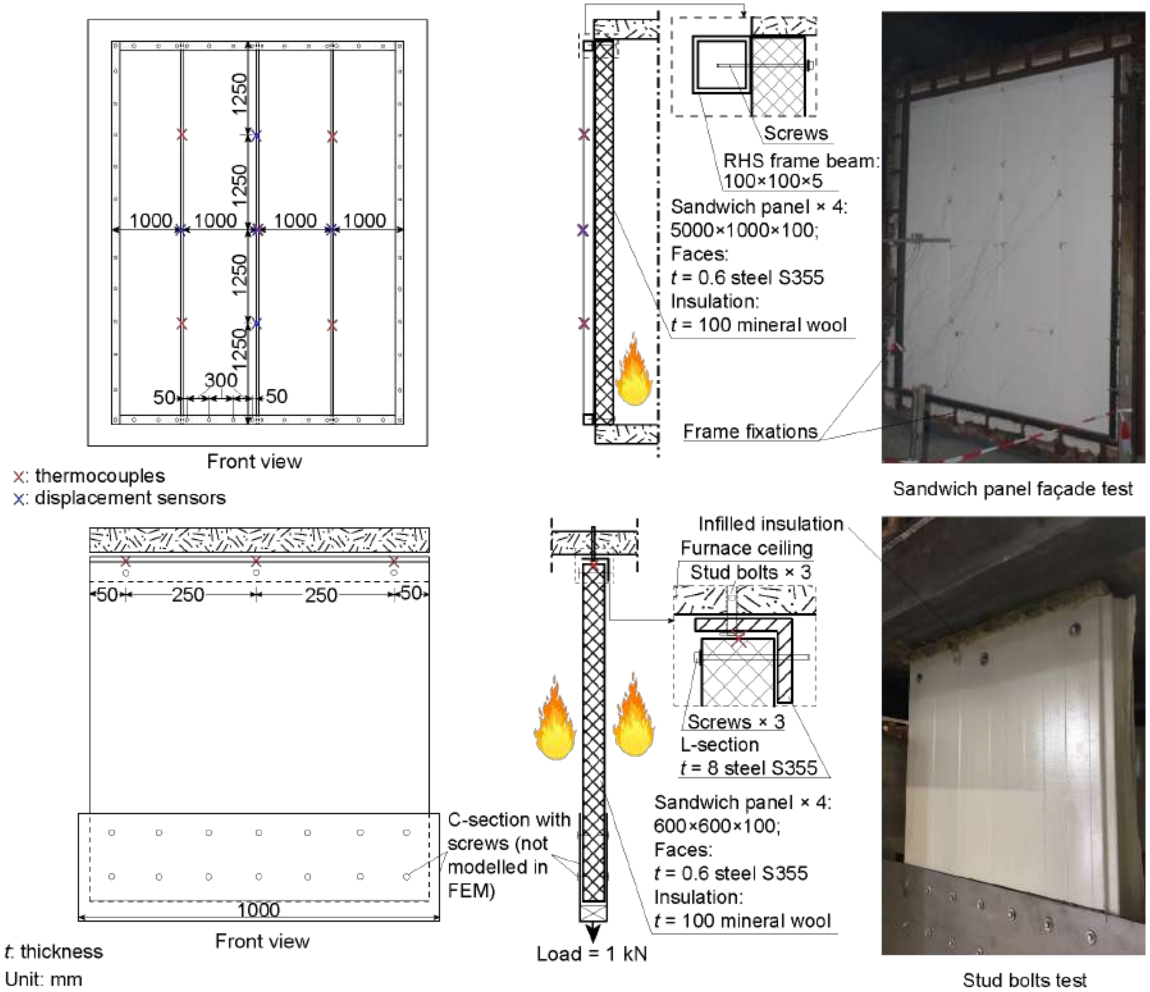
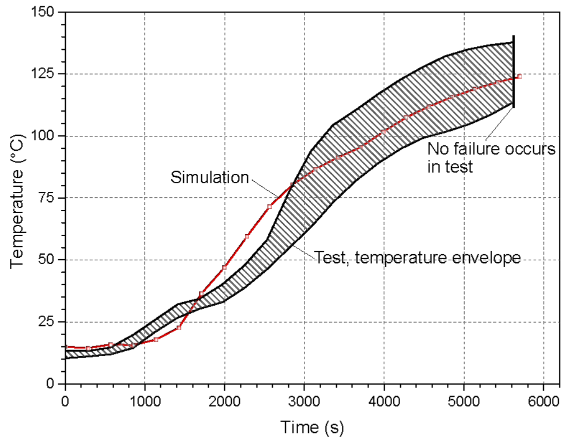
Full-scale fire tests

Setup of fire resistance tests

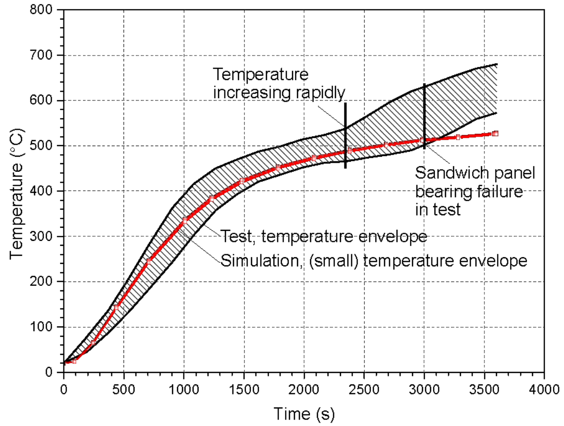
Top row: Sandwich panel façade test;
Bottom row: Stud bolts test.



