


FISHWALL

FIre and Seismic performances of Hybrid fire WALLs in case of single-storey industrial and commercial steel buildings


SESSION: Numercial modelling and parametric analyses

- Fire performance assessment of steel structures associated with partition fire walls using “fusible” links
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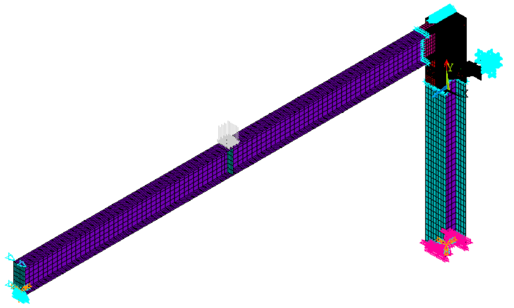
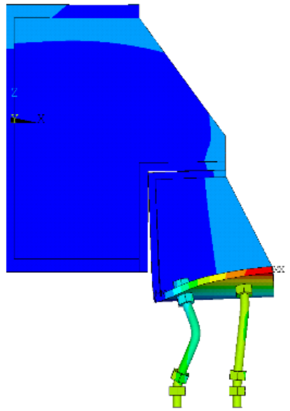
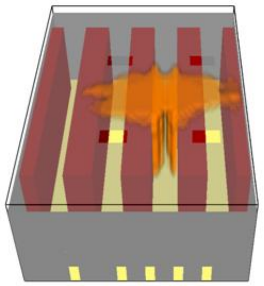
- CTICM

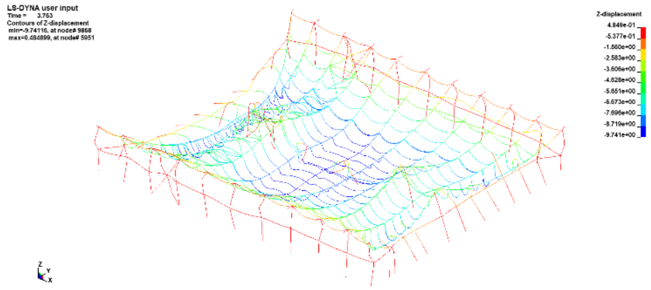
Contents

- FE numerical modelling of the fire test on steel frames associated to fusible links
- FE numerical study on the fire resistance of the investigated fusible links
- FE numerical study of the mechanical response of steel structures associated with fire walls using “fusible” links under realistic fire conditions



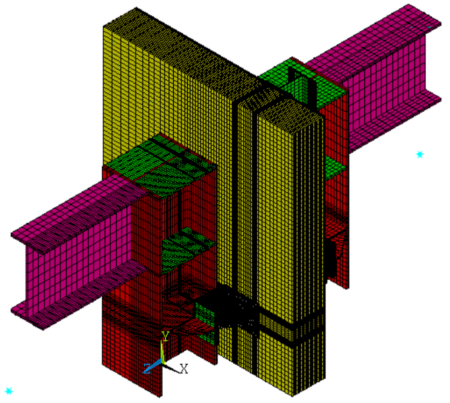




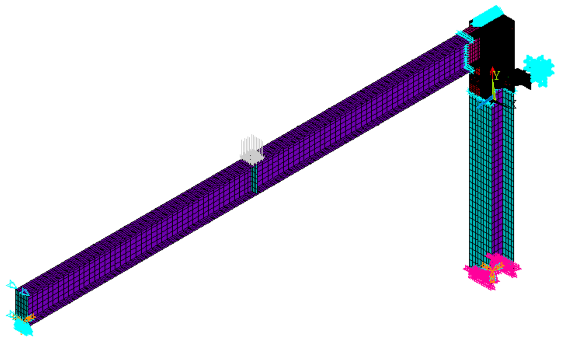


Numerical modelling of the fire test

- **Thermal–mechanical analyses conducted from 3D FE models utilising a sequentially coupled method**
  - Step 1: Heat transfer analysis:
    - Modelling of a part of the test specimen (wall, fusible systems and steel members connected on both wall sides) with 3D brick finite elements, according to the fusible system considered



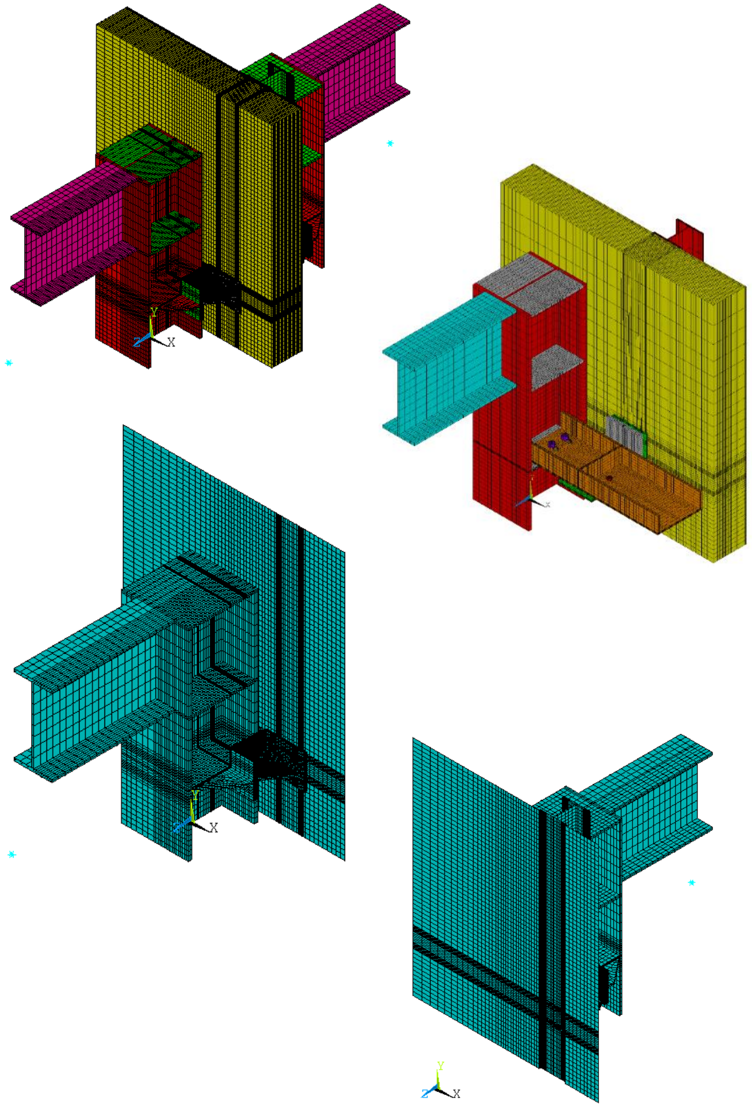
  - Step 2: Nonlinear structural (static & dynamic) analysis
    - Modelling of the fusible link exposed to fire, parts of the steel portal frame near the fusible link and the steel threaded rods, with a finite element mesh composed of 3D brick elements identical to the mesh used for the heat transfer analysis.



    - Modelling of other parts of the portal frame with shell elements
    - Nodal temperature histories from Step 1 directly attributed to the structural model

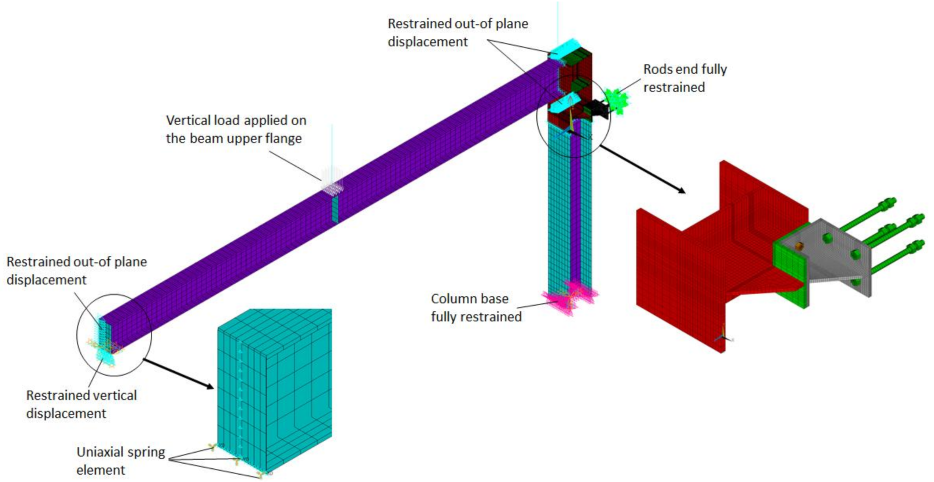
Numerical modelling of the fire test

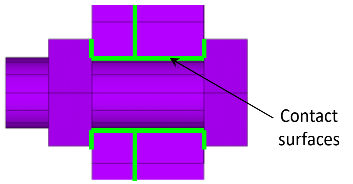
- **FE modelling assumptions :**
  - Thermal model:
    - Thermal actions according to EN 1991-1-2, considering the standard fire exposure
    - Shadow effect taken into account : radiative heat exchanges are evaluated considering view factors reduced by the geometry
    - Material properties of steel in accordance with the EN 1993-1-2
    - Thermal properties of insulated sandwich panels (mineral wool) calibrated against test data (test on reference walls)
    - Perfect thermal continuity assumed between all contact surfaces (wall, purlin, encasement, steel decking, insulation, etc..)

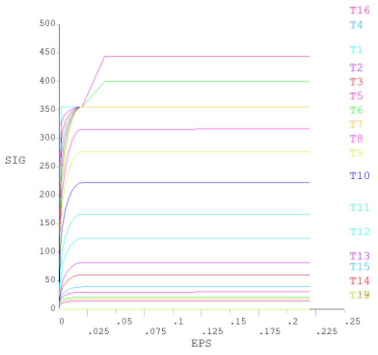


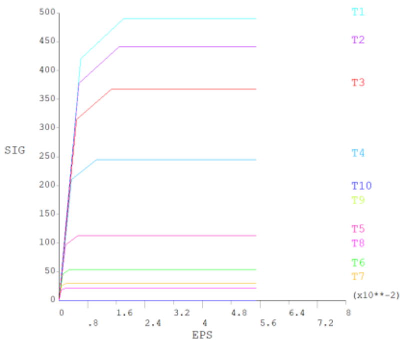
Numerical modelling of the fire test

- **FE modelling assumptions:**
  - Mechanical model:
    - Appropriate boundary conditions for non-modelled parts of the test specimen
    - Fusible link modelled as detailed as possible
    - Automatic surface-to-surface contact used for all contact surfaces, including friction phenomenon: contact between the steel profiles, between the bolts (heads and shanks) and the steel profiles (upper surface and holes)
    - Material models at elevated temperature:
      - Mechanical properties of steel at elevated temperature taken from EN 1993-1-2
      - Material behaviour of bolts and steel rods at elevated temperature represented by a tri-linear elasto-plastic model considering reductions factor from EN 1999-1-2 or EN 1993-1-2





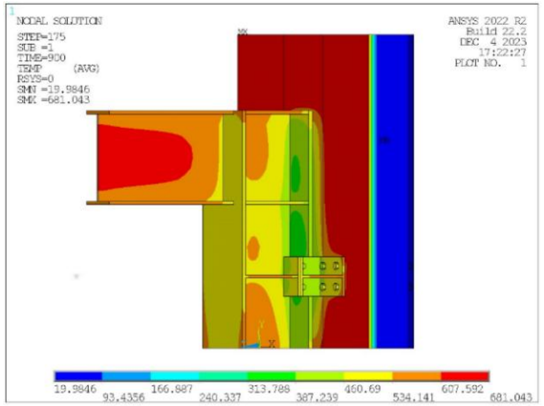


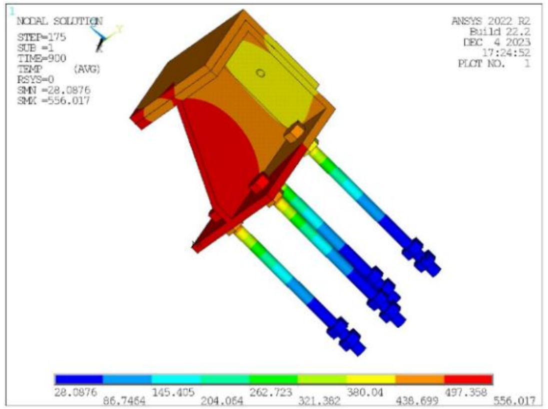


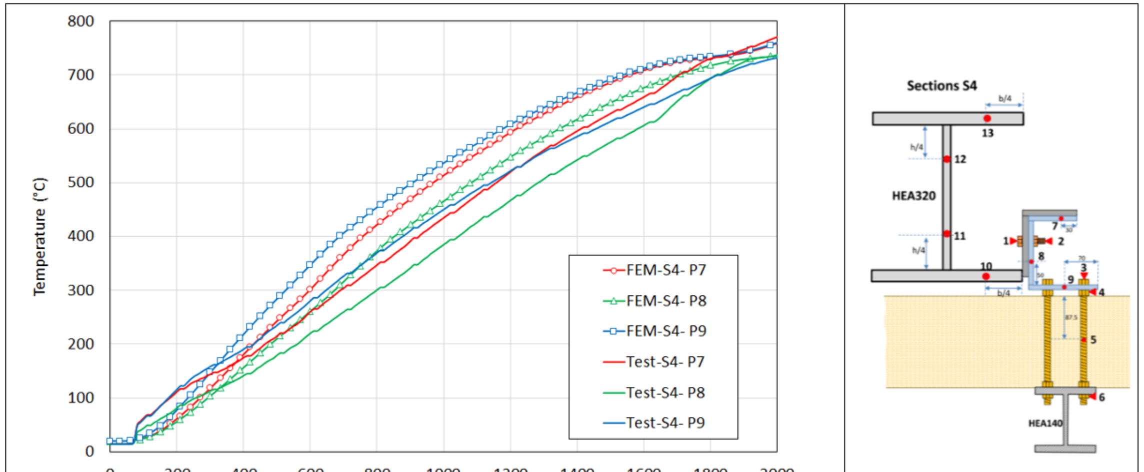
Numerical modelling of the fire test

➢ Comparison with test results

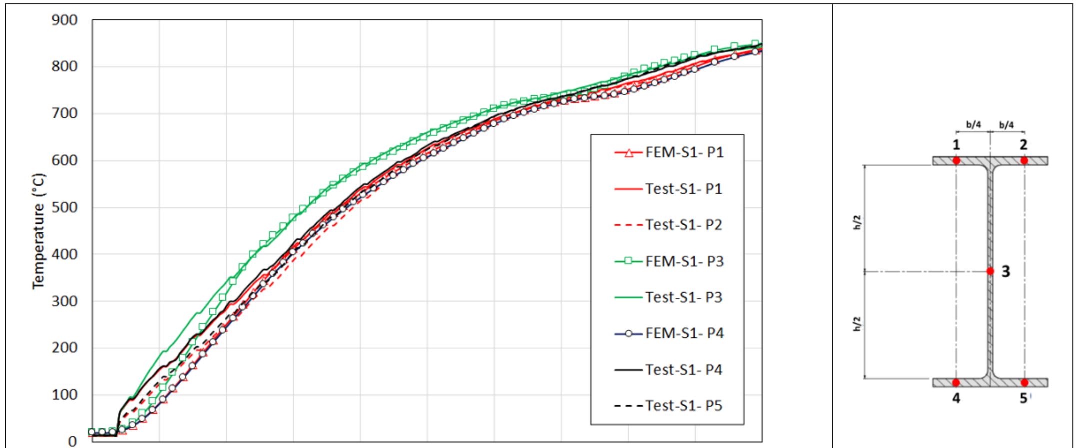
❖ Heating of the test specimen



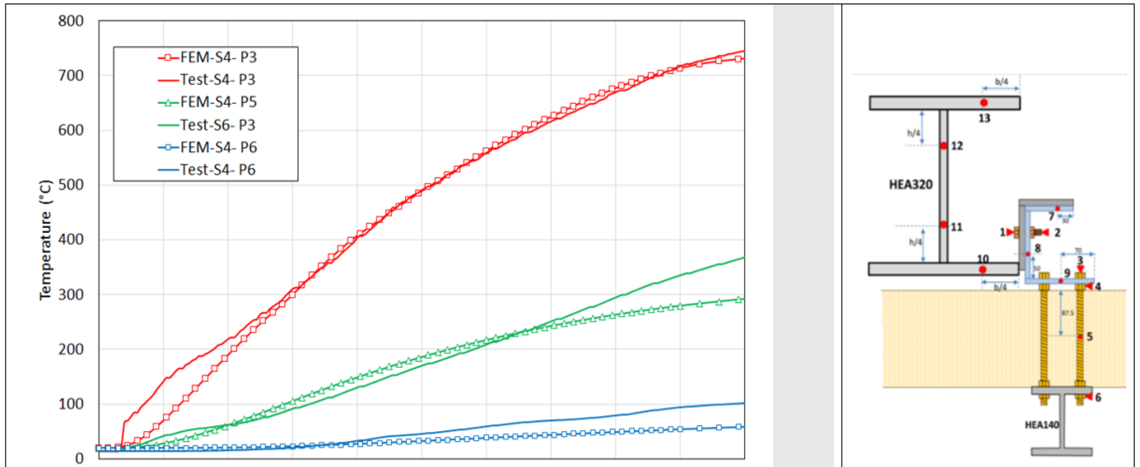




Steel profile



Steel beam

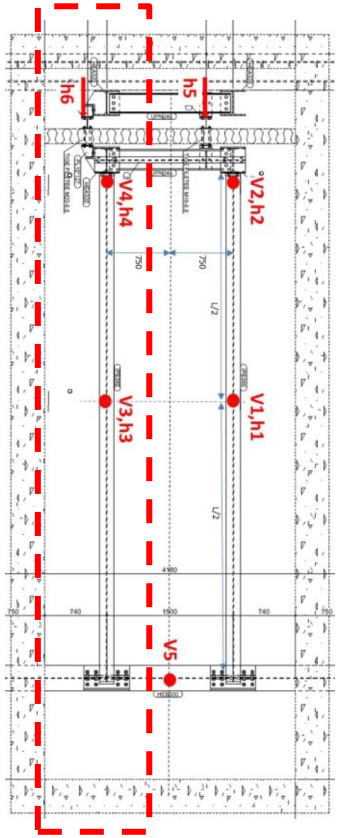


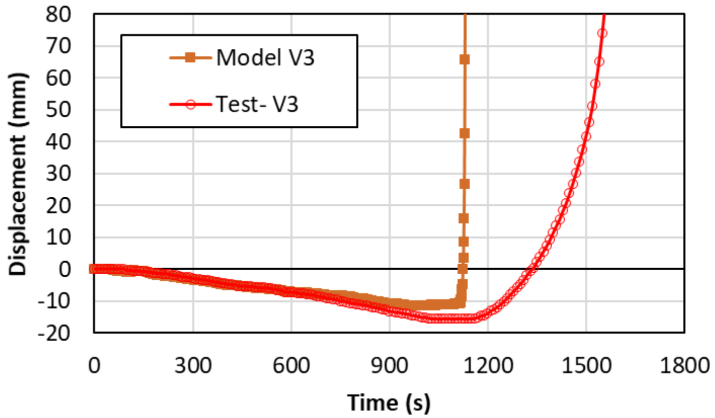
Steel rods

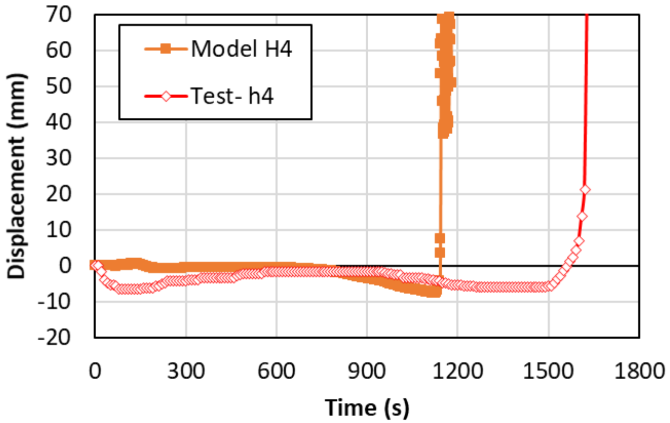
Numerical modelling of the fire test

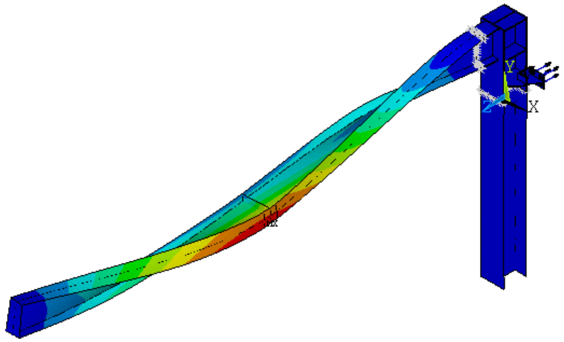
➢ Comparison with test results

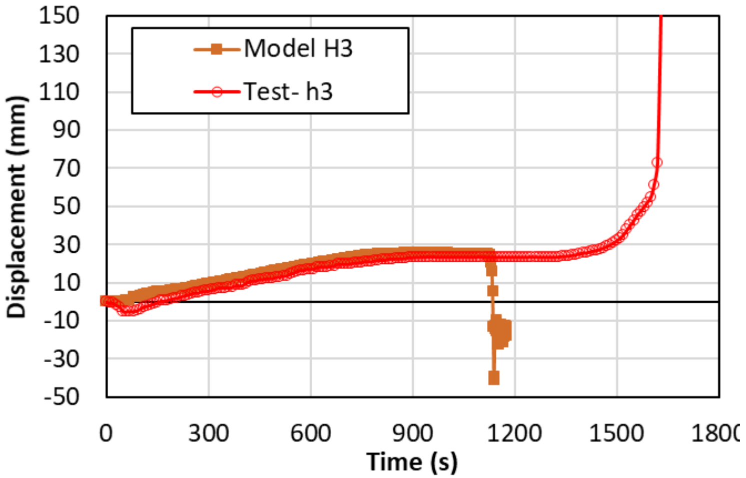
❖ Displacement curves and failure mode

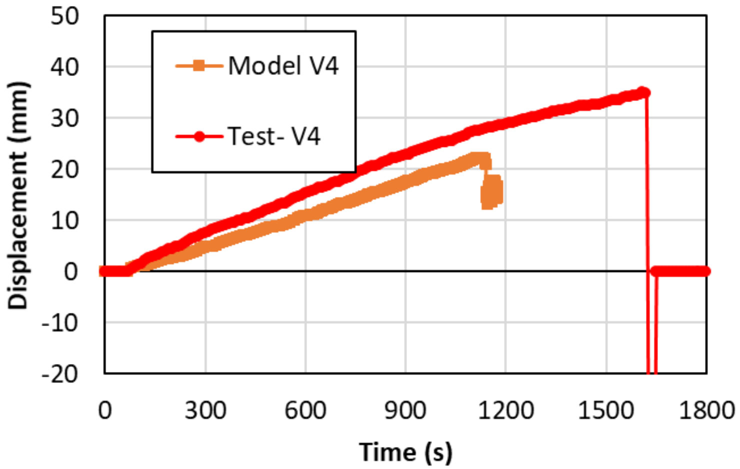


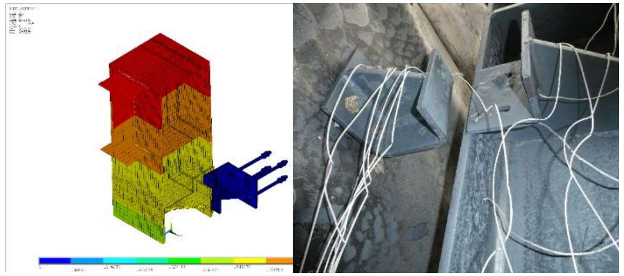










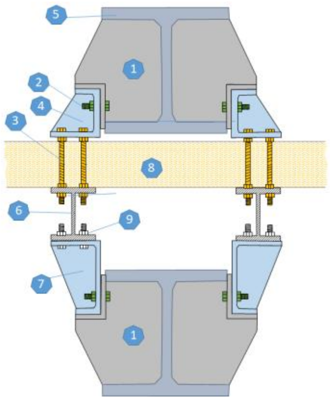


Parametric study on fusible links

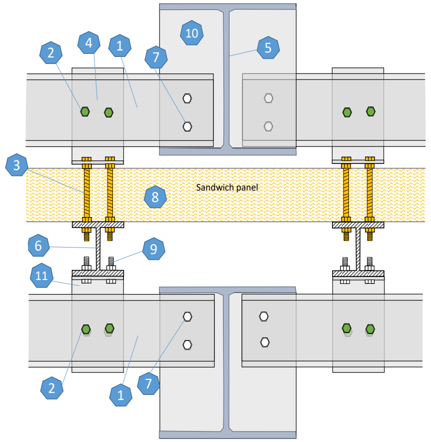
Objectives

- Investigate from the 3D FE numerical models developed in the project, the fire behavior of fusible link solutions to identify all possible failure modes and to develop simple/analytical models for evaluating the ultimate bearing capacity of links when exposed to fire
- Critical situation: Thermal expansion of a heated steel structure which results in pushing forces in “fusible” links.