Results-1

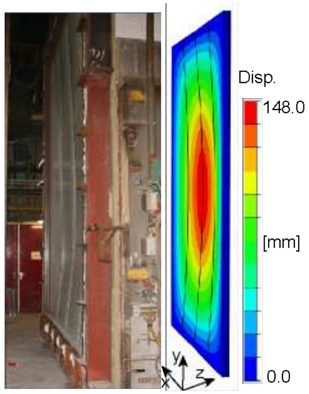


a) Test 1: Sandwich panel facade test

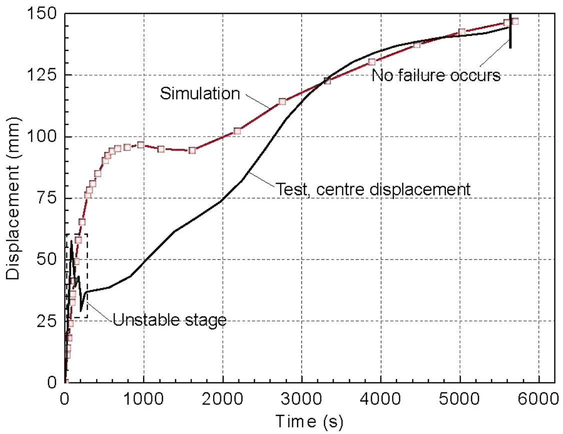


b) Test 2: Stud bolts test

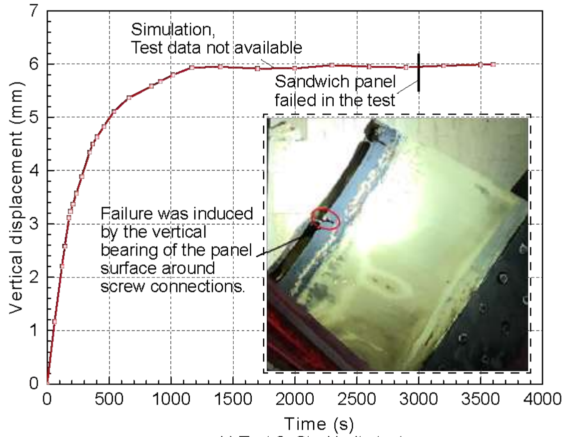
Heat transfer analysis



Time = 5500 s



a) Test 1: Sandwich panel facade test

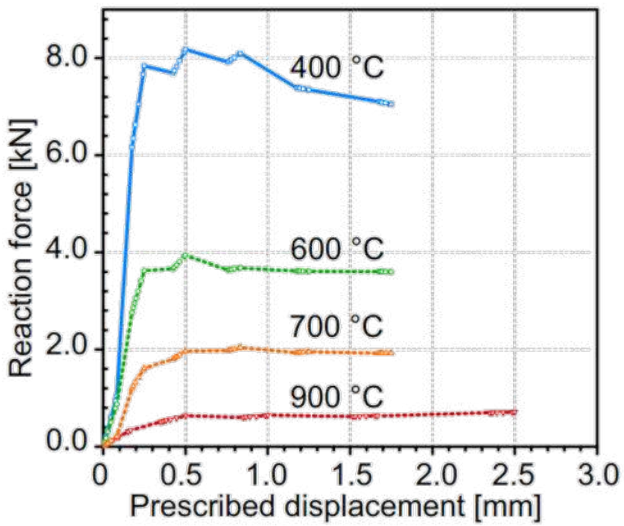


b) Test 2: Stud bolts test

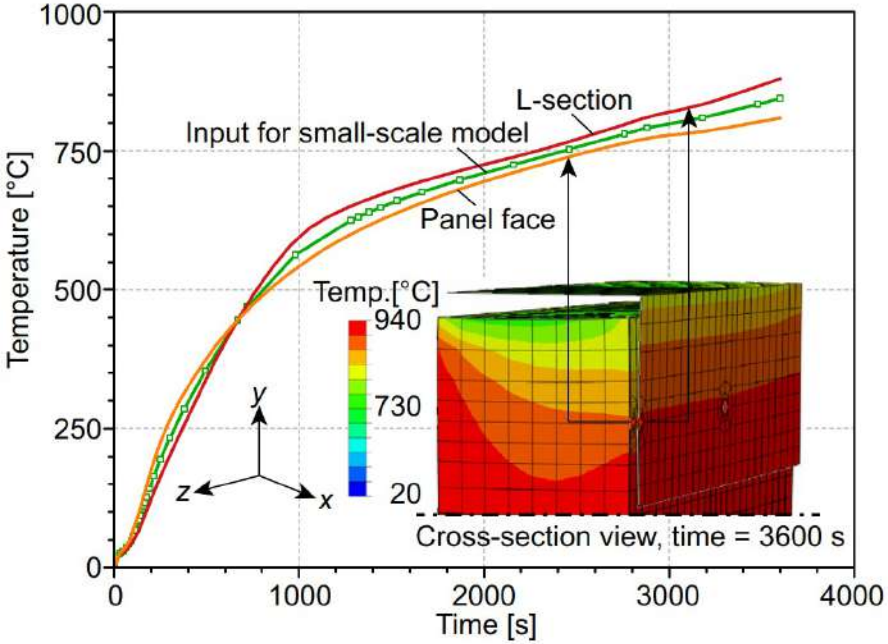
Structural responses analysis

Finding:
Simulation can reasonably predict the temperature distribution and structural deformation during a fire.

Results-2



(a) Loading position



Finding: The proposed two-scale model can predict the failure temperature of small-scale connections in a large-scale structure.
Test: failure time of screw connections : 3000 s → temperature at this moment is **800 °C**;
Simulation: when temperature is **800 °C**, the maximum external load is **1 kN** (this is the load at the bottom of sandwich panel).

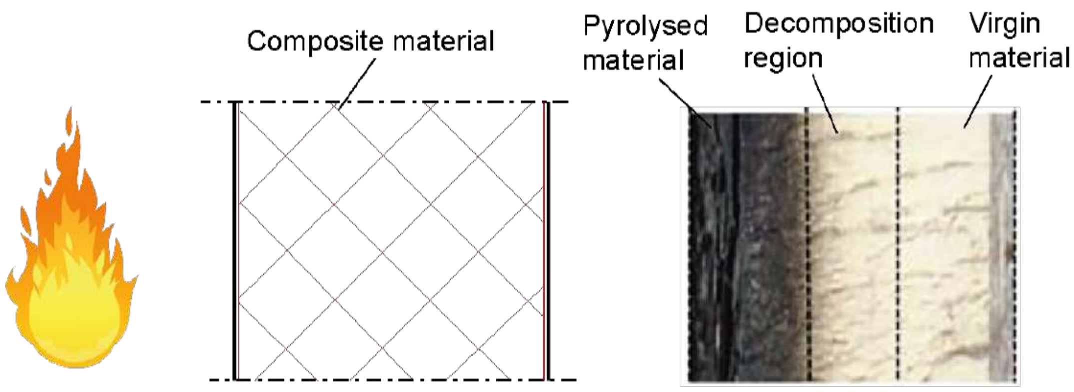
Xu, Q., Hofmeyer, H., Maljaars, J. and van Herpen, R.A., (2023). Full-Scale Fire Resistance Testing and Two-Scale Simulations of Sandwich Panels with Connections. *Fire Technology*. https://doi.org/10.1007/s10694-023-01463-y

Xu, Q., Hofmeyer, H., Maljaars, J. and van Herpen, R.A., (2022). Thermomechanical modelling of sandwich panels with connections in fire resistance tests. In *SiF 2022-The 12th International Conference on Structures in Fire* (pp. 703-714).

Fire Safe Buildings with Thin-Walled Steel + Insulation Systems

- Modelling the small-scale connections in the large-scale façade
- The modelling and its verification of sandwich panels including connections in fire resistance tests
- Pyrolysis modelling of composite materials in coupled fire-structure simulations

Problem description – pyrolysis model



Sandwich panel with a composite core under fire

Governing equation of heat transfer:

$$\frac{\partial}{\partial t}(\rho h) = \nabla\left(k_1\frac{\partial T}{\partial x}\mathbf{i} + k_2\frac{\partial T}{\partial y}\mathbf{j} + k_3\frac{\partial T}{\partial z}\mathbf{k}\right) - \boxed{\frac{\partial}{\partial x}(\dot{m}_g h_g)} - \boxed{Q_i\frac{\partial \rho}{\partial t}}$$

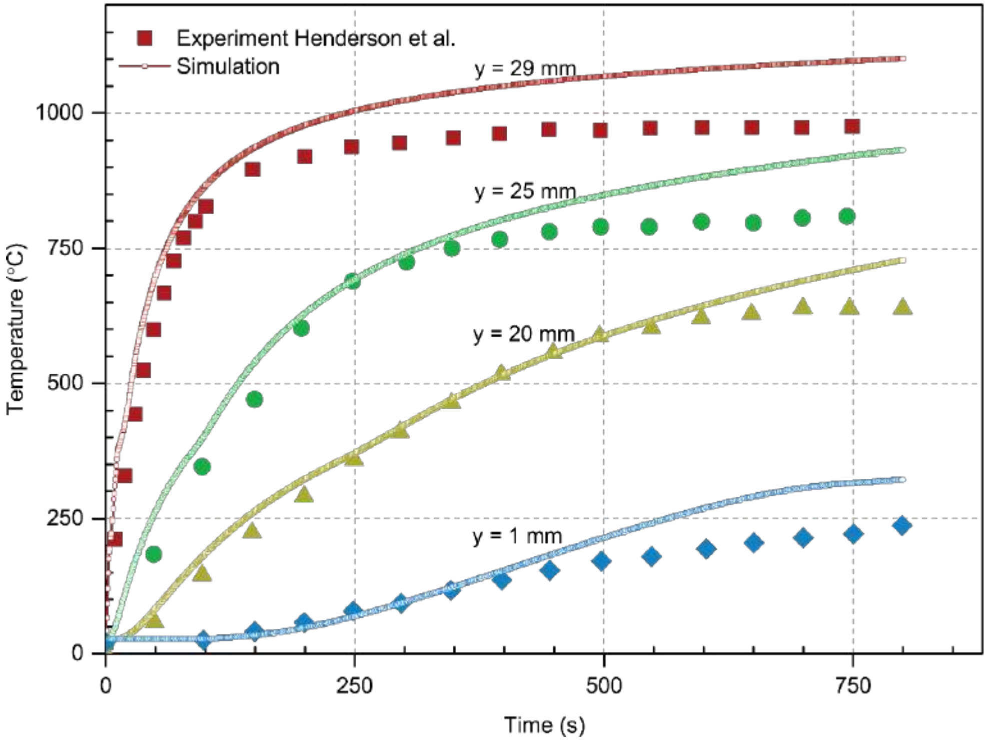
Pyrolysis reaction (Arrhenius Equation):