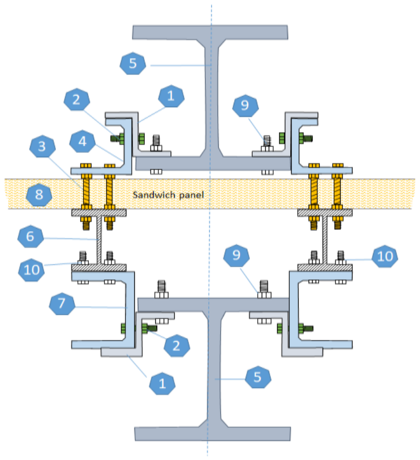
Investigated fusible links solutions



1. Gusset steel plate
2. Aluminium bolts
3. Steel rods
4. U-shaped steel with stiffener
5. Steel column of portal frame
6. Steel column
7. U-shaped steel profile with stiffener
8. Sandwich panels
9. Steel bolts



1. UPN steel profile
2. Aluminium bolts
3. Steel rods
4. L-shaped steel profile
5. Steel column of portal frame
6. Steel column
7. Steel bolts
8. Fire wall
9. Steel bolts
10. Welded steel stiffener
11. L-shaped steel profile



1. Z-shaped steel profile
2. Aluminium bolts
3. Steel rods
4. U-shaped steel profile
5. Steel column of portal frame
6. Steel column
7. U-shaped steel profile
8. Fire wall
9. Steel bolts
10. Steel bolts

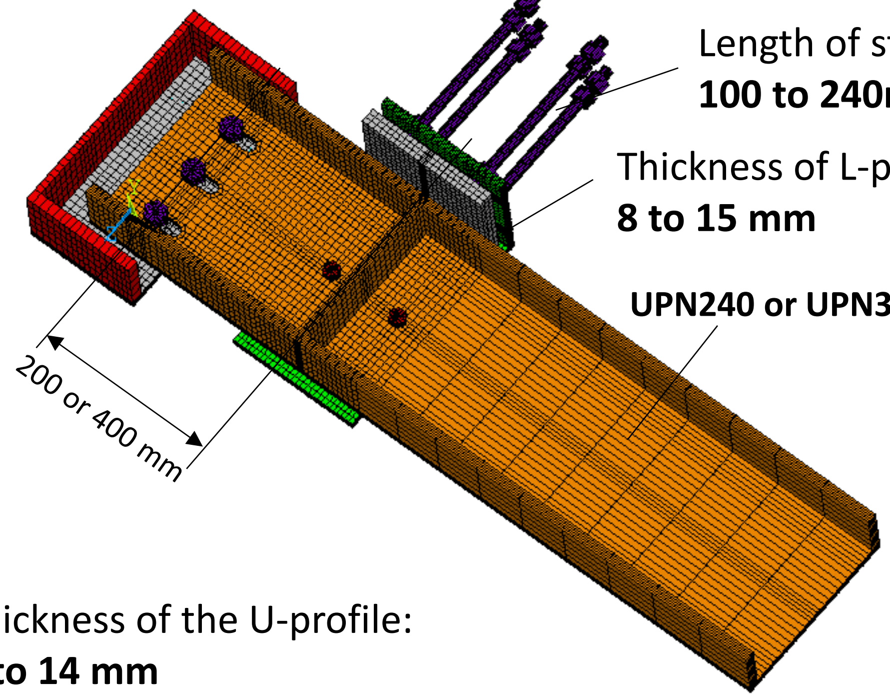
Parametric study on fusible links

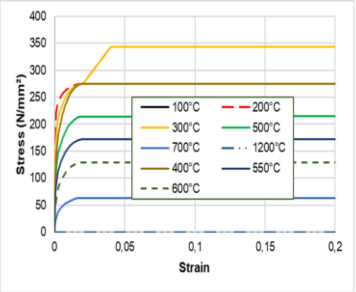
- **Step 1: FE analyses at ambient temperature**
  - Calculate the ultimate load-bearing capacity at ambient temperature N_{ult}
    - Thermal load: T=20°C
    - Mechanical load: A pushing load V gradually increased until failure

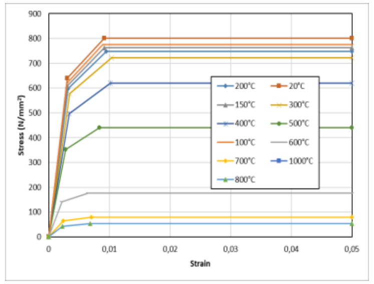
- **Step 2: FE analyses at elevated temperatures**
  - Calculate the load-bearing capacity at elevated temperatures
    - Thermal load: the calculated temperature under ISO fire conditions
    - Mechanical load: A constant pushing load fixed to 30, 50 and 70% of the ultimate load-bearing capacity predicted at 20°C

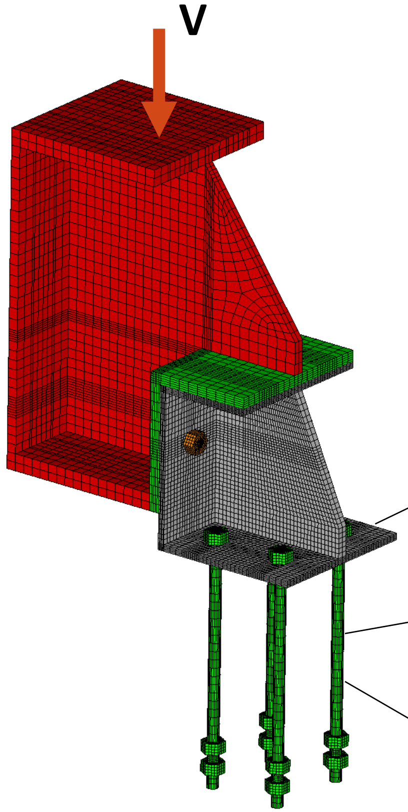
Parametric study on fusible links

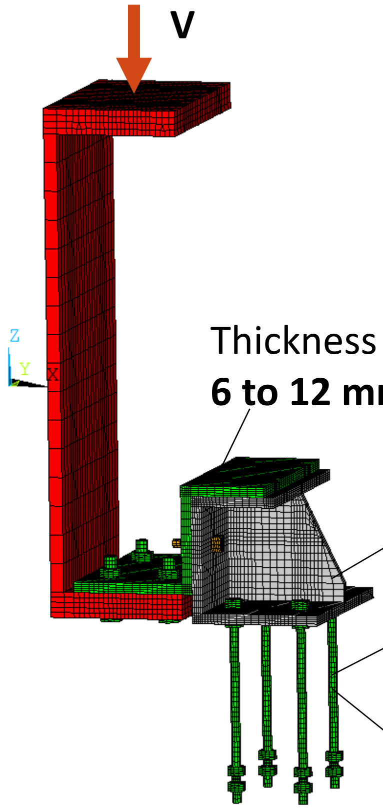
- **Investigated parameters**





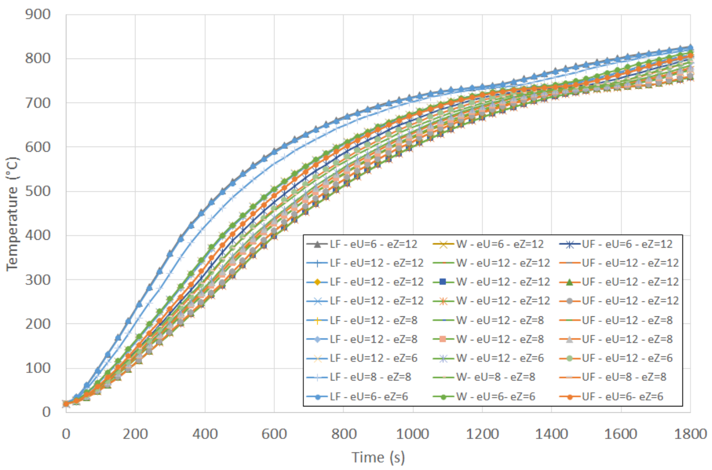


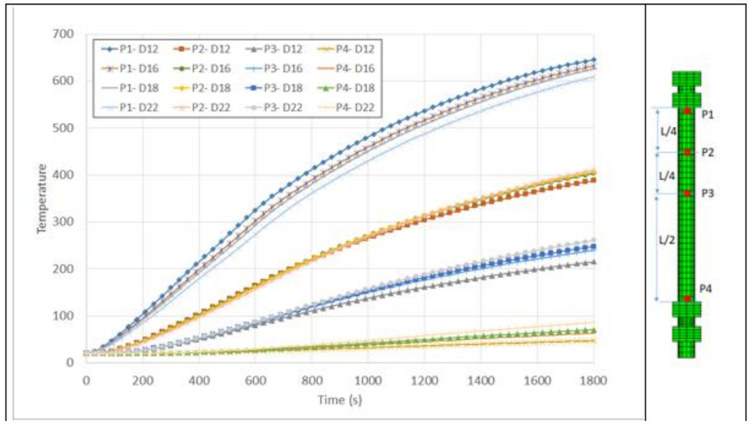




Parametric study on fusible links

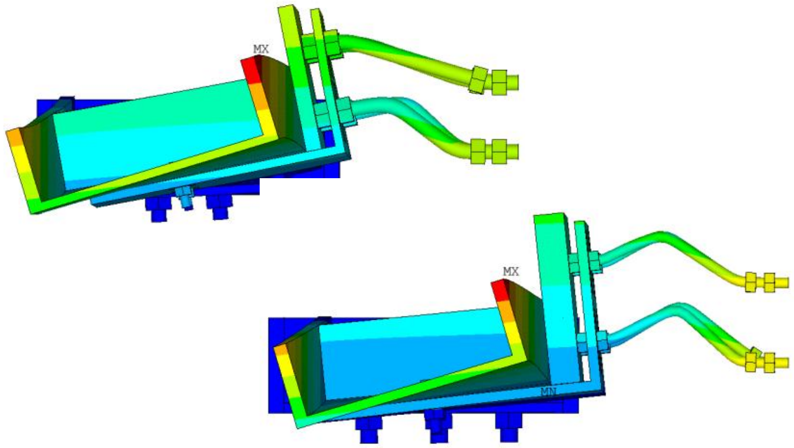
- **Lessons from FE analyses**
  - **Heating of link components**
    - There are temperature gradients between all the link components and the walls profile, which diminish with increasing the fire exposure time (different thicknesses and shadow effect)
    - The temperatures of bolts are found to be close to those of the connected steel profiles
    - Temperature gradients are more pronounced along the steel rods, with steeper gradients occurring at longer exposure time.
    - The thinner the profile or the larger the rod's diameter, the greater the temperature increase of the part of the rod located on the wall side exposed to the fire

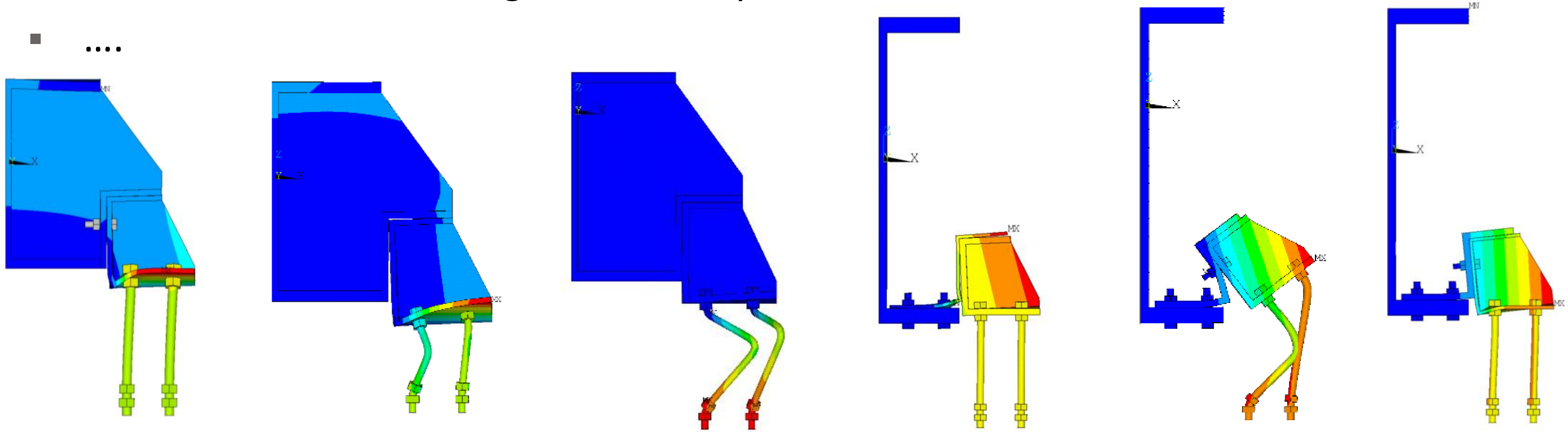




Parametric study on fusible links

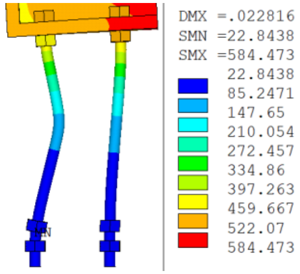
- **Lessons from FE analyses**
  - **Failures modes of fusible links:**
    - Bending of the bottom flange of the U-profile
    - Bending of the Z-profile
    - Buckling/bending of the steel rods
    - Yielding of the rods section (at the fire exposed side)
    - Lateral torsional buckling of the UPN profile
    - ....

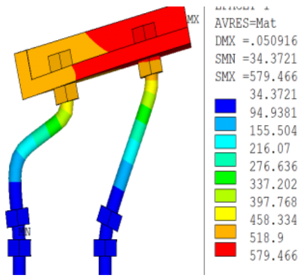




Parametric study on fusible links

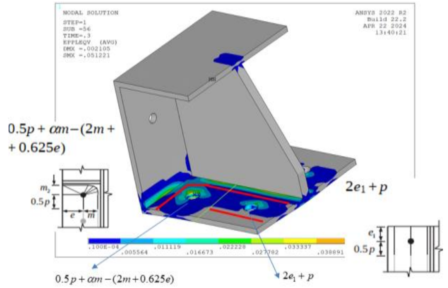
- **Lessons from FE analyses**
  - Failure mode of fusible links:
    - Fire resistance of steel rods affected by:
      - The flexibility of the steel profiles:
        - The bottom flange of a U-section
        - The Z-section profile
      - The change in the temperature gradient occurring along the rods with the fire exposure time
      - The rod buckling can occur in different places:
        - At mid height of the rod, or
        - In the upper part (i.e. over half the length on the side exposed to fire)
      - The change in axial forces with the temperature rise

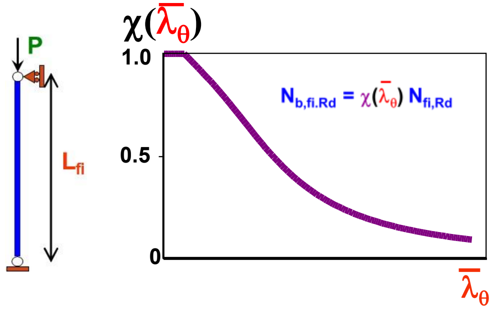




Parametric study on fusible links

- **Outcomes**
  - **Development of simplified design rules:**
    - Based on existing rules
    - Heating calculation:
      - Temperature in steel profiles and bolts assessed from the simplified method of EN 1993-1-2 using appropriate local or global A/V value of the considered parts forming the link
      - Temperatures in steel rods calculated from the temperature rise in steel profiles and appropriate correction factors
    - Bearing resistance pf links calculated according to the resistance of the basic components:
      - From design rules of EN 1993-1-2
      - From design rules of EN 1993-1-1 and EN 1993-1-8, changed to take account of the temperature effects

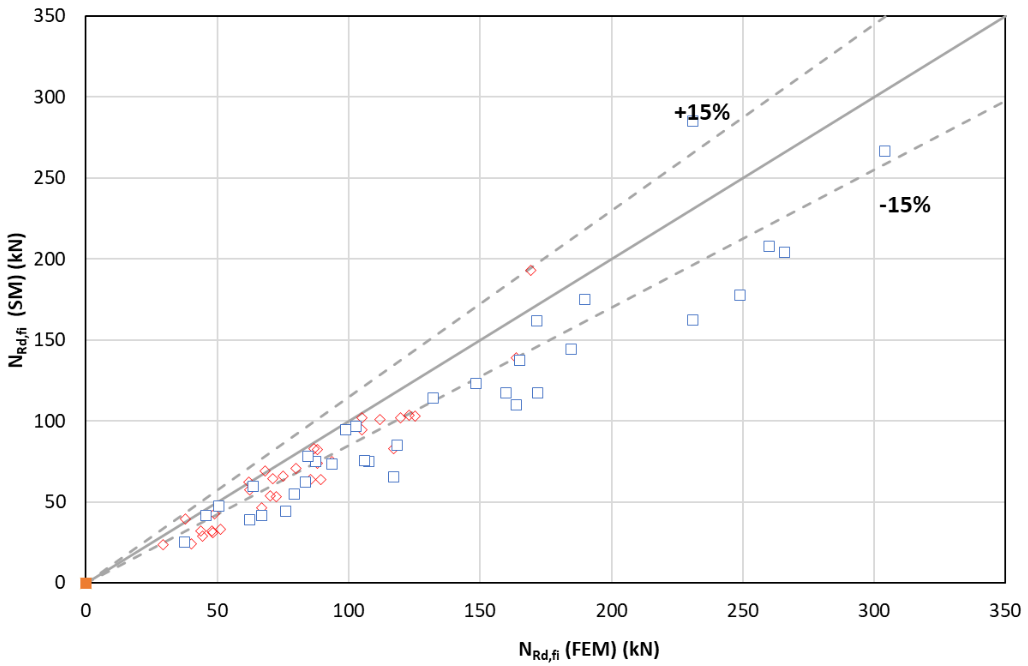


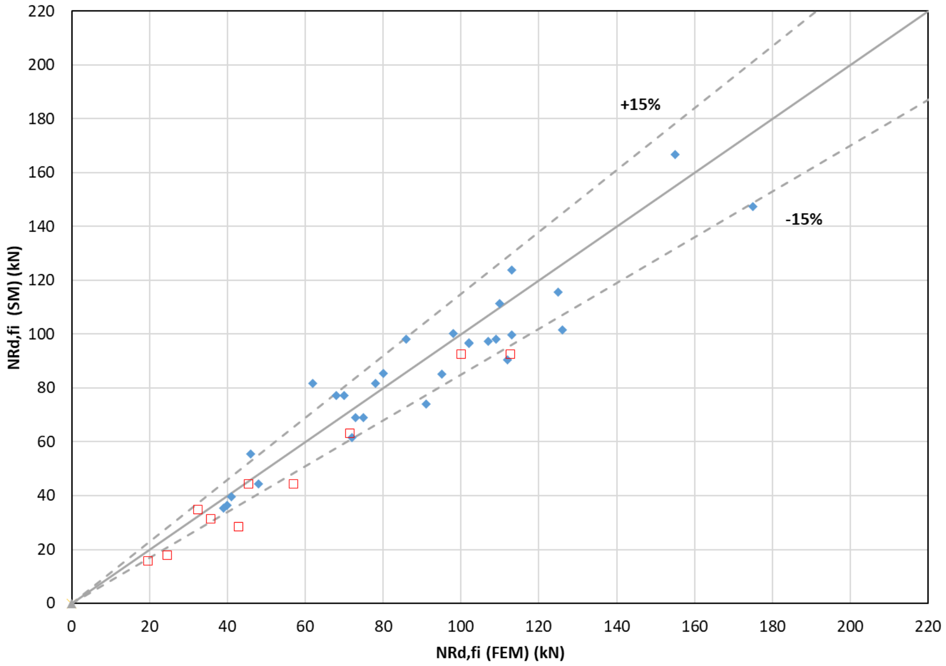


Parametric study on fusible links

Outcomes

- Development of simplified design rules
  - Some comparison with FE numerical results