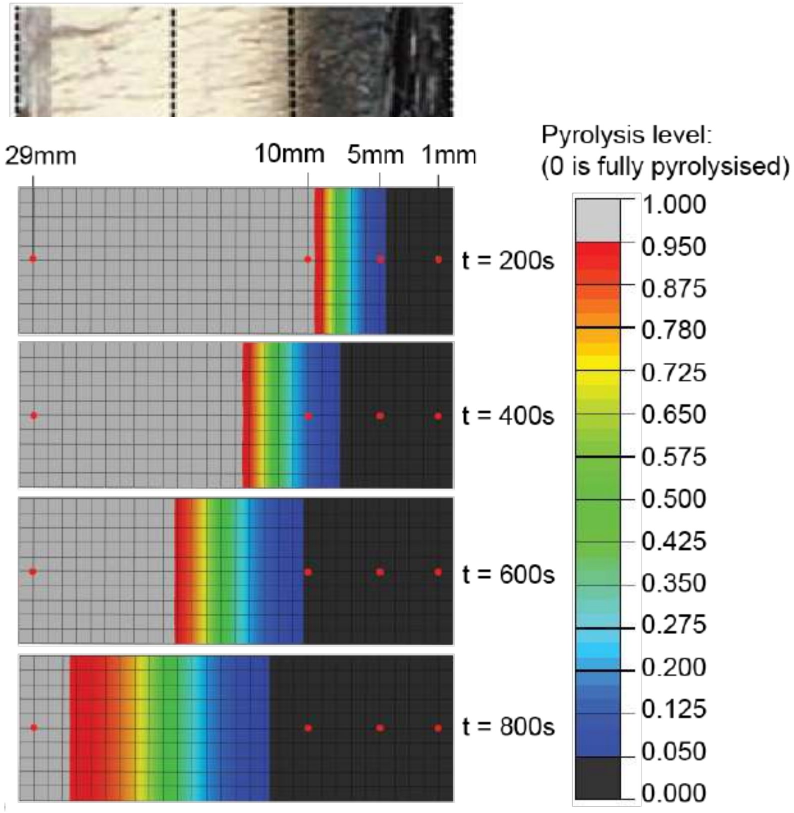
$$\frac{\partial m}{\partial t} = -A_i m_v\left[\frac{m - m_c}{m_v}\right]^{n_i} e^{-\frac{E}{RT}}$$

The mass flux of pyrolysis gas at an arbitrary location x:

$$\dot{m}_g = \int_l^x \frac{\partial \rho}{\partial t}dx$$

Pyrolysis modelling

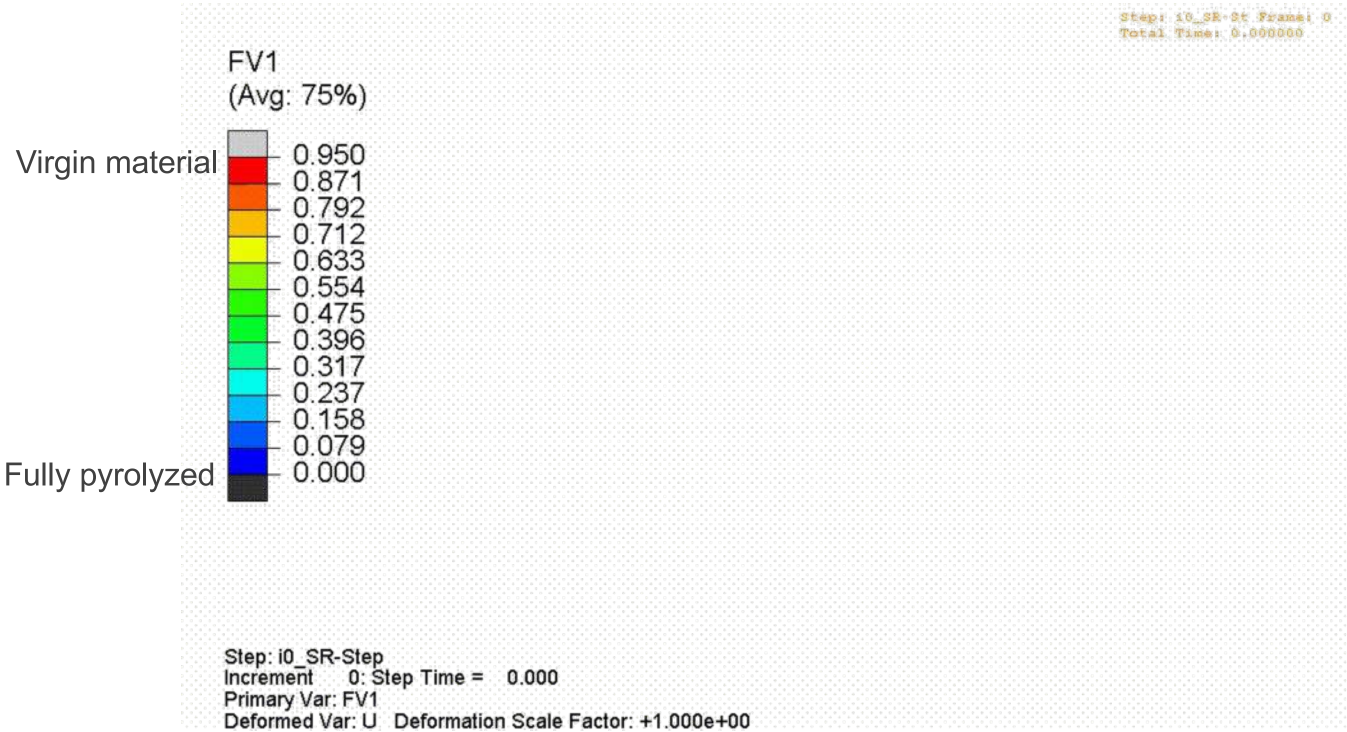




Temperature of FE model VS. experiment

Henderson, J. B., Wiebelt, J. A., & Tant, M. R. (1985). A model for the thermal response of polymer composite materials with experimental verification. Journal of composite materials, 19(6), 579-595.

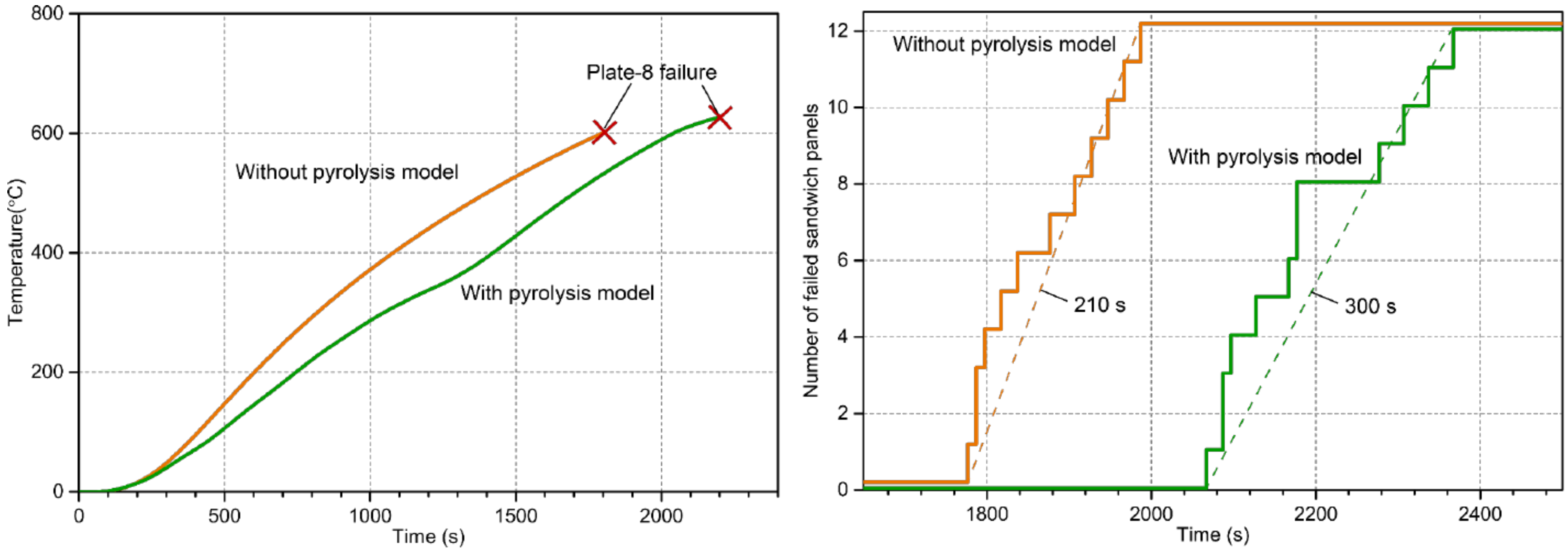
Implementation of the pyrolysis model



Implementation of the pyrolysis model in a One-Way Coupled (OWC) fire-structure simulation (Abaqus)

Examples (pyrolysis and without pyrolysis)

Comparisons of the simulation with/without considering the pyrolysis behaviour (TWC, door width = 1.2 m)



(a) Temperature in plate-8 (unexposed side, centre point)

(b) Progress failure infromation of the plates

The pyrolysis reaction absorbs heat from the fire, which consequently postpones structural failure → more accurate failure prediction

Summary for structural fire resistance

- The full-scale tests are the best way to measure the fire resistance of structures, as they are realistic and informative.
- The costs for full-scale fire tests are extremely high, and in some extreme cases, cannot be conducted. Therefore, fire-structural coupled simulations can be the best alternative.
- Fire-structure coupled simulations are very complex because they concern problems in two different domains (CFD and FEM), and interactions between these two domains need to be taken into account.
- The accuracy of the numerical model (fire/structural) depends on how many details are considered. However, computational costs should also be taken into consideration when creating the model.

Content

Fire resistance capability of structures: Buildings with Connections + Insulation Systems