Parametric study on whole steel structures

➢ Objective

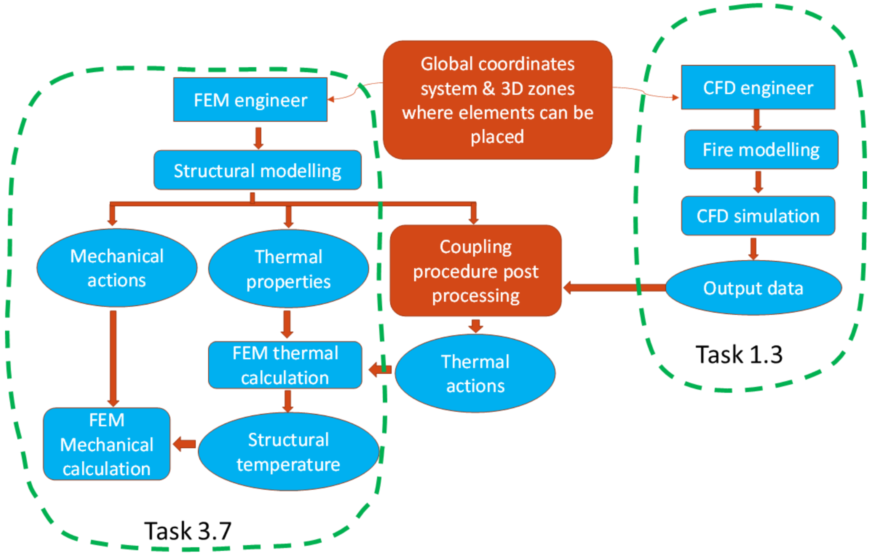
❖ 3D global structural analyses to investigate the mechanical response of steel structures associated with fire walls using "fusible" links under realistic fire conditions

❖ Checking the appropriate behaviour of fusible links:

- Fusible links located on both sides of the wall must resist the pushing phase
- Fusible links located on the fire-exposed side must fail first for the tensile phase

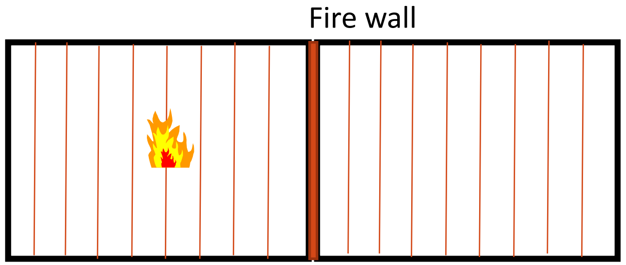
➢ Simulations procedure

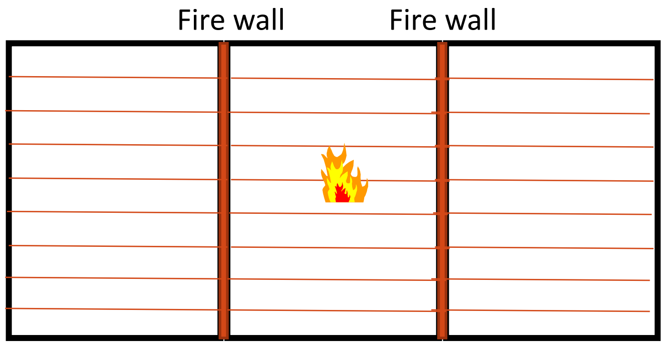
❖ Coupling procedure coming from the project FIRESTRUC

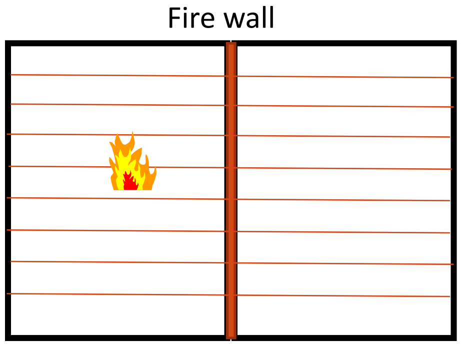


Parametric study on whole steel structures

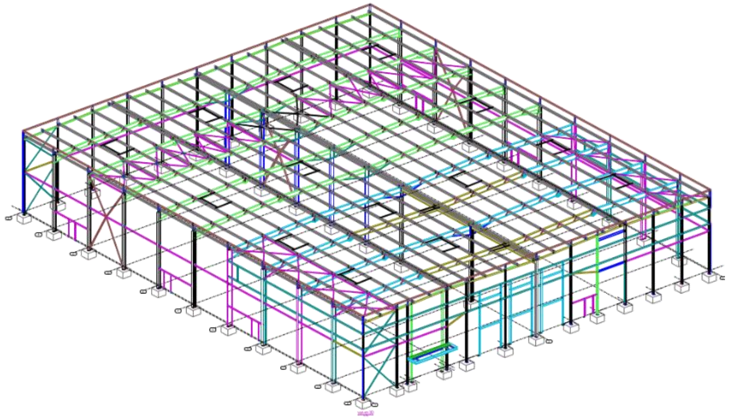
- **Selected Parameters**
  - Building configuration
    - Fire compartmentation



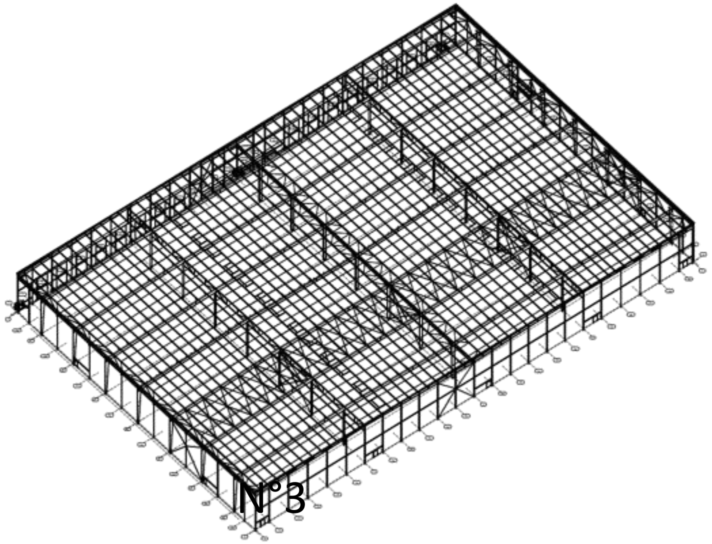




    - Steel structures



Reference building N°2



Reference building N°4

Parametric study on whole steel structures

Selected Parameters

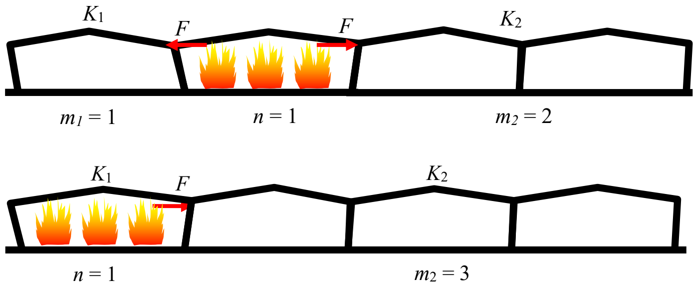
Fire scenarios

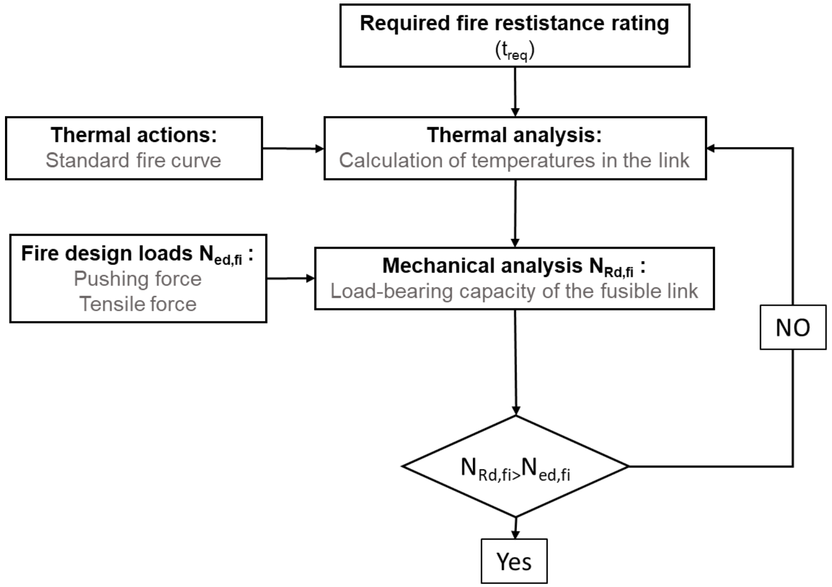
Fire scenario	Building	Occupancy type	Location of the fire source
W.1.1	1	Warehouse (rack storage)	In the middle of the single row rack, near one of the longer compartment sides
W.1.2	1	Warehouse (rack storage)	At the end of the central double row rack, near one of the shorter compartment sides
W.1.3	1	Warehouse (rack storage)	In the middle of the central double row rack
S.1.1	1	Supermarket (shelf storage)	At the end of the central double row shelf, near one of the longer compartment sides
S.1.2	1	Hypermarket (shelf storage)	In the middle of a single row shelf, near one of the shorter compartment sides
S.1.3	1	Supermarket (shelf storage)	In the middle of the central double shelf
I.1.1	1	Industrial building (bulk storage)	in a bulk storage, near one of the longer compartment sides
I.1.2	1	Industrial building (bulk storage)	In a bulk storage, near one of the shorter compartment sides
I.1.3	1	Industrial building (bulk storage)	In a bulk storage in the centre of the building
W.2.1	2	Warehouse (rack storage)	At the end of the central double row rack, near one of the longer compartment sides
W.2.2	2	Warehouse (rack storage)	In the middle of the single row rack, near one of the shorter compartment sides
W.2.3	**2**	**Warehouse (rack storage)**	**In the middle of the central double row rack**

Fire scenario	Building	Occupancy type	Location of the fire source
S.2.1	2	Supermarket (shelf storage)	At the end of the central double row shelf, near one of the longer compartment sides
S.2.2	2	Supermarket (shelf storage)	In the middle of a single row shelf, near one of the shorter compartment sides
S.2.3	**2**	**Supermarket (shelf storage)**	**In the middle of the central double row shelf**
I.2.1	2	Industrial building (bulk storage)	In a bulk storage near one of the longer compartment sides
I.2.2	2	Industrial building (bulk storage)	In a bulk storage near one of the shorter compartment sides
I.2.3	2	Industrial building (bulk storage)	In a bulk storage in the centre of the building
W.3.1	3	Warehouse (rack storage)	In the middle of the single row rack, near one of the longer compartment sides
W.3.2	3	Warehouse (rack storage)	At the end of the central double row rack, near one of the shorter compartment sides
W.3.3	3	Warehouse (rack storage)	In the middle of the central double row rack
W.4.1	**4**	**Warehouse (rack storage)**	**In the middle of the single row rack, near one of the longer compartment sides**
W.4.2	4	Warehouse (rack storage)	At the end of the central double row rack, near one of the shorter compartment sides
W.4.3	4	Warehouse (rack storage)	In the middle of the central double row rack

Parametric study on whole steel structures

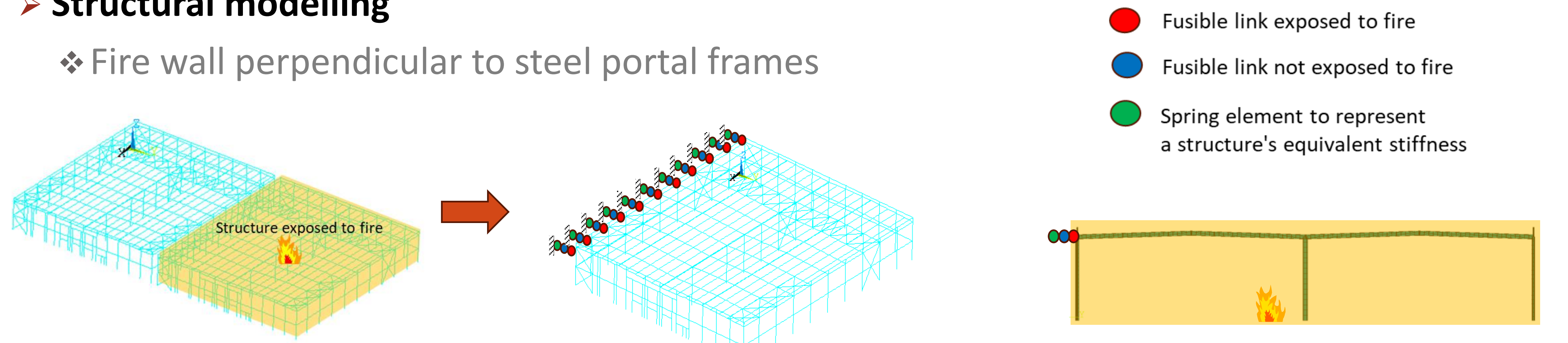
- **Structural design approach**
  - Calculation of the design loading:
    - Pushing force, tensile force
    - Using simple rules of previous research works
  - Design of fusible links:
    - R15 standard fire resistance under compression
    - Resistance to tensile forces at normal temperature
  - Conduction of 3D global FE analyses
    - Thermal analyses
    - Mechanical analyses
  - Fire performance checking of fusible links



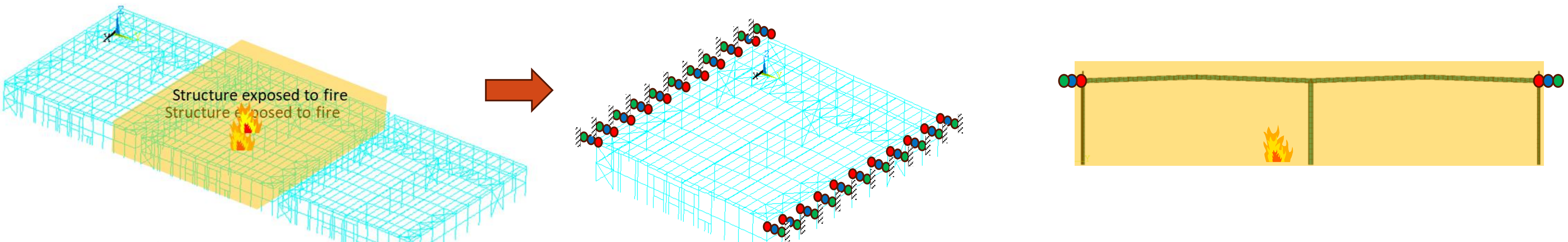


Parametric study on whole steel structures

- **Structural modelling**
  - Fire wall perpendicular to steel portal frames



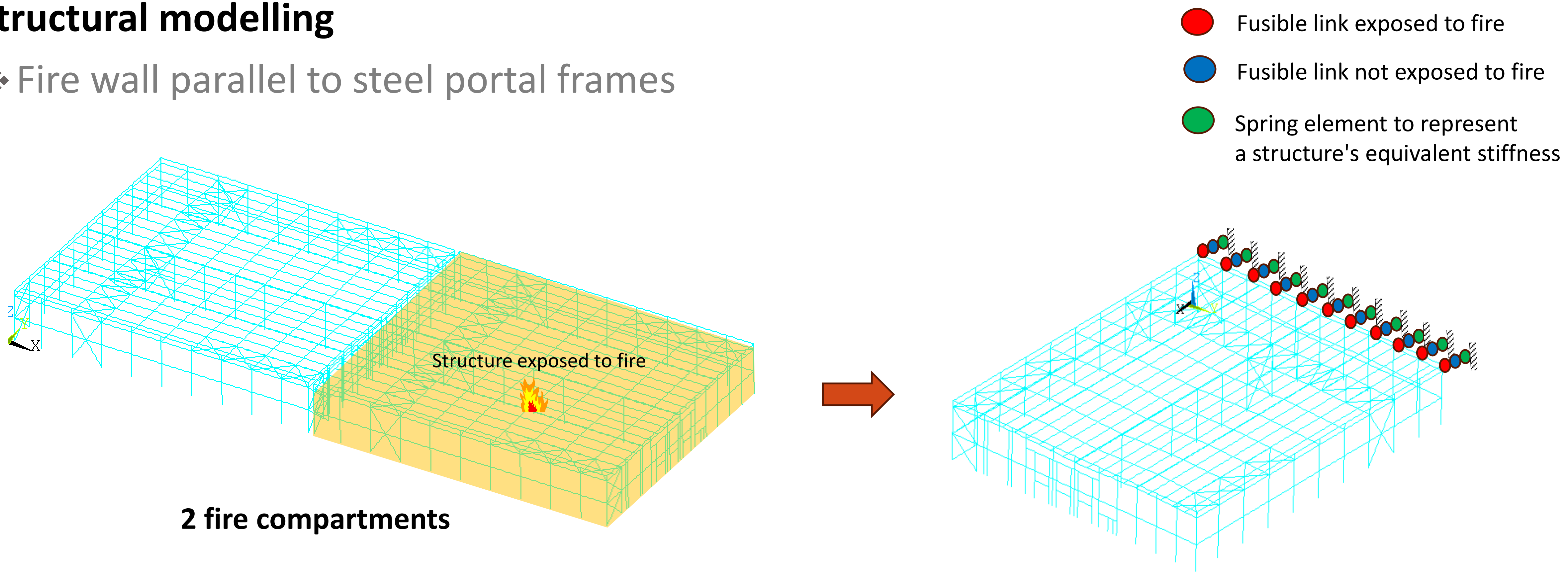
2 fire compartments



3 fire compartments

Parametric study on whole steel structures

- **Structural modelling**
  - Fire wall parallel to steel portal frames



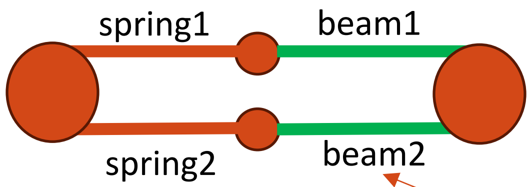
Parametric study on whole steel structures

➢ Structural modelling

❖ Modelling of fusible links as an assembly of springs and beam elements

Acting in compression

- Linear elastic – perfectly plastic material model
- Fully resistant



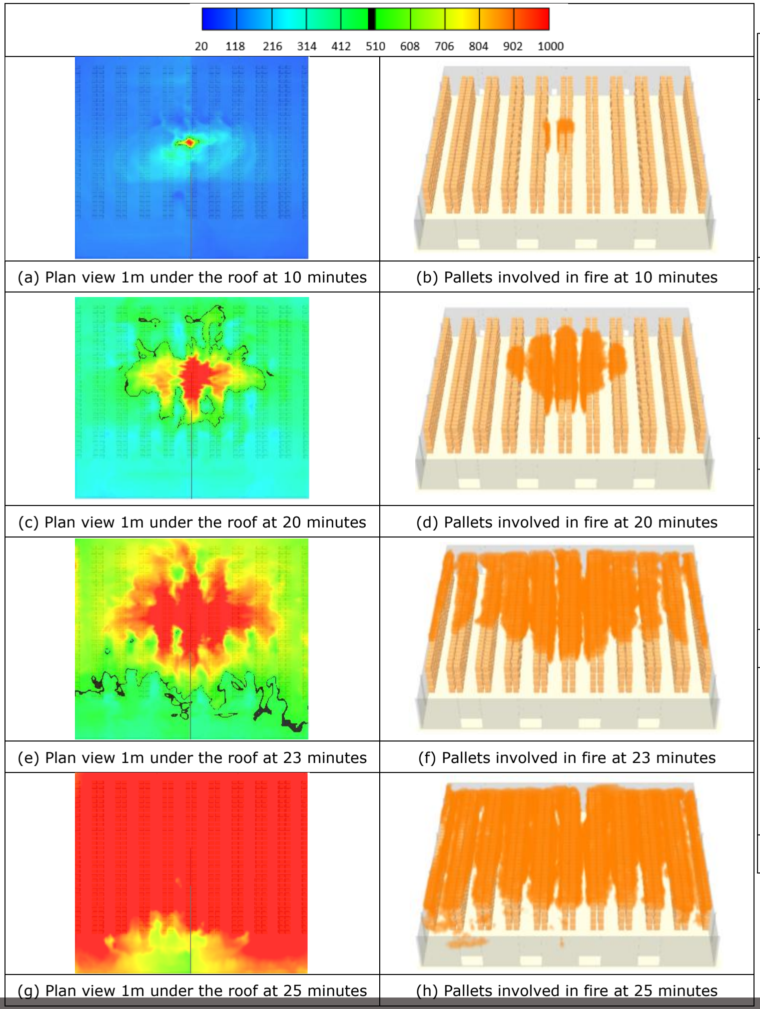
Acting in tension

- linear elastic – perfectly plastic material model
- Yield stress calibrated from the load-bearing capacity of the link under tension at elevated temperature (shear resistance of aluminum bolts)

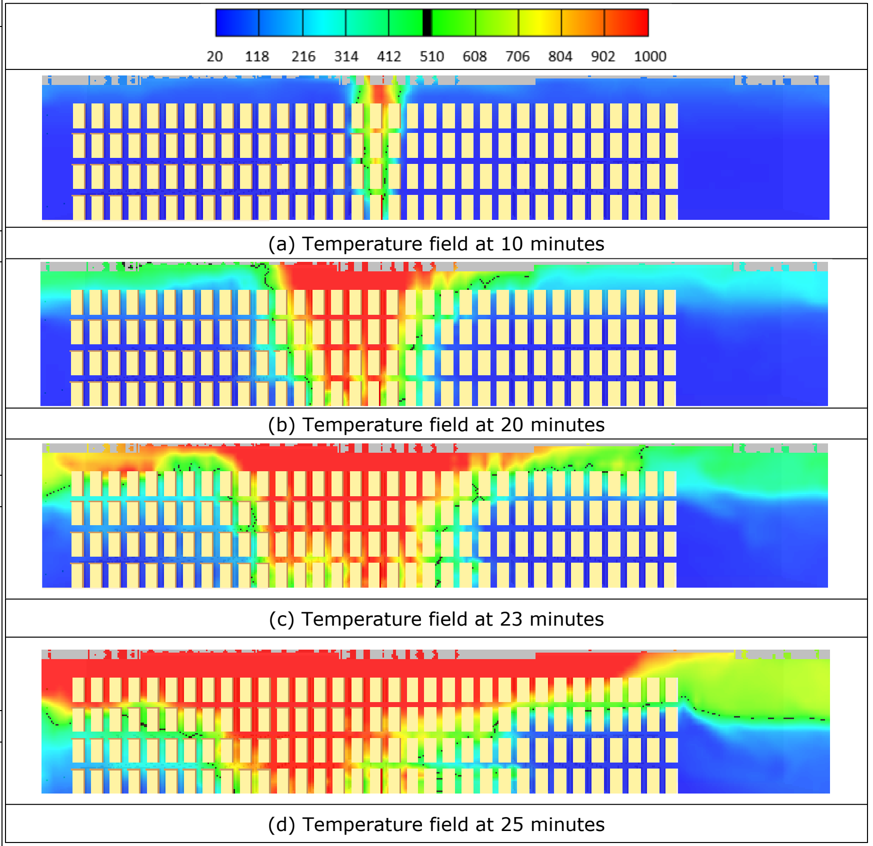
Parametric study on whole steel structures