Fire safety design and risk analyses in projects

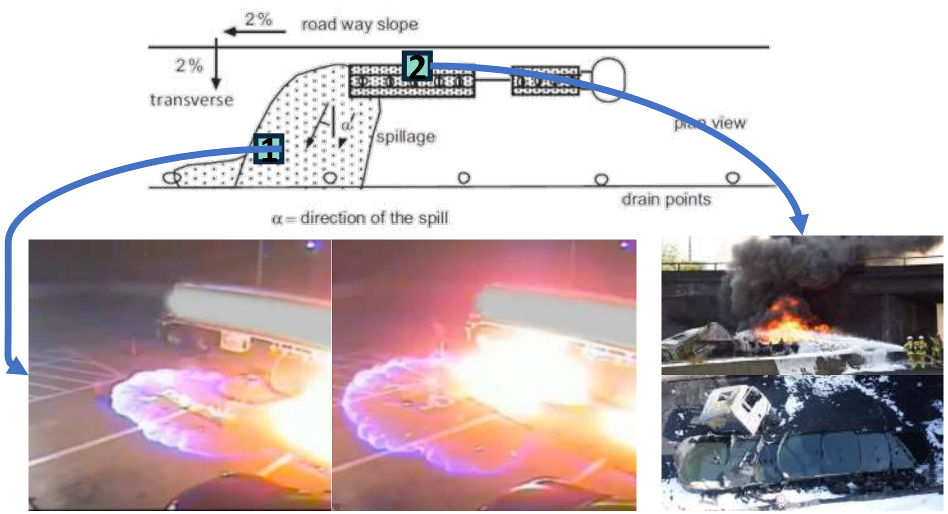
Introduction

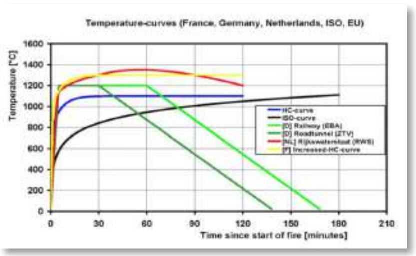
Overview of the Oosterweel project in Antwerp

https://www.oosterweelverbinding.be/

Pool fire

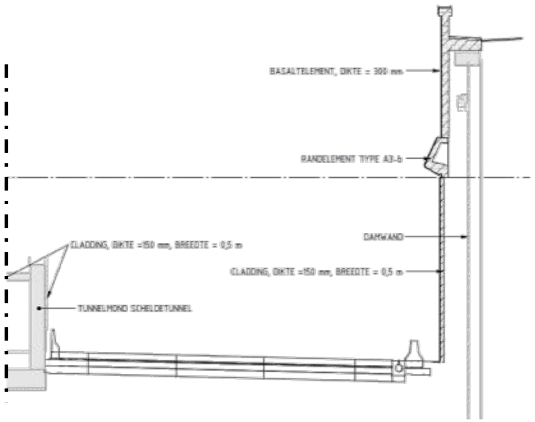
- Transportation of dangerous goods → Leakage accident → Pool fire → Fire resistance of wall → Protection needed?

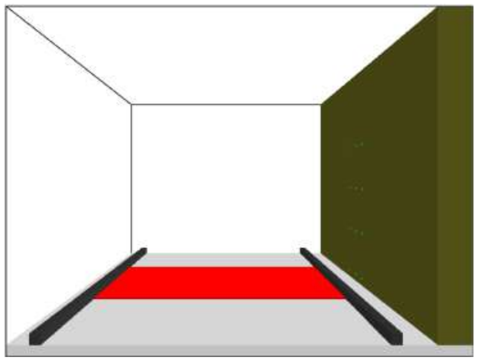


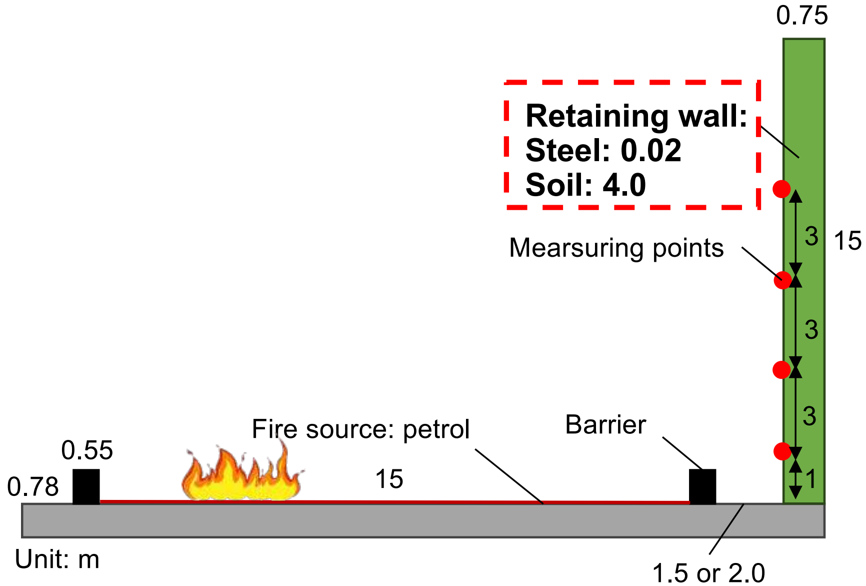


Directly apply to the steel pile surface → Overestimated, as the wall is not engulfed by flame.

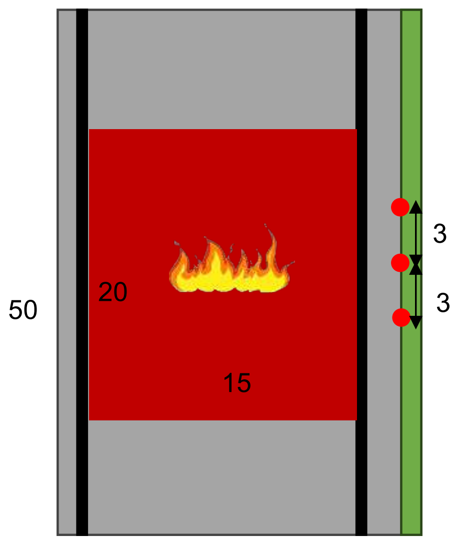
Model setup





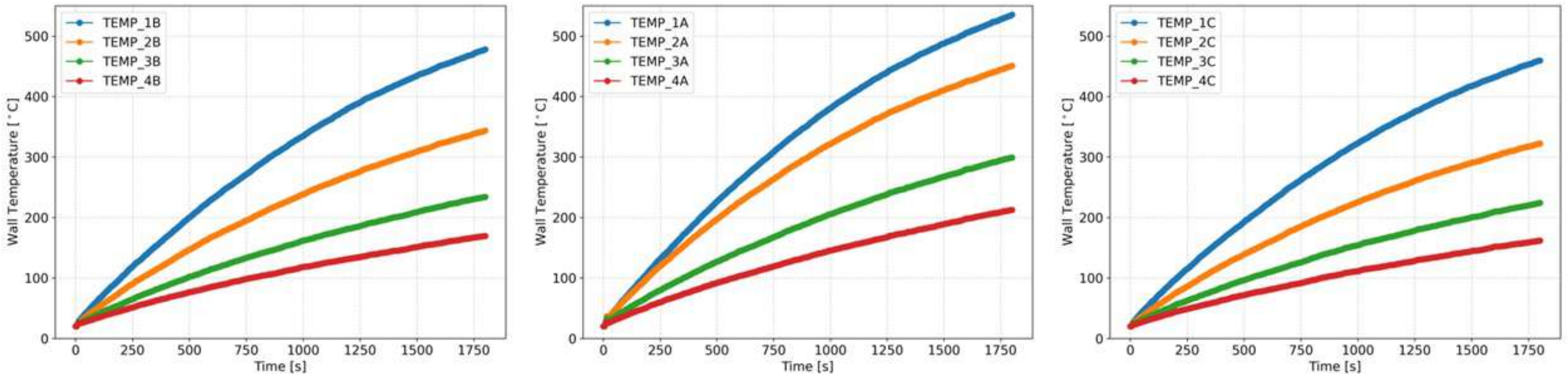


Front view



Top view

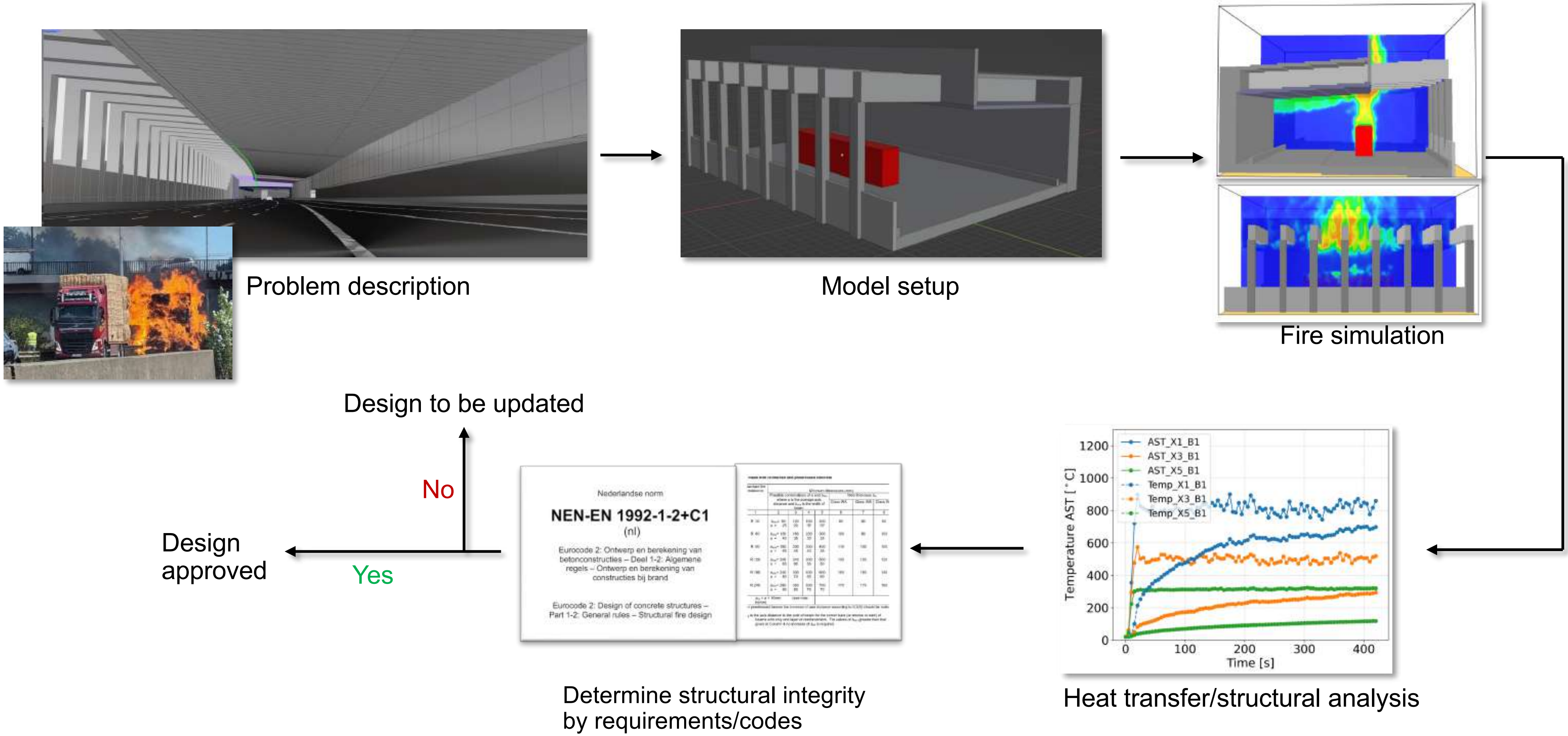
Findings (fire time = 30 minutes)



For a 30 minutes pool fire, the maximum surface temperature of the steel sheet pile (1.5 m away from the fire) is 535 °C, which is lower than the failure criteria of 550 °C from the stability analysis.