➢ Study of building n°2 with fire scenario W.2.3

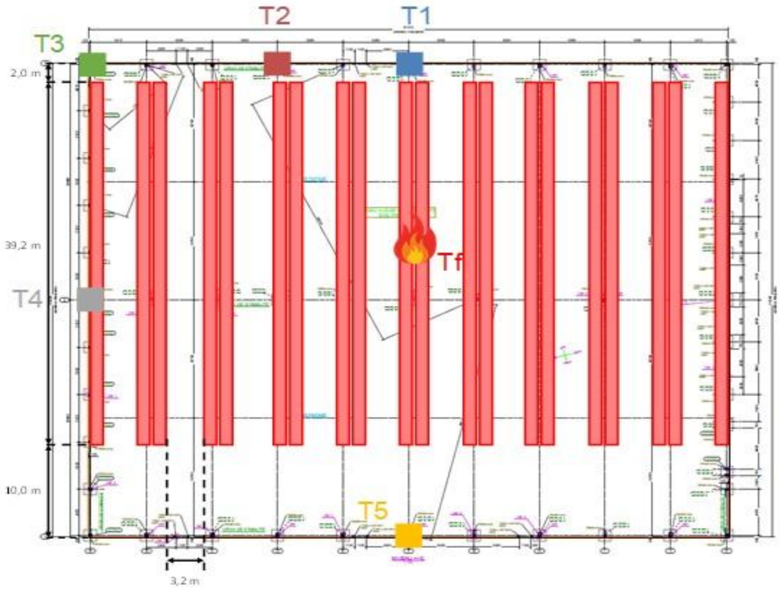
❖ Fire development

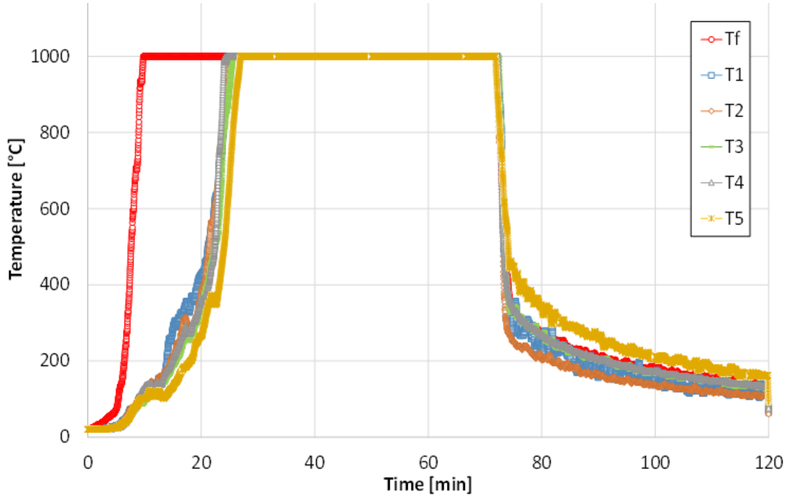


(a) Plan view 1m under the roof at 10 minutes
(b) Pallets involved in fire at 10 minutes
(c) Plan view 1m under the roof at 20 minutes
(d) Pallets involved in fire at 20 minutes
(e) Plan view 1m under the roof at 23 minutes
(f) Pallets involved in fire at 23 minutes
(g) Plan view 1m under the roof at 25 minutes
(h) Pallets involved in fire at 25 minutes



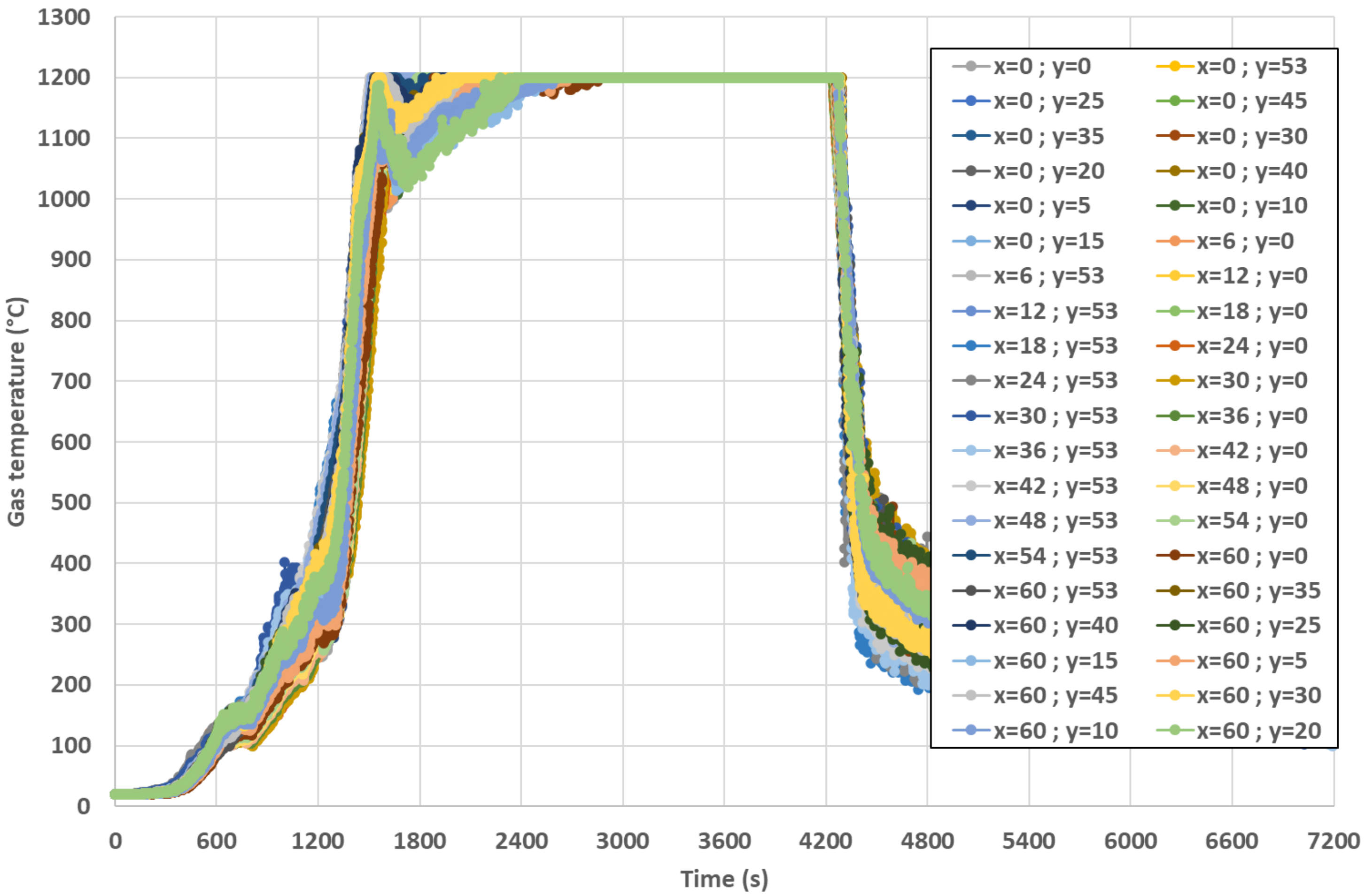
(a) Temperature field at 10 minutes
(b) Temperature field at 20 minutes
(c) Temperature field at 23 minutes
(d) Temperature field at 25 minutes

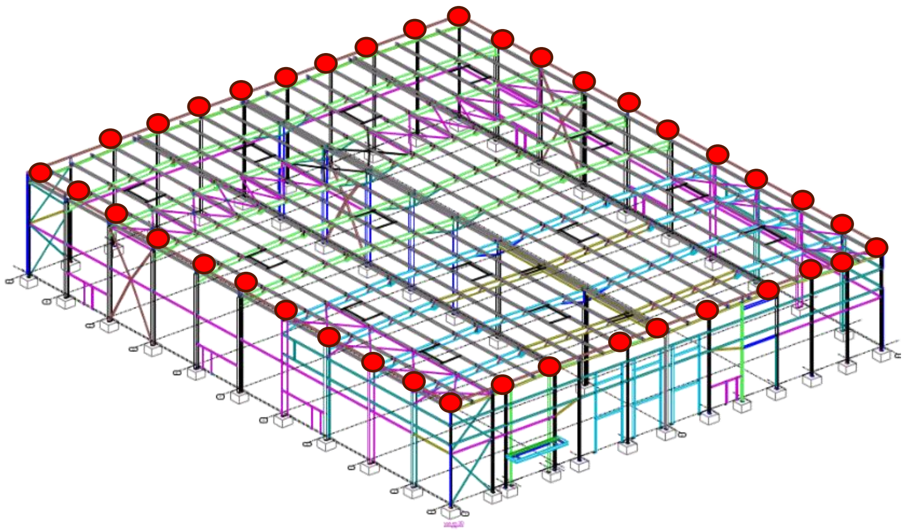




Parametric study on whole steel structures

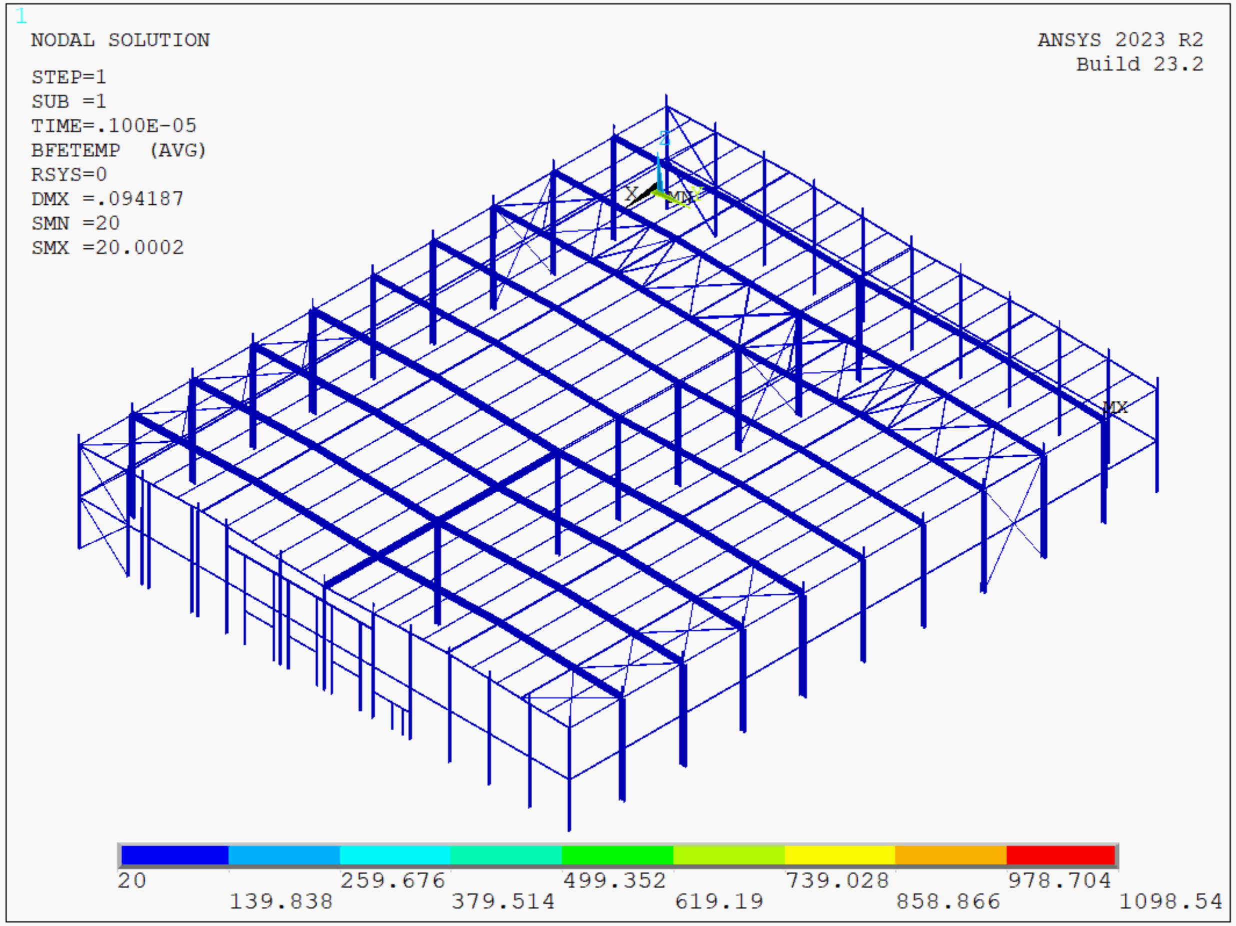
- **Study of building n°2 with fire scenario W.2.3**
  - **Fire development**

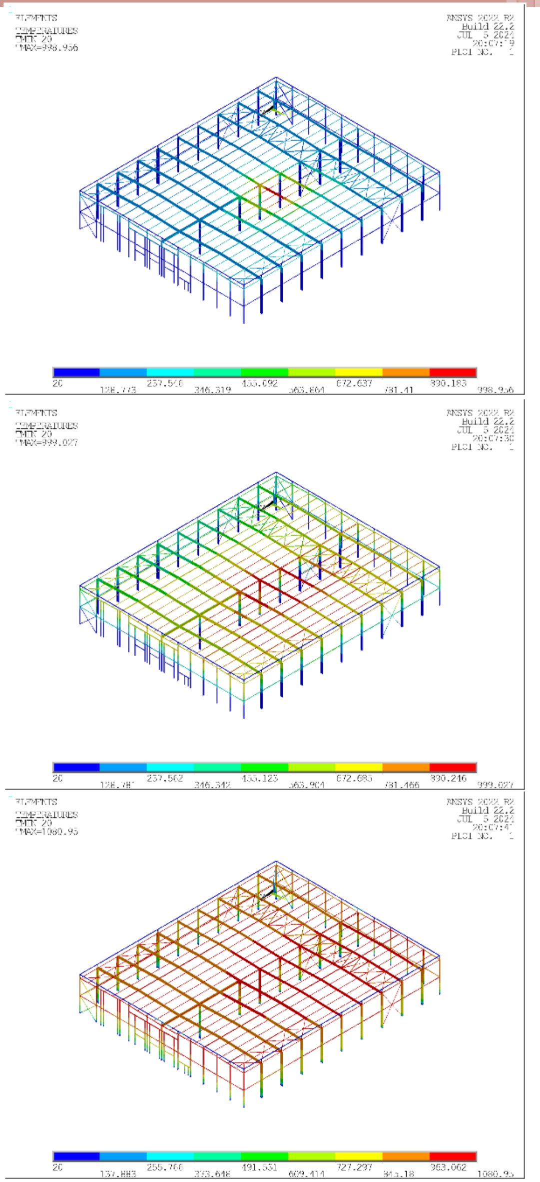




Parametric study on whole steel structures

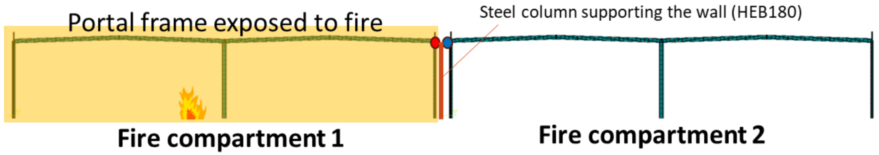
- **Study of building n°2 with fire scenario W.2.3**
  - Thermal analysis

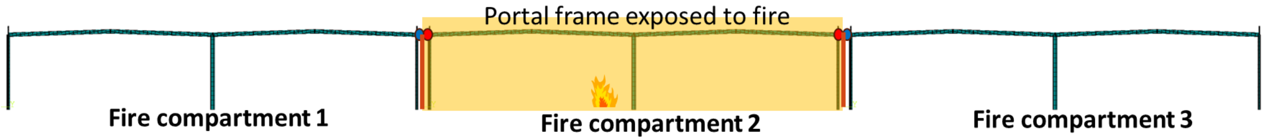




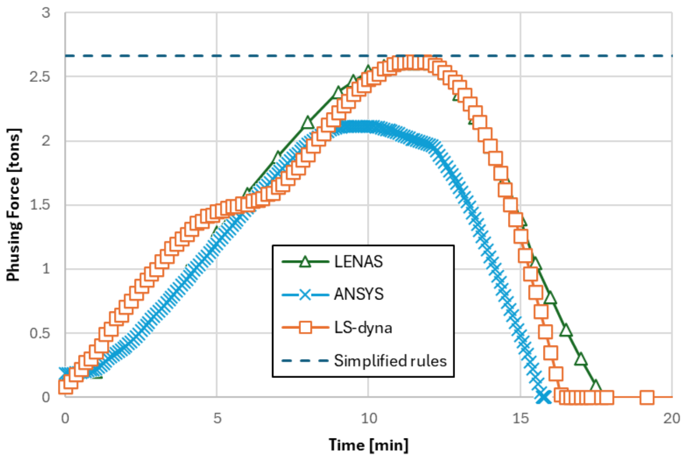
Parametric study on whole steel structures

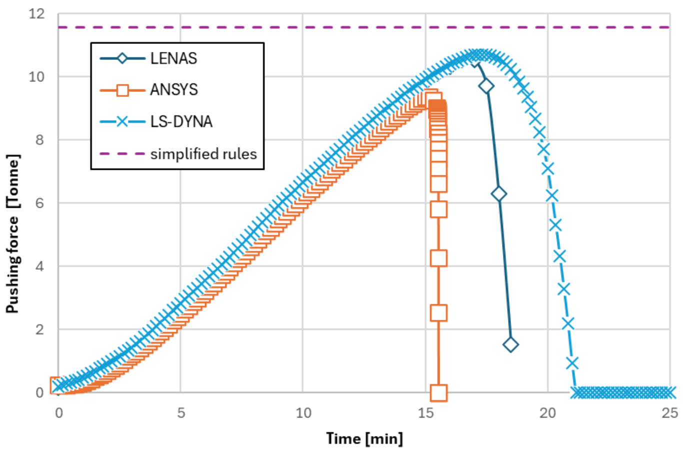
➢ Study of building n°2 with fire scenario W.2.3





❖ Design pushing force





❖ Design tensile force

$$F_t = c_p n_{eff} q_{fi,Ed} \mathrm{L} = 123\mathrm{KN}$$

$$F_t = c_p n_{eff} q_{fi,Ed} \mathrm{L} = 246\mathrm{KN}$$

Table 3 : values of n_{eff}

Number of bays in fire	Setting of the compartment exposed to fire	
	Building end	Building center
$n = 1$	n_{eff}=0,5	n_{eff}=1,0
$n \geq 2$	n_{eff}=1,0	n_{eff}=2,0

Table 4 : values of c_p

Slope of the roof	c_p
0%	1,19
5%	1,16
10%	1,10

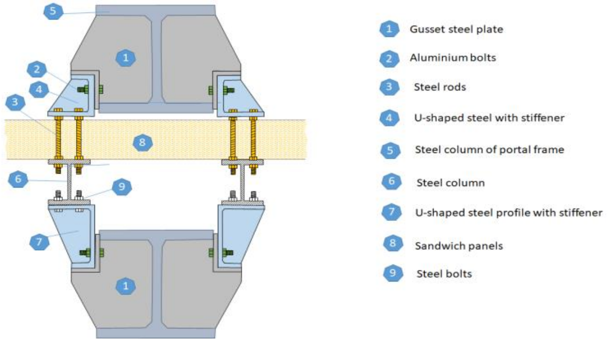
Parametric study on whole steel structures

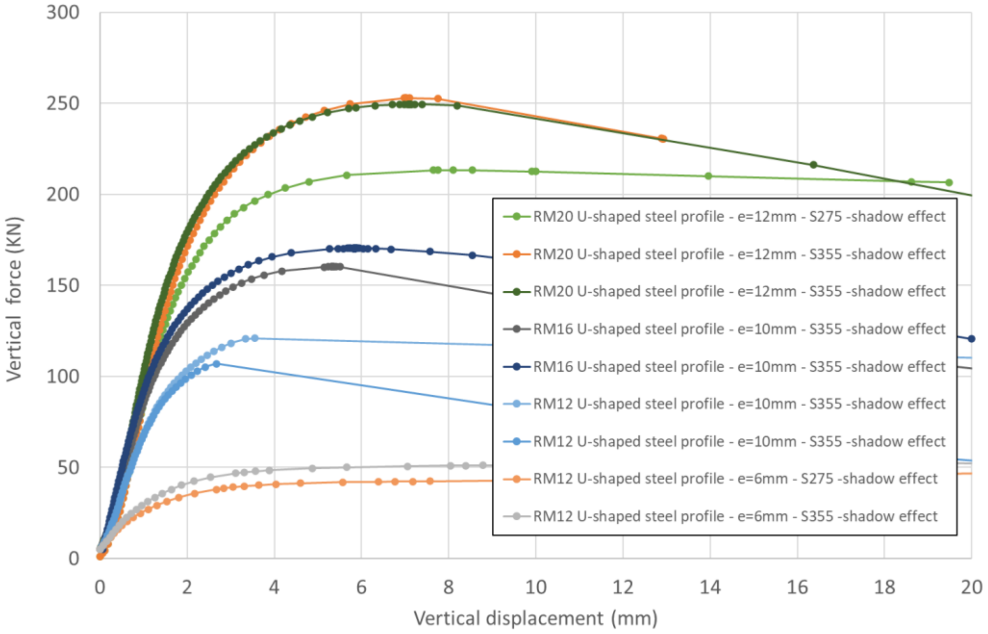
- **Study of building n°2 with fire scenario W.2.3**
  - Design of fusible links
    - From the developed simplified design rules
    - From design forces
      - Tensile forces (normal temperature)

d (mm)	fy (N/mm²)	fu (N/mm²)	A (mm²)	Nb	alphav	γM	Fv,fRd (KN)
16	420	490	157	4	0.5	1	153.86
16	420	490	157	8	0.5	1	307.72
12	420	490	84.3	4	0.5	1	82.614
12	420	490	84.3	8	0.5	1	165.228

      - Pushing forces

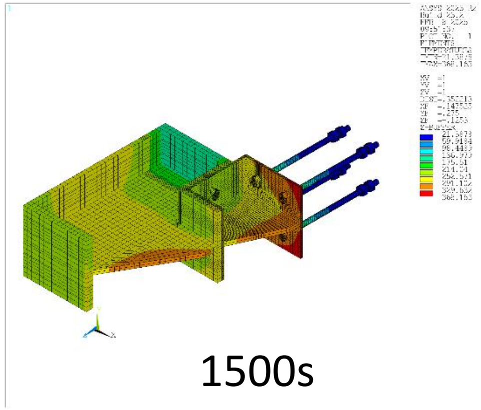
Attache n°3	time (s)	NRd.fi.c (KN)	e_U (mm)
M12_L175_eU6_dx35_70	900	21	6
M12_L175_eU8_dx35_75	900	46	8
M12_L175_eU9_dx35_70	900	64	9