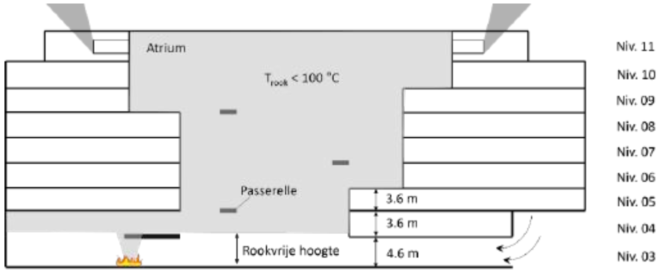
Therefore, the protection is not necessarily needed.

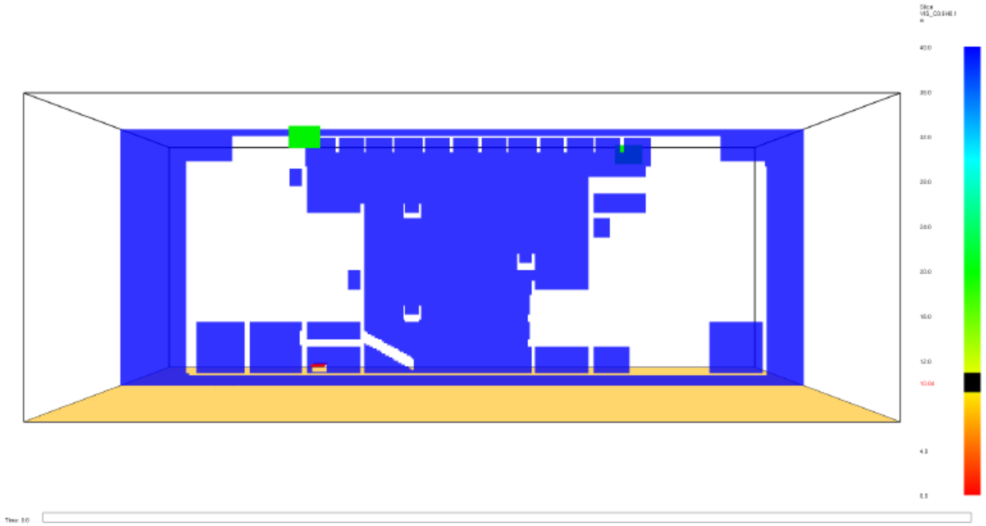
Truck fire



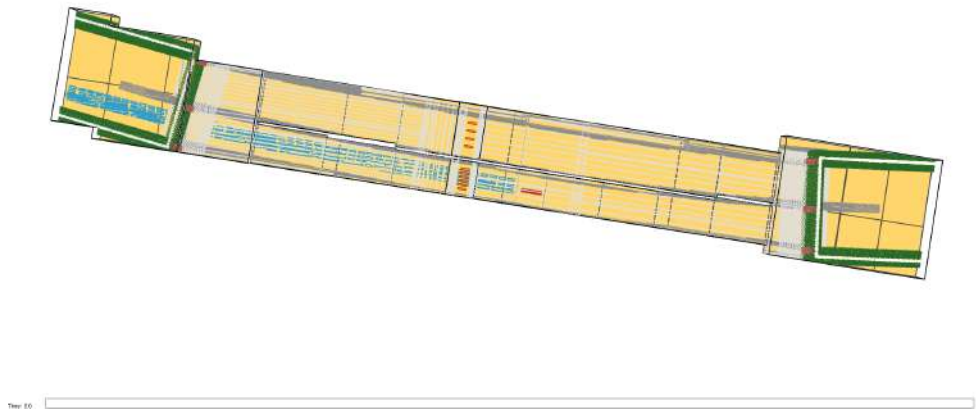
Problem description
Model setup
Fire simulation
Heat transfer/structural analysis
Temperature AST [°C]
Time [s]
AST_X1_B1
AST_X3_B1
AST_X5_B1
Temp_X1_B1
Temp_X3_B1
Temp_X5_B1
Nederlandse norm
NEN-EN 1992-1-2+C1
(nl)
Eurocode 2: Ontwerp en berekening van betonconstructies – Deel 1-2: Algemene regels – Ontwerp en berekening van constructies bij brand
Eurocode 2: Design of concrete structures – Part 1-2: General rules – Structural fire design
Determine structural integrity by requirements/codes
Design to be updated
No
Yes
Design approved

And more implementations …





Fire simulations for buildings



Fire simulations for tunnels

Summary for fire safety design in projects

1) Fire simulations are essential to solve practical problems, particularly in project-oriented fire safety design. Buildings or structures will not always 100% comply with the regular specifications in standards or codes.

2) Compared to standard fire tests, fire simulations could help to simulate different fire sizes, locations, durations, and fuel types and will give better insight in fire loads for assessment of fire protection measures.

3) Since fire simulations can accurately capture combustion physics, including oxygen consumption and smoke production, they are important for designing effective fire safety strategies for building or tunnel ventilation systems.

Team members

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Thanks for listening!

Questions?

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