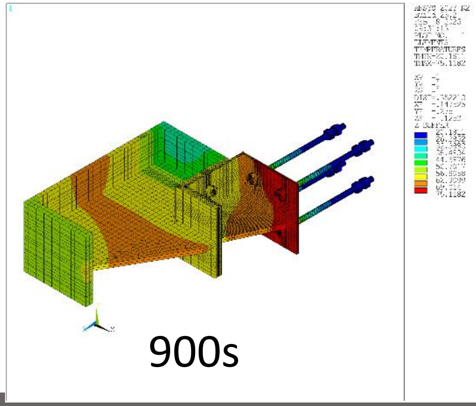


Parametric study on whole steel structures

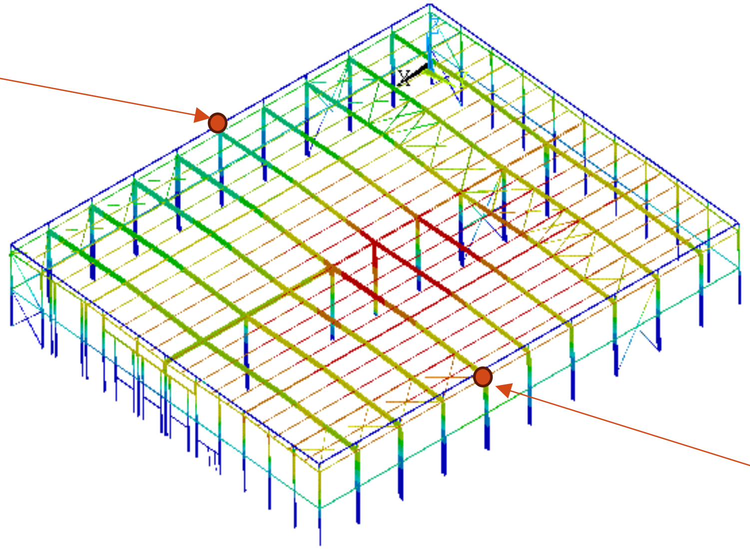
- **Study of building n°2 with fire scenario W.2.3**
  - Calculation of the fusible links heating
    - From the simplified design rules developed in task 3.5
    - From 3D FE models developed in task 3.5

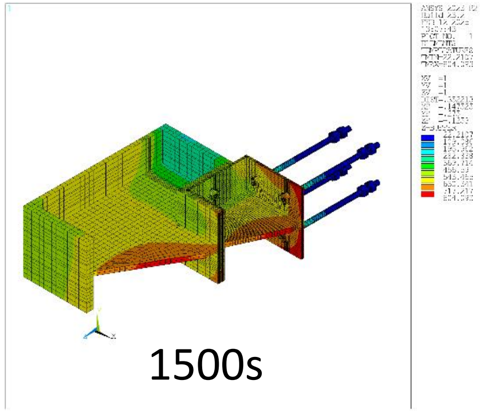


1500s



900s





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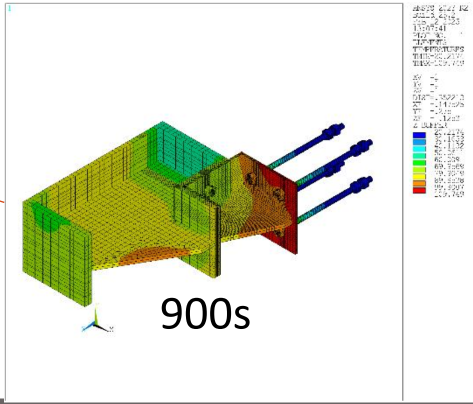
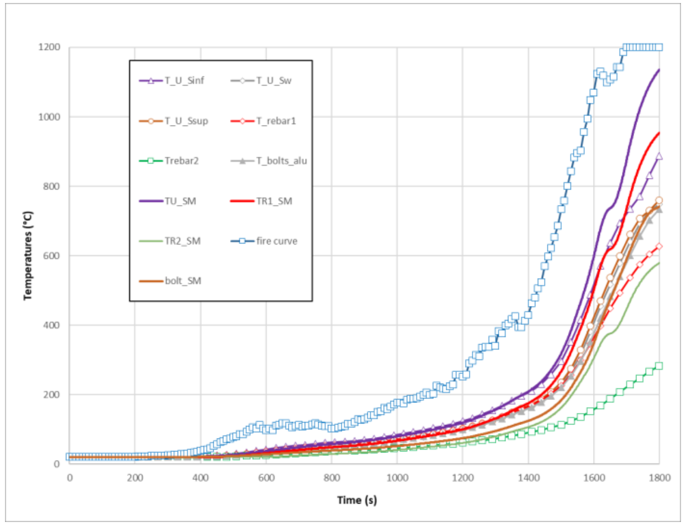
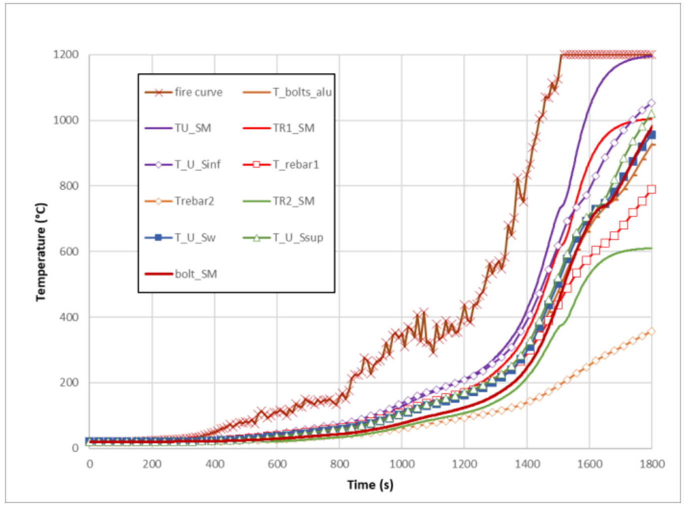


900s

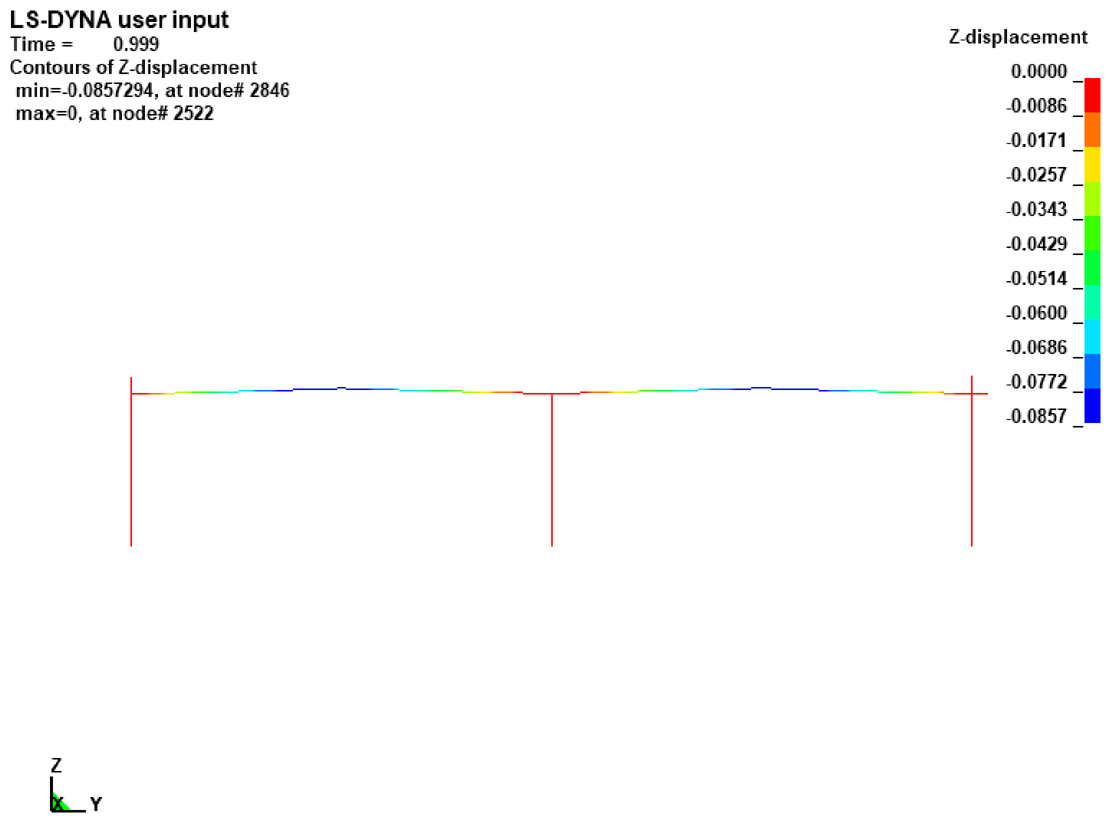


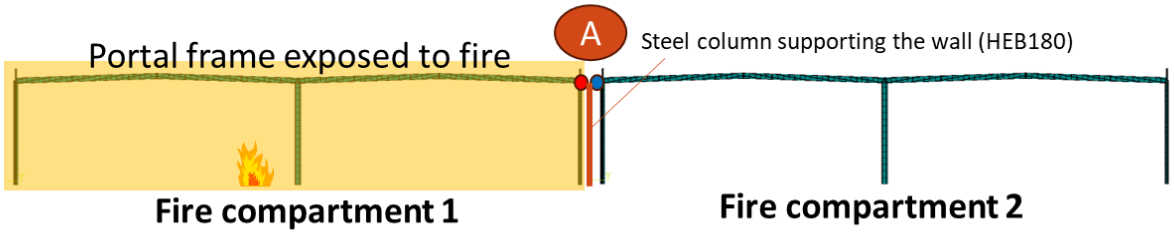


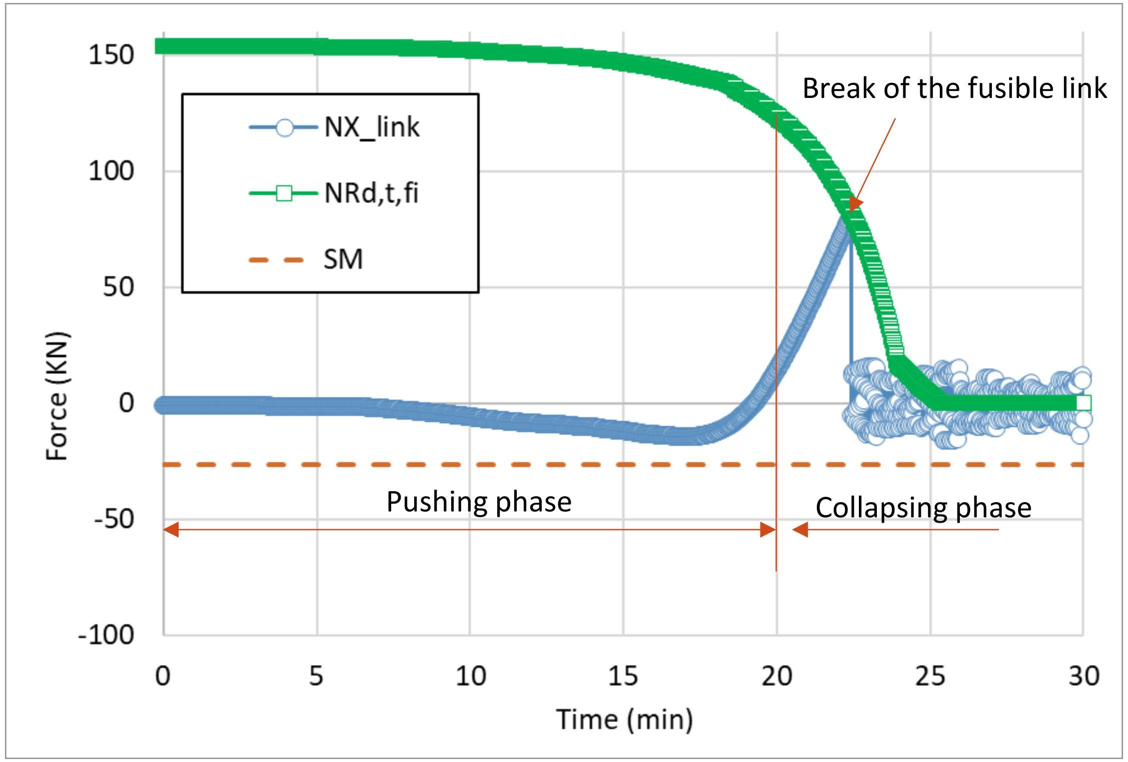
Parametric study on whole steel structures

➢ Study of building n°2 with fire scenario W.2.3

❖ Fire behaviour – 2D analysis



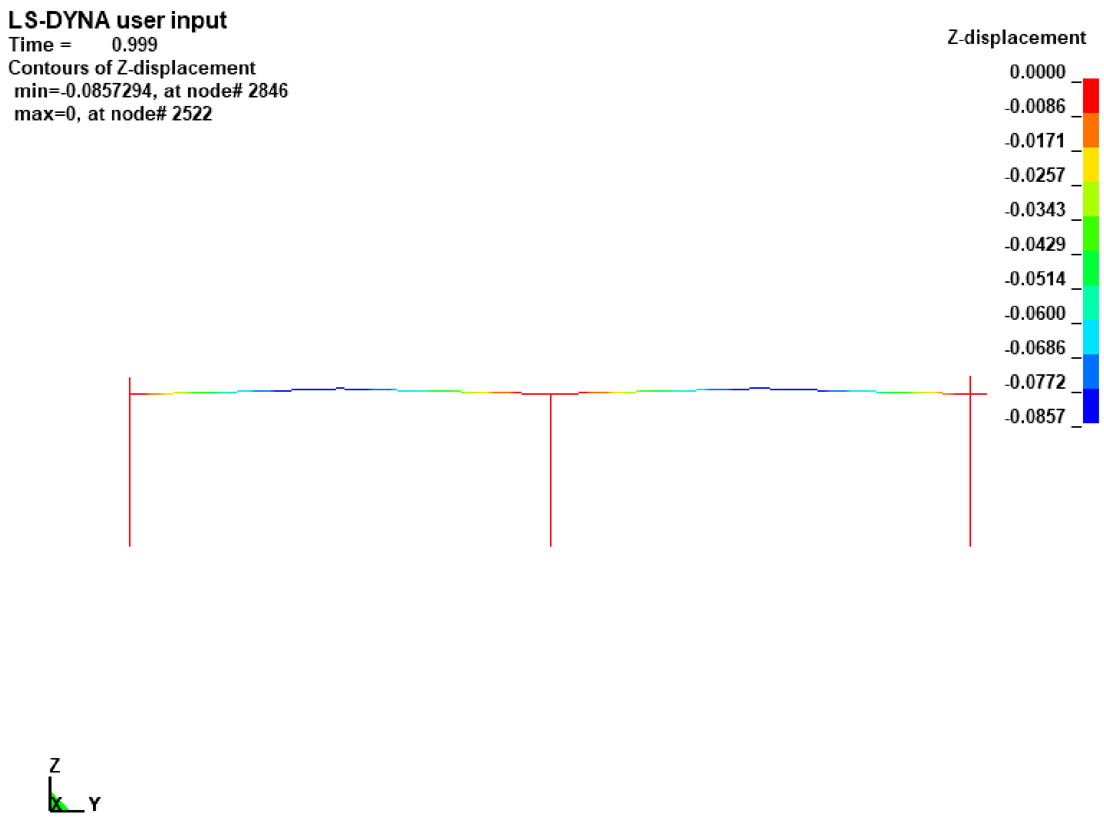


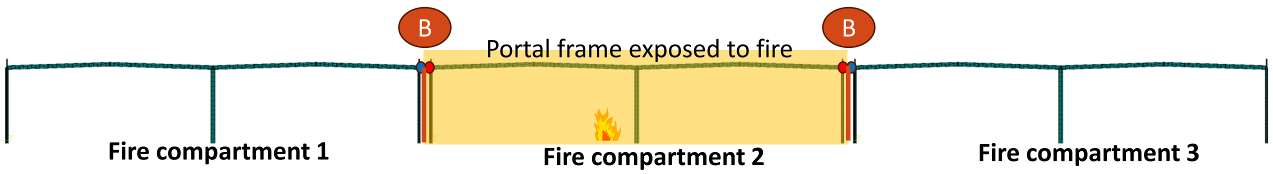


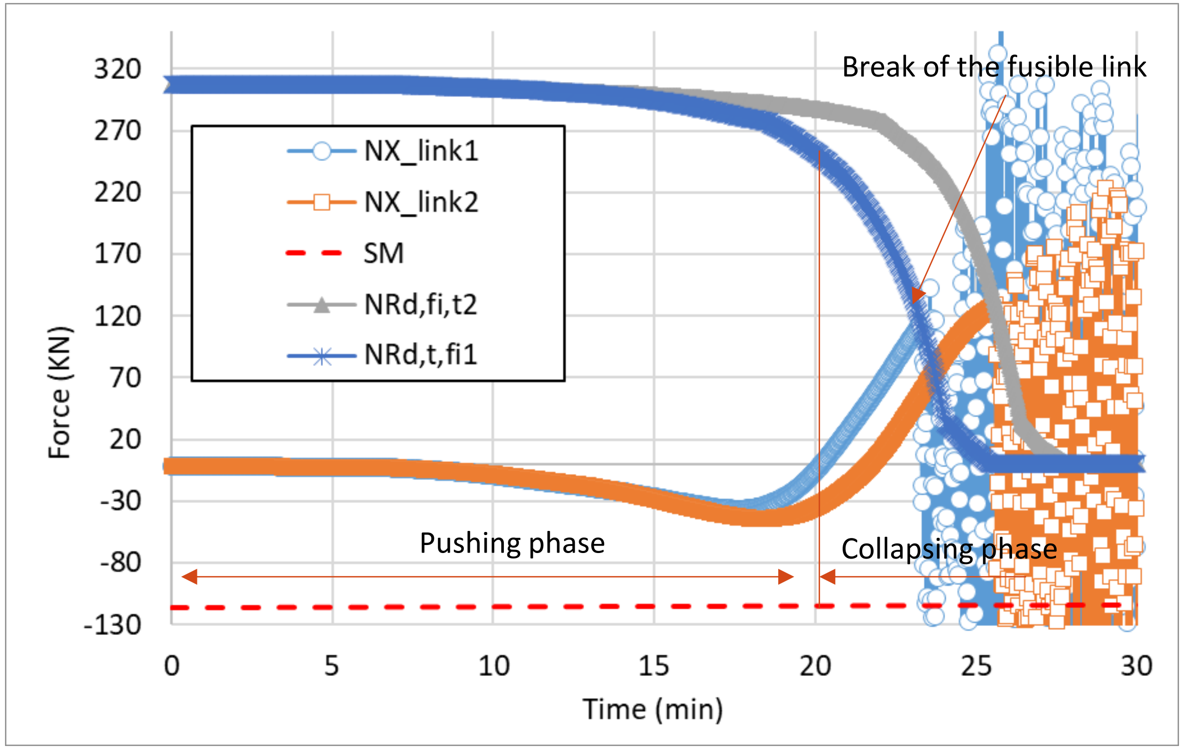
Parametric study on whole steel structures

➢ Study of building n°2 with fire scenario W.2.3

❖ Fire behaviour – 2D analysis



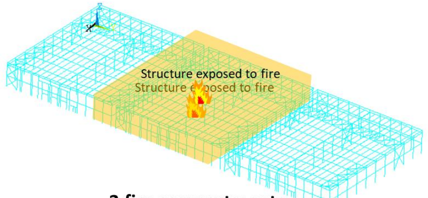




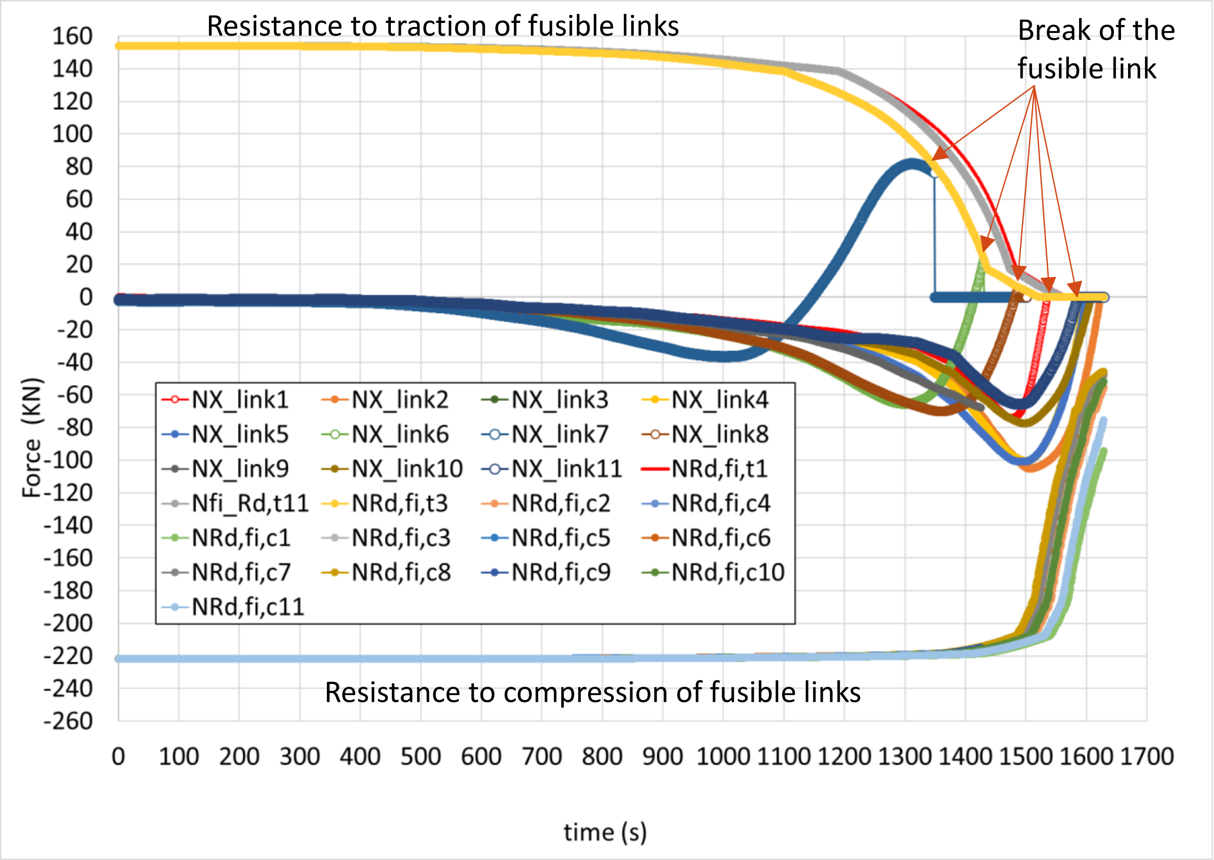
Parametric study on whole steel structures

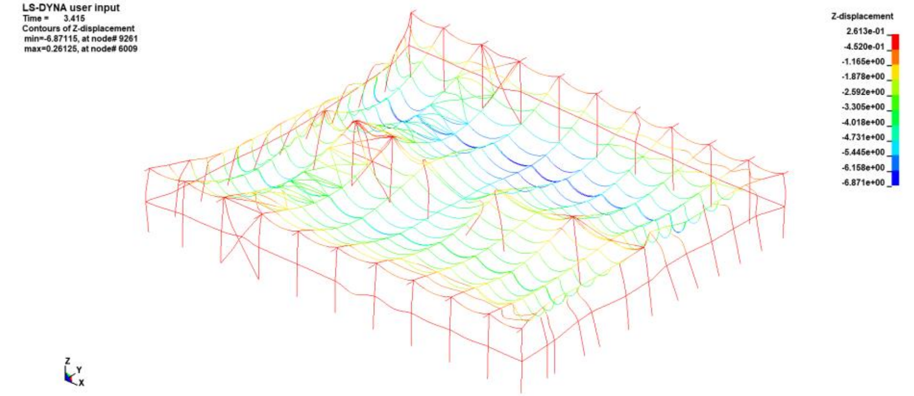
➢ Study of building n°2 with fire scenario W.2.3

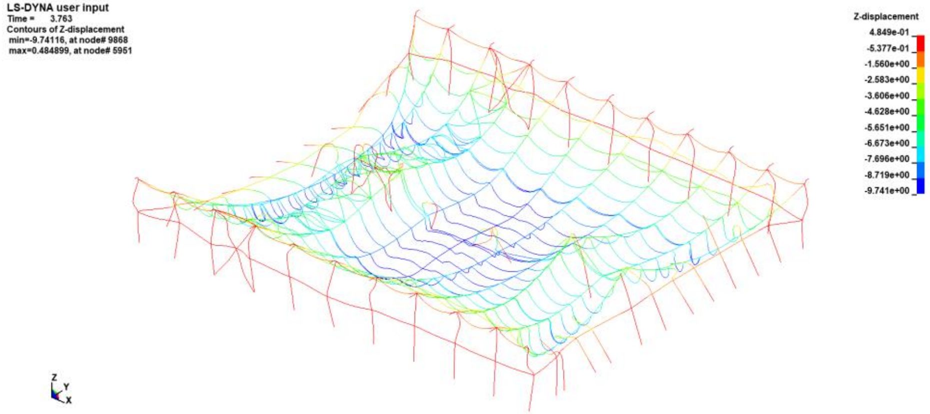
❖ Fire behaviour – 3D analysis



3 fire compartments



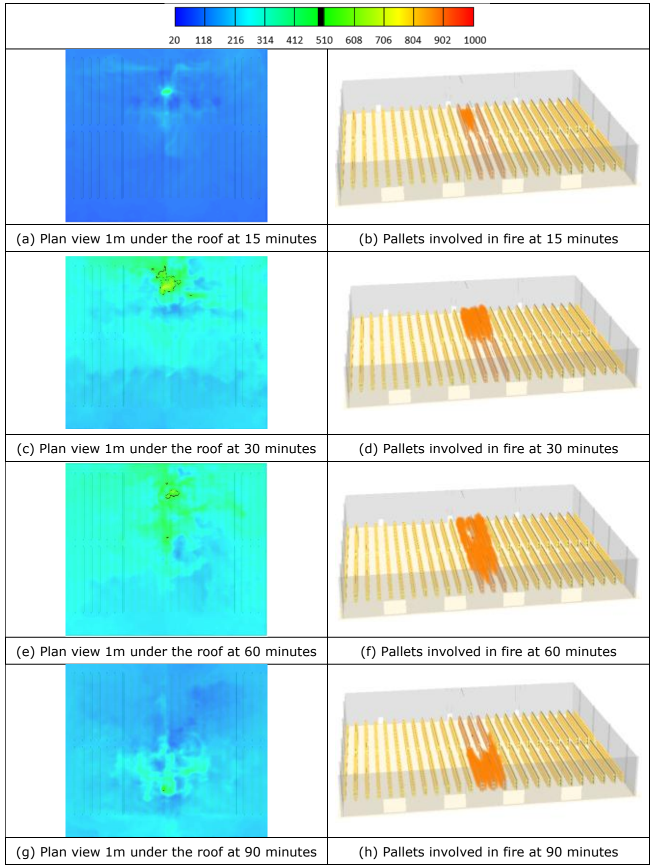




Parametric study on whole steel structures

➢ Study of building n°2 with fire scenario S.2.3

❖ Fire behaviour – 3D analysis



(a) Plan view 1m under the roof at 15 minutes

(b) Pallets involved in fire at 15 minutes

(c) Plan view 1m under the roof at 30 minutes

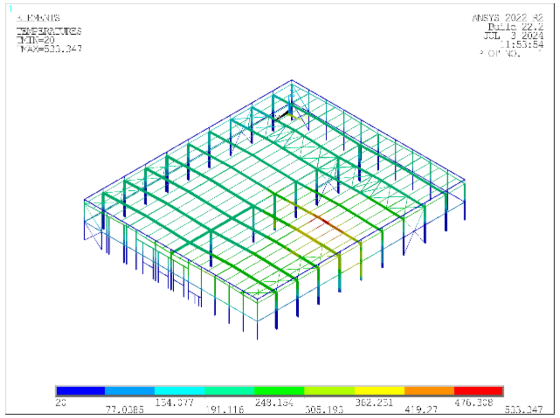
(d) Pallets involved in fire at 30 minutes

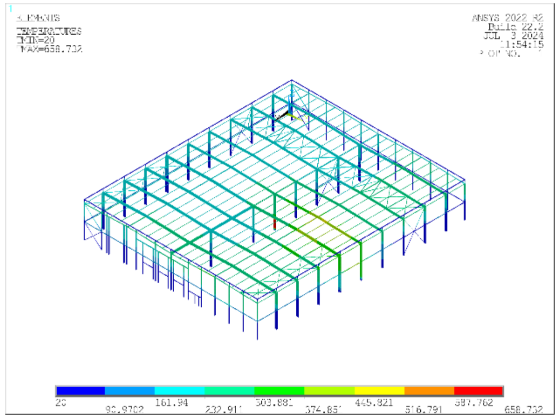
(e) Plan view 1m under the roof at 60 minutes

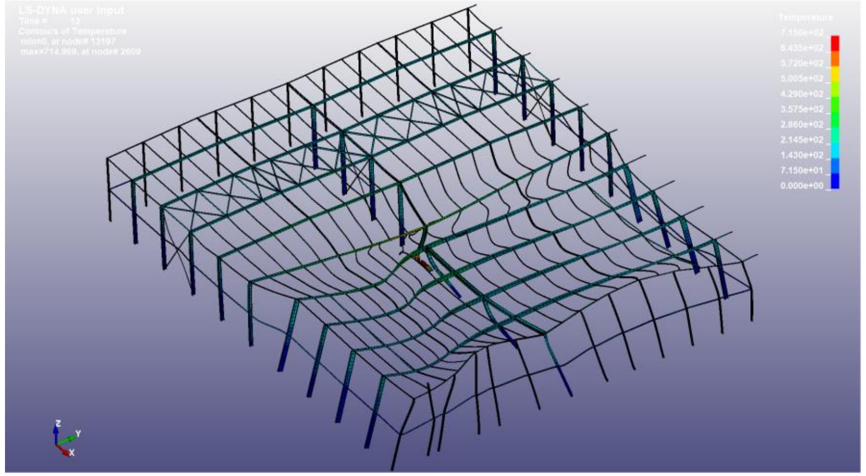
(f) Pallets involved in fire at 60 minutes

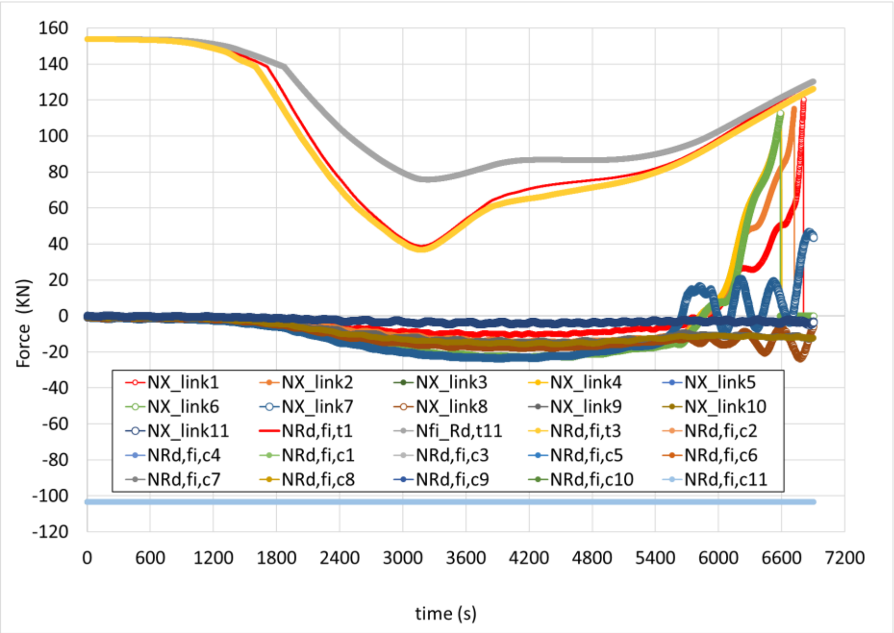
(g) Plan view 1m under the roof at 90 minutes

(h) Pallets involved in fire at 90 minutes









CONCLUSIONS

- **Main results of the numerical studies**
  - In the case of fully engulfed fires, all fusible links break progressively due to the high temperatures reached by the aluminium bolts, which either melt or undergo shear failure
  - In the event of a localised fire, some of the fusible links will break depending on the deformation of the heated part of the steel structure and the temperature rise of the aluminium bolts. In all simulated cases, the tensile forces acting on the links are lower than those considered in the design process.
  - If they are designed to achieve at least an R15 fire resistance rating under the standard fire curve, fusible links exposed to fire can resist the pushing phase

L'ENVELOPPE MÉTALLIQUE DU BÂTIMENT
ASSOCIATION DES FABRICANTS DE PANNEAUX, PROFILS ET SYSTÈMES

JORISIDE
THE STEEL FUTURE

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l'ingéniosité au service de la construction métallique

CTU
CZECH TECHNICAL UNIVERSITY IN PRAGUE

UNIVERSITY OF TRENTO

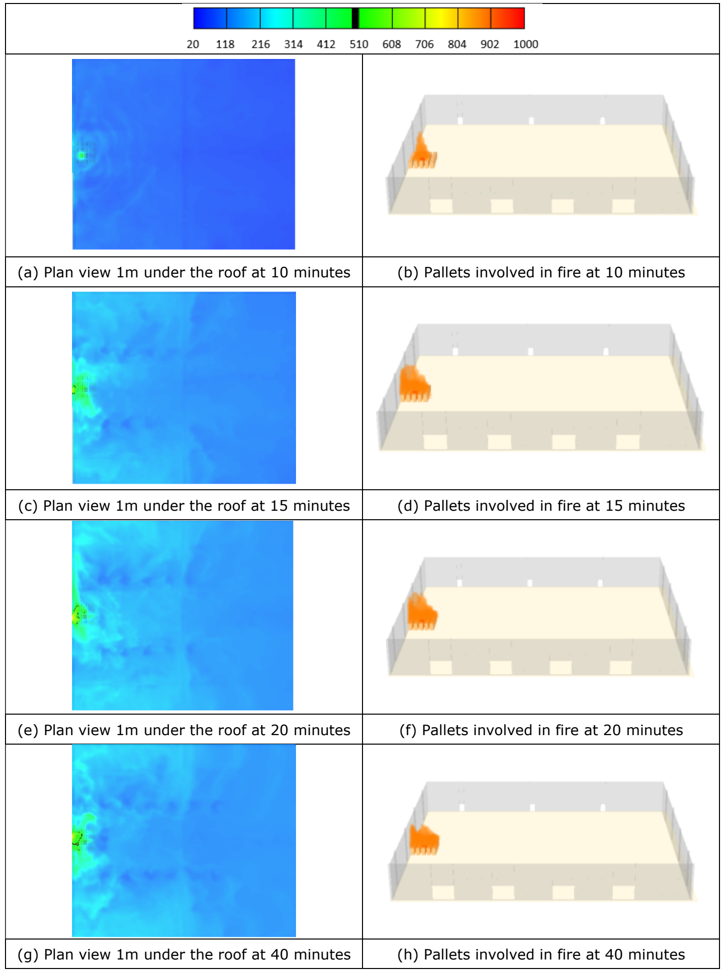
Thank you for your attention!

Christophe Renaud
CTICM
crenaud@cticm.com

Parametric study on whole steel structures

➢ Fire scenarios I.2.2

❖ Fire development



(a) Plan view 1m under the roof at 10 minutes

(b) Pallets involved in fire at 10 minutes

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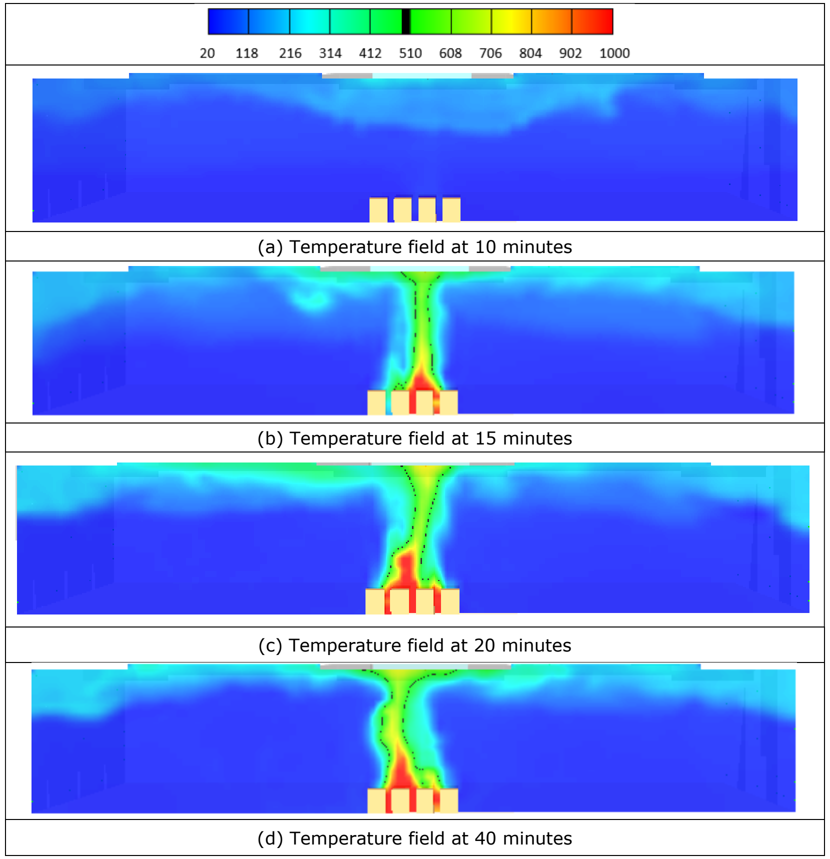
(d) Pallets involved in fire at 15 minutes

(e) Plan view 1m under the roof at 20 minutes

(f) Pallets involved in fire at 20 minutes

(g) Plan view 1m under the roof at 40 minutes

(h) Pallets involved in fire at 40 minutes



(a) Temperature field at 10 minutes

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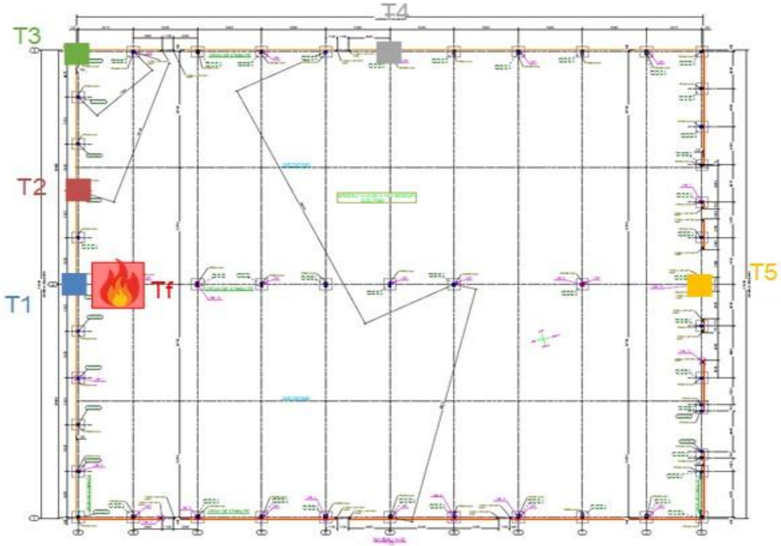
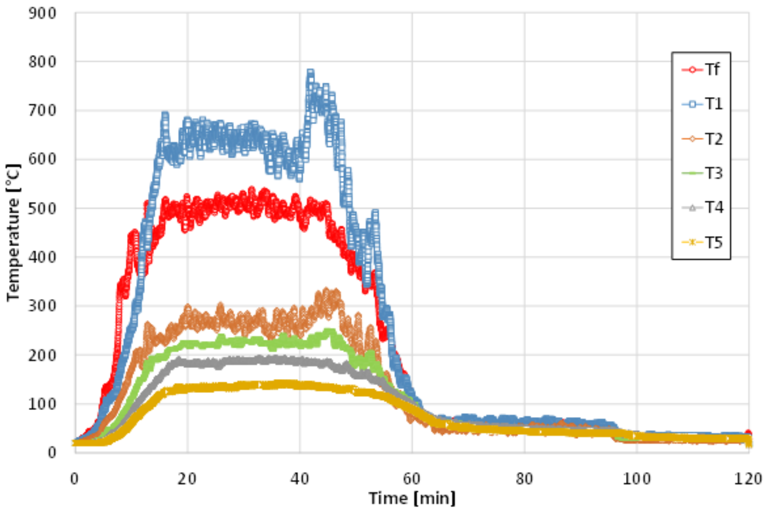
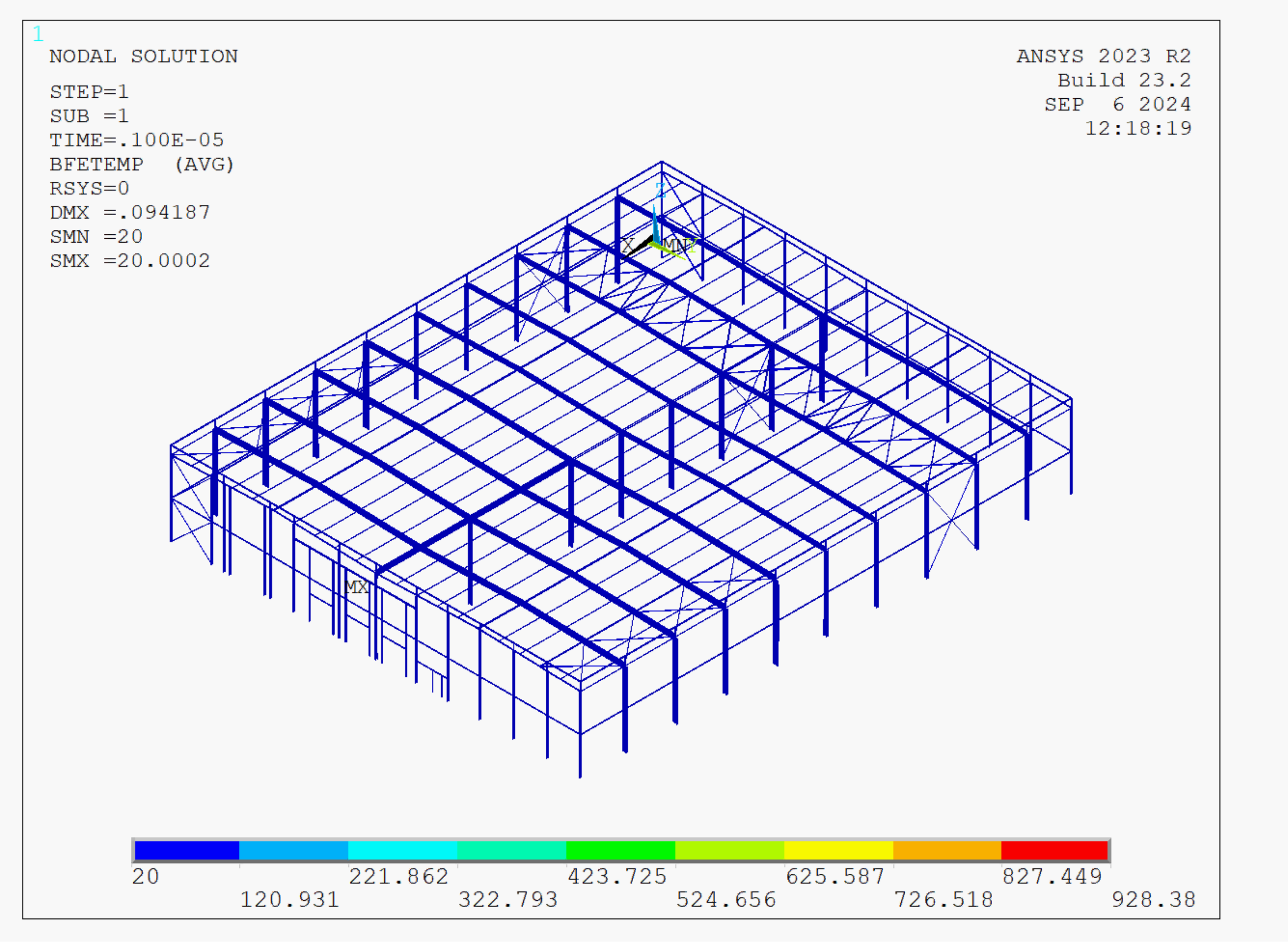
(d) Temperature field at 40 minutes





Parametric study on whole steel structures

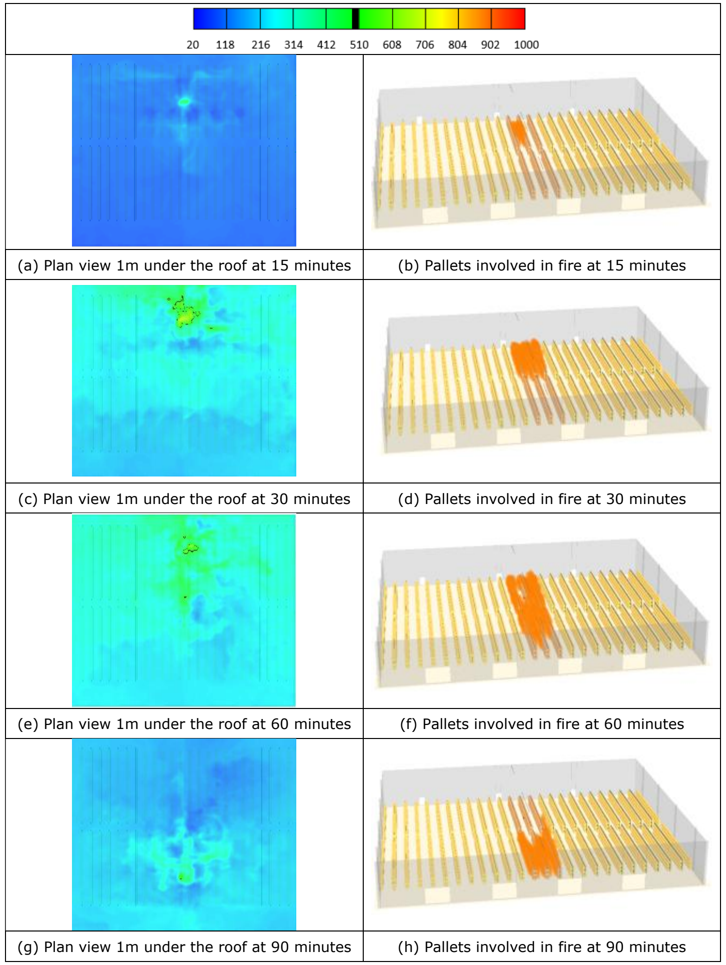
- **Fire scenarios I.2.2**
  - Thermal analyse



Parametric study on whole steel structures

➢ Fire scenarios S.2.3

❖ Fire development



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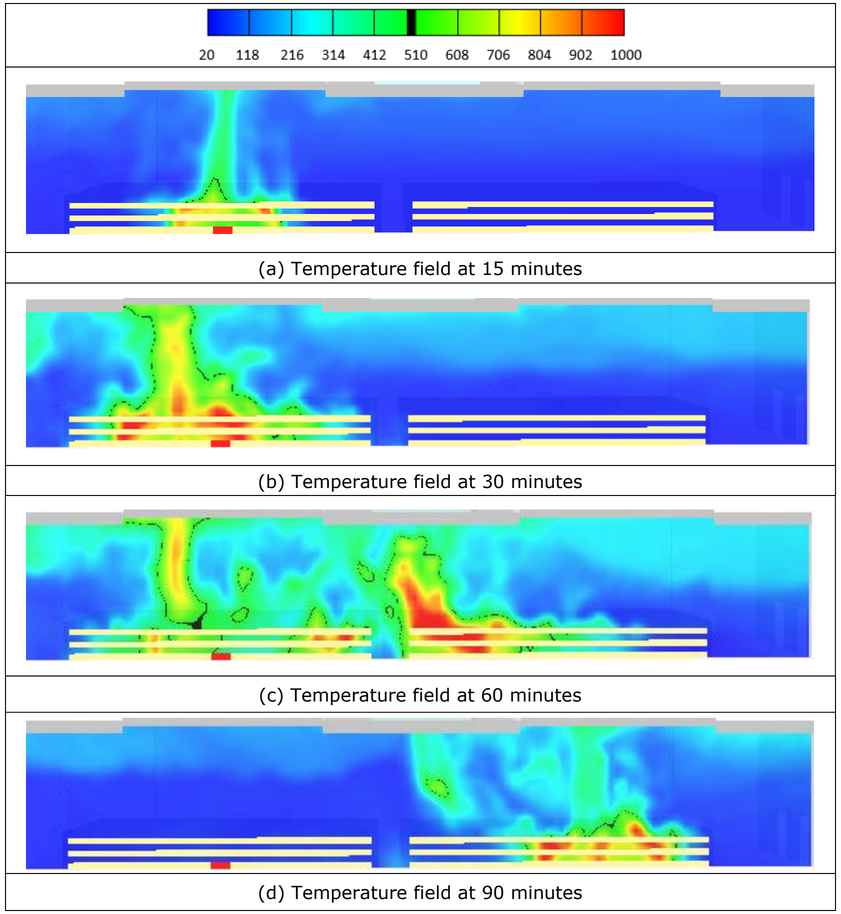
(f) Pallets involved in fire at 60 minutes
(g) Plan view 1m under the roof at 90 minutes
(h) Pallets involved in fire at 90 minutes



(a) Temperature field at 15 minutes
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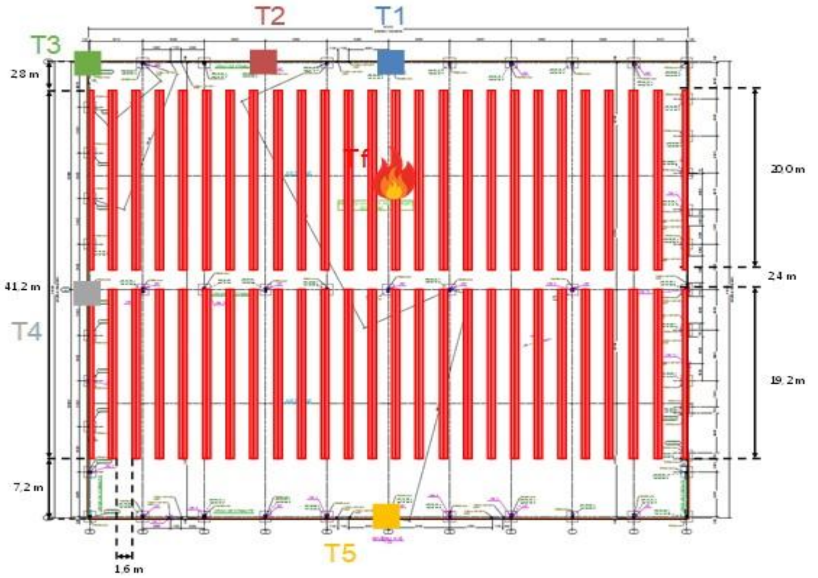
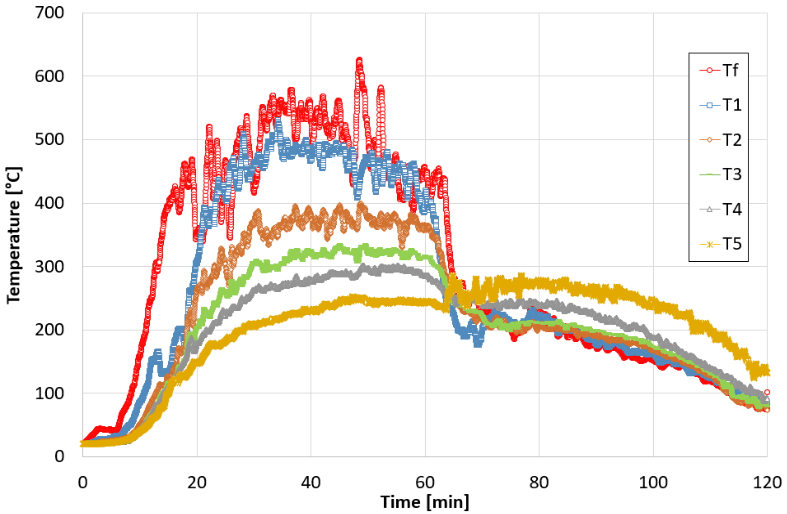
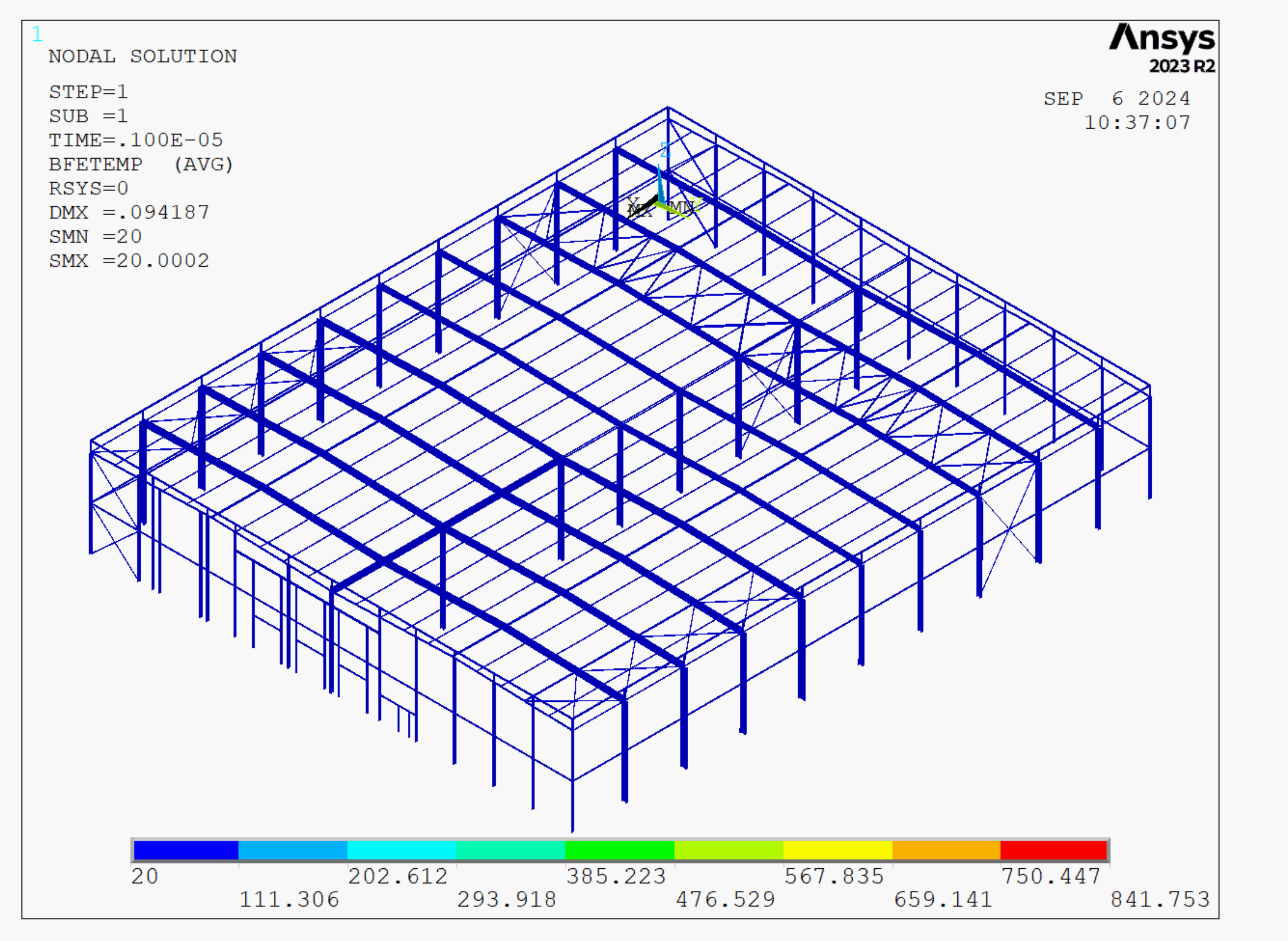




Parametric study on whole steel structures

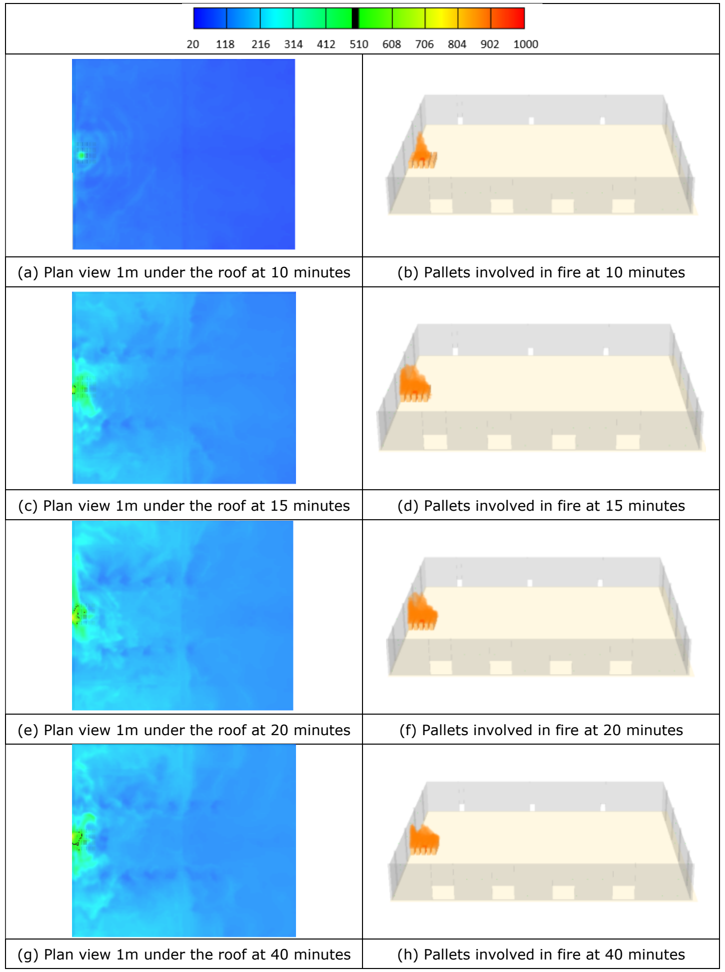
- **Fire scenarios S.2.3**
  - Thermal analyse



Parametric study on whole steel structures

➢ Fire scenarios I.2.2

❖ Fire development



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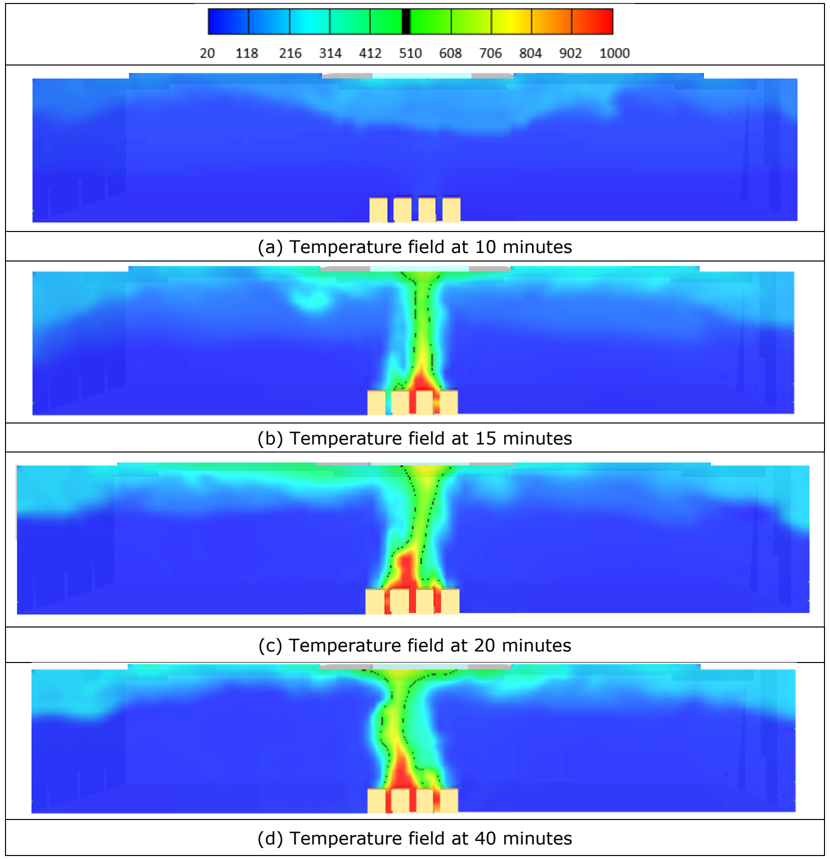
(f) Pallets involved in fire at 20 minutes
(g) Plan view 1m under the roof at 40 minutes
(h) Pallets involved in fire at 40 minutes



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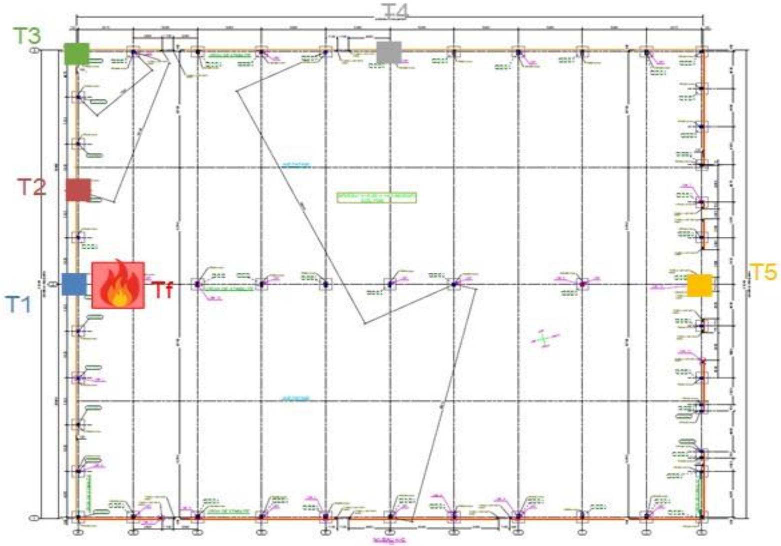
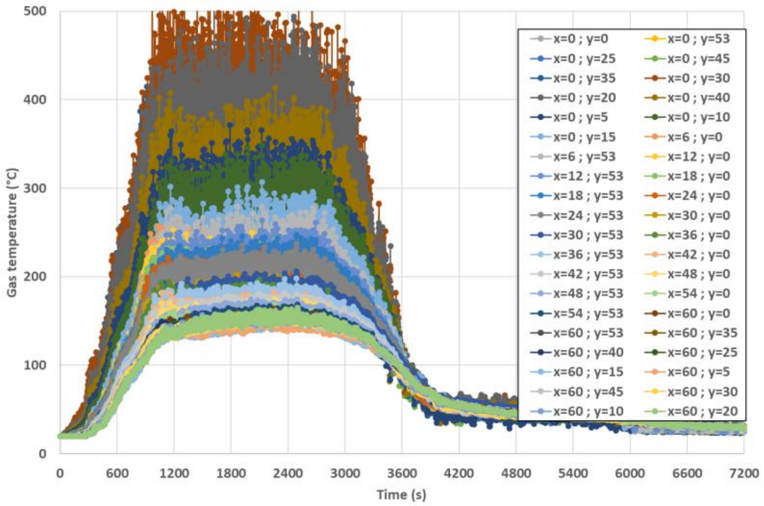
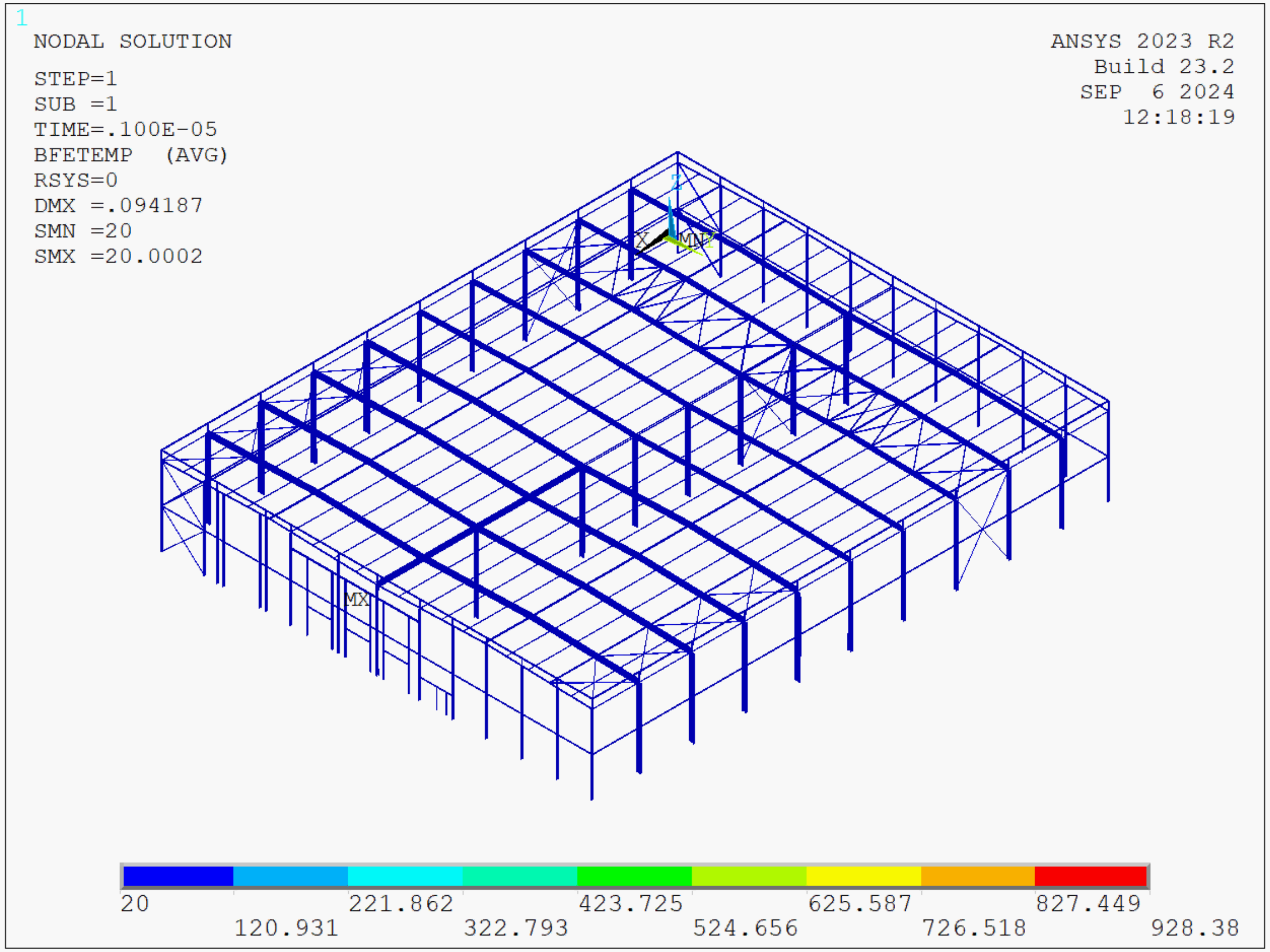




Parametric study on whole steel structures

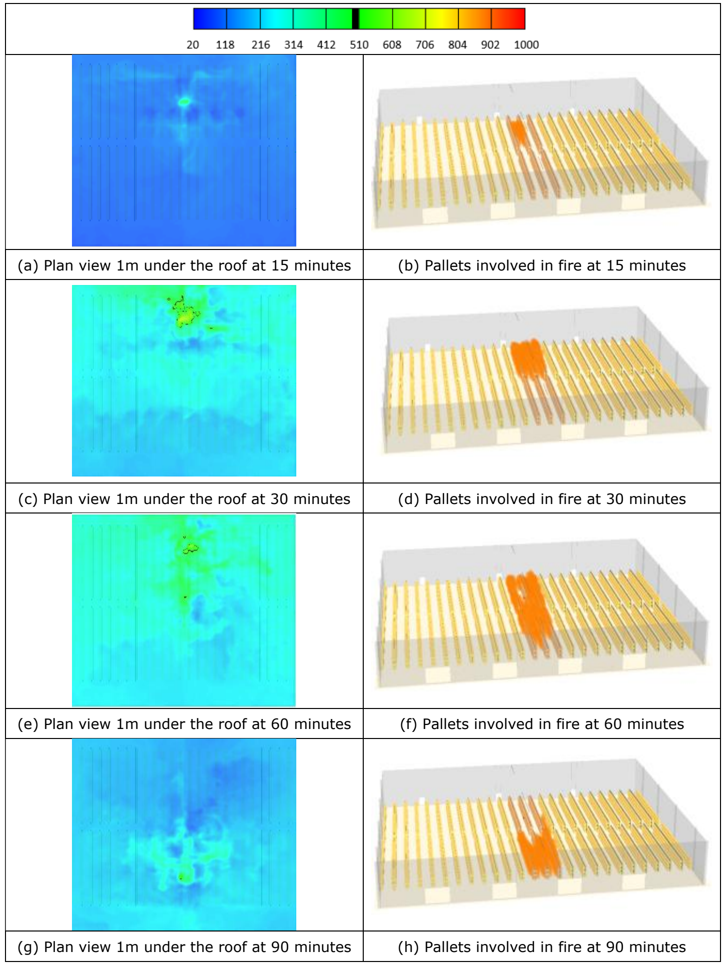
- **Fire scenarios I.2.2**
  - **Thermal analysis**



Parametric study on whole steel structures

➢ Fire scenarios S.2.3

❖ Fire development



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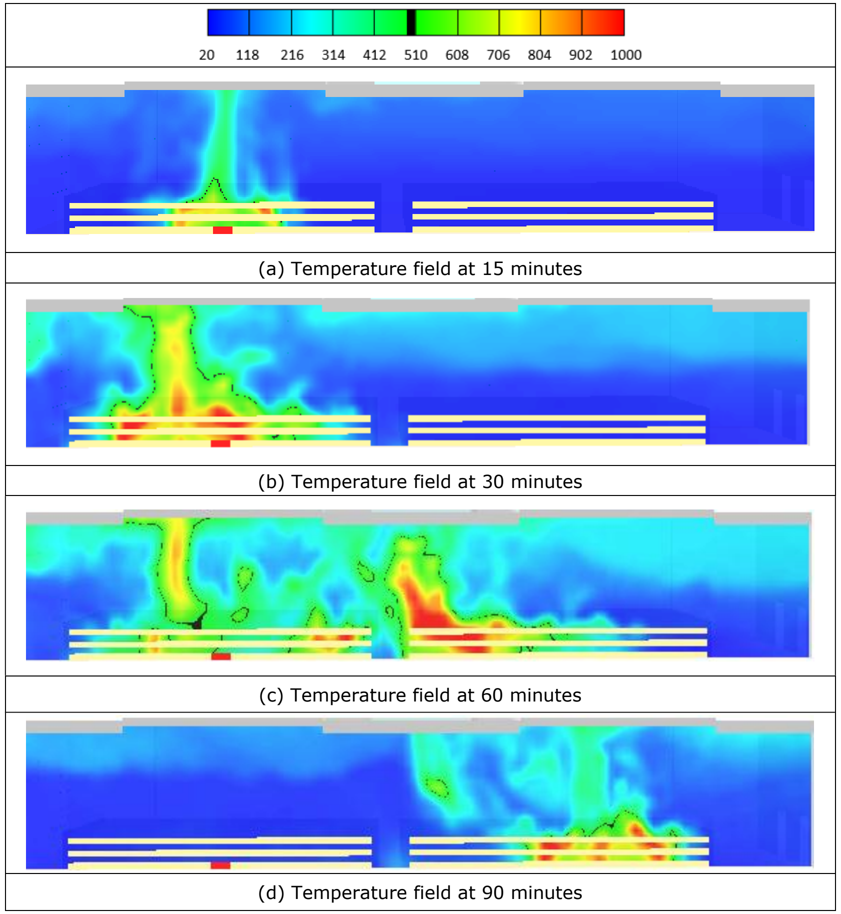
(f) Pallets involved in fire at 60 minutes

(g) Plan view 1m under the roof at 90 minutes

(h) Pallets involved in fire at 90 minutes

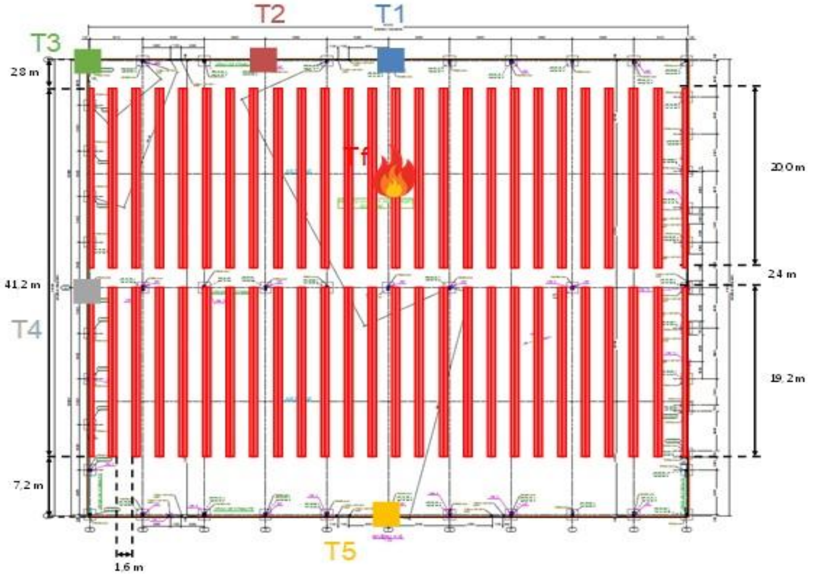


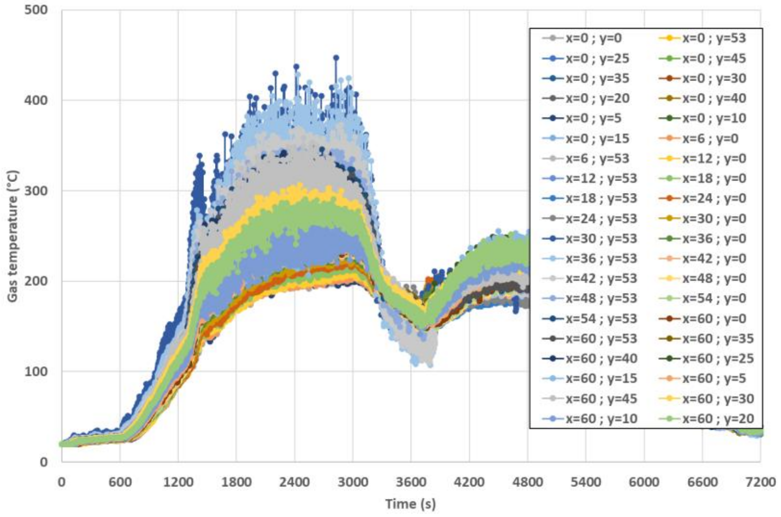
(a) Temperature field at 15 minutes

(b) Temperature field at 30 minutes

(c) Temperature field at 60 minutes

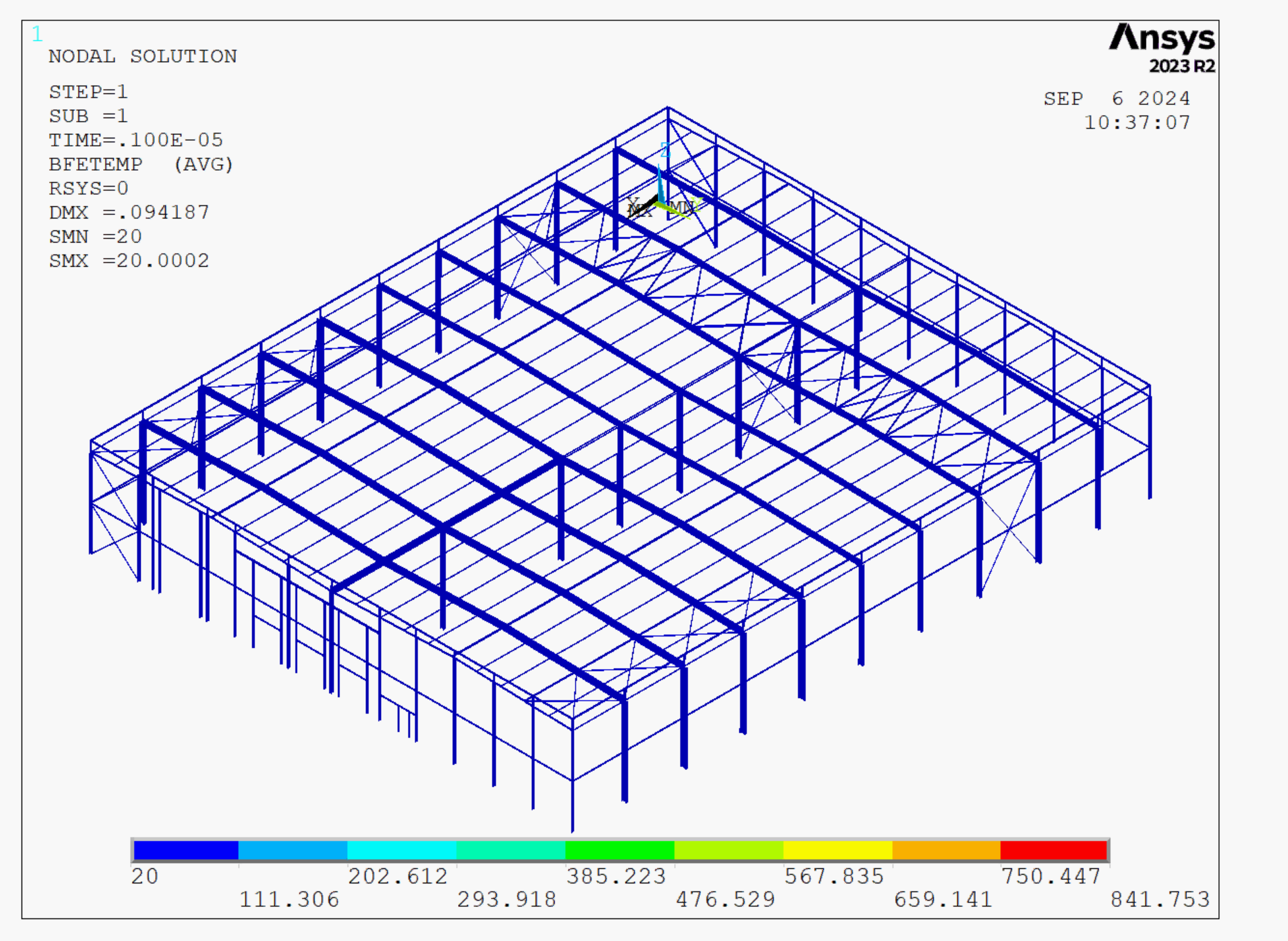
(d) Temperature field at 90 minutes





Parametric study on whole steel structures

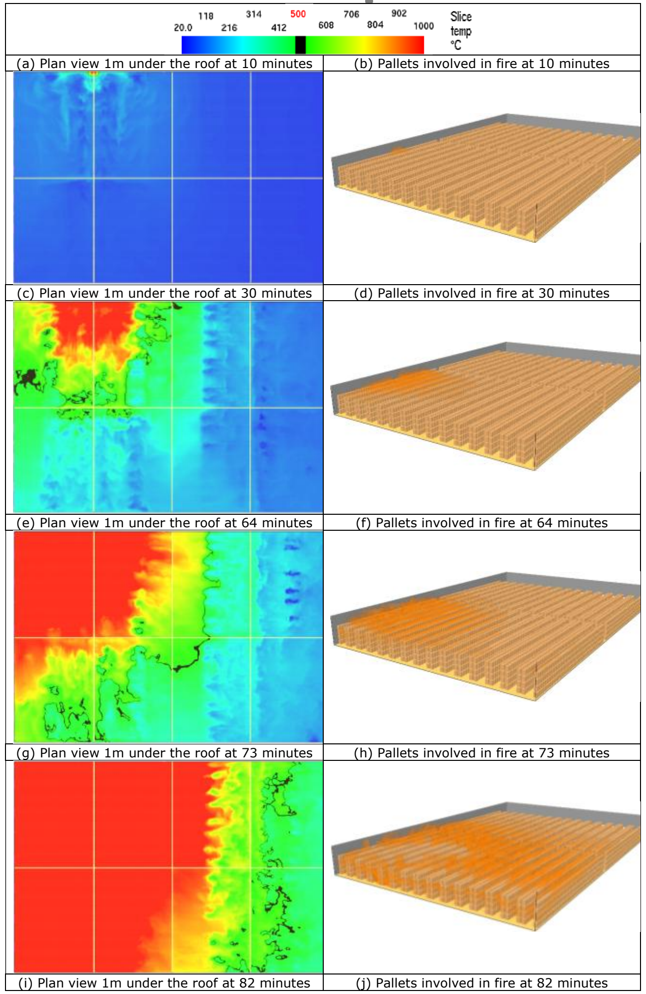
- **Fire scenarios S.2.3**
  - Thermal analysis

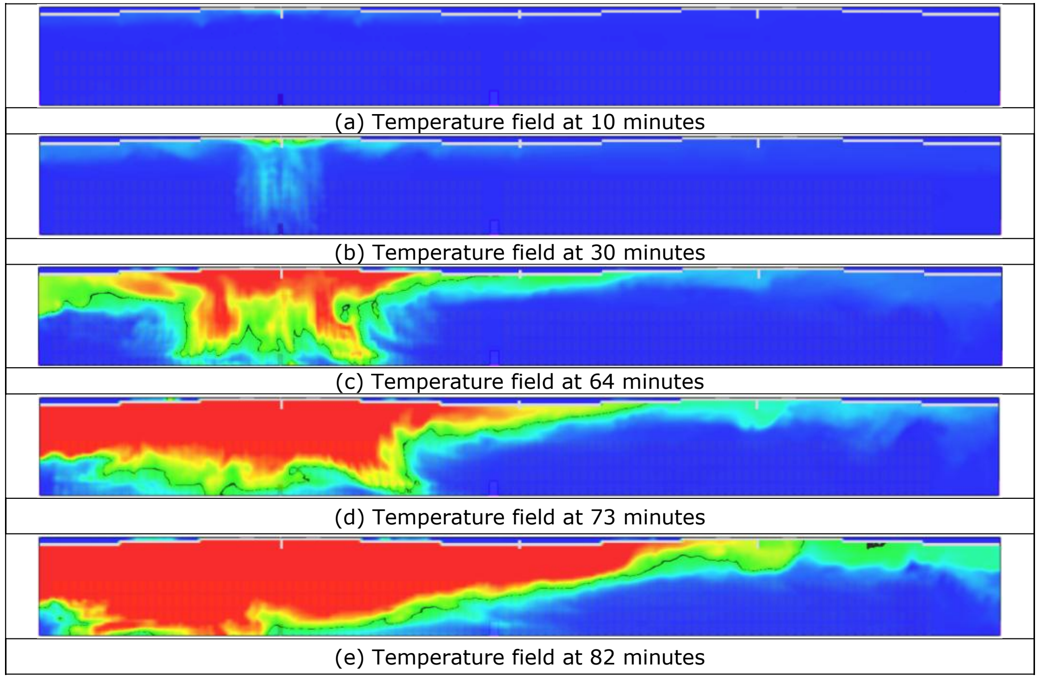


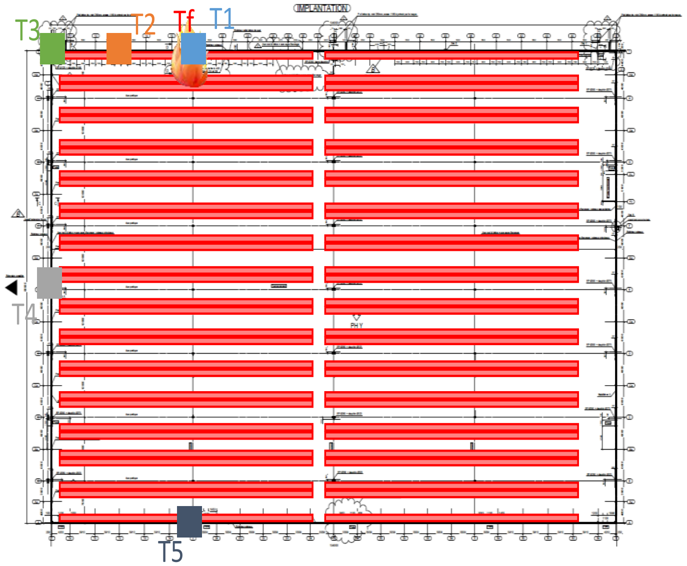
Parametric study on whole steel structures

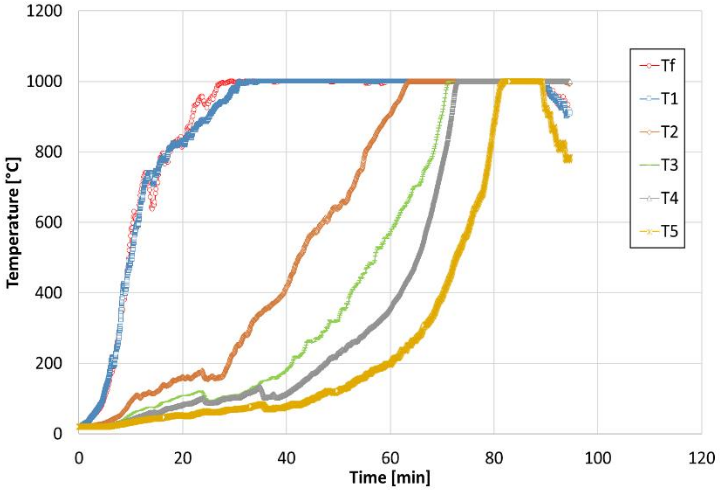
Fire scenarios W.4.1

Fire development



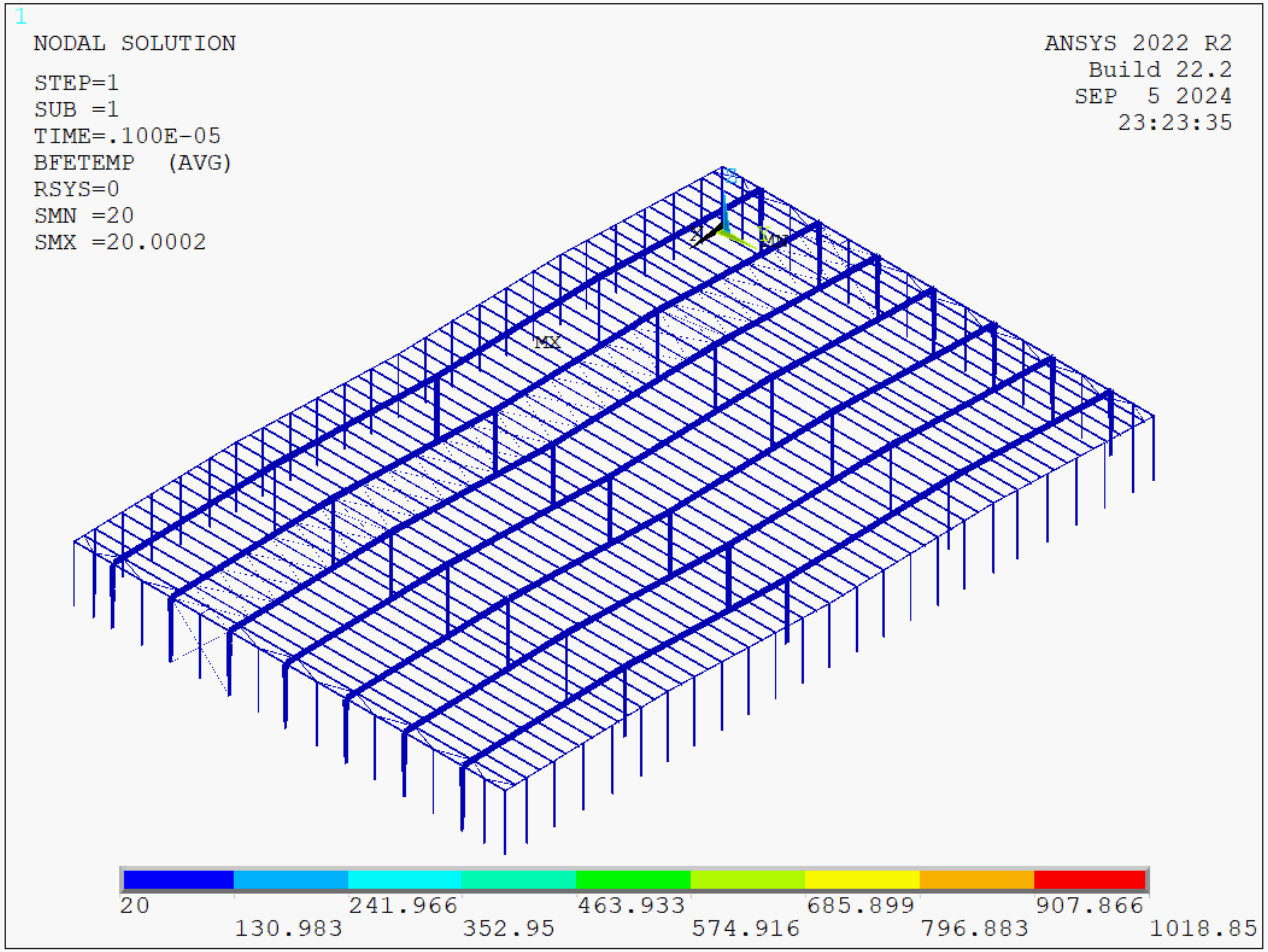






Parametric study on whole steel structures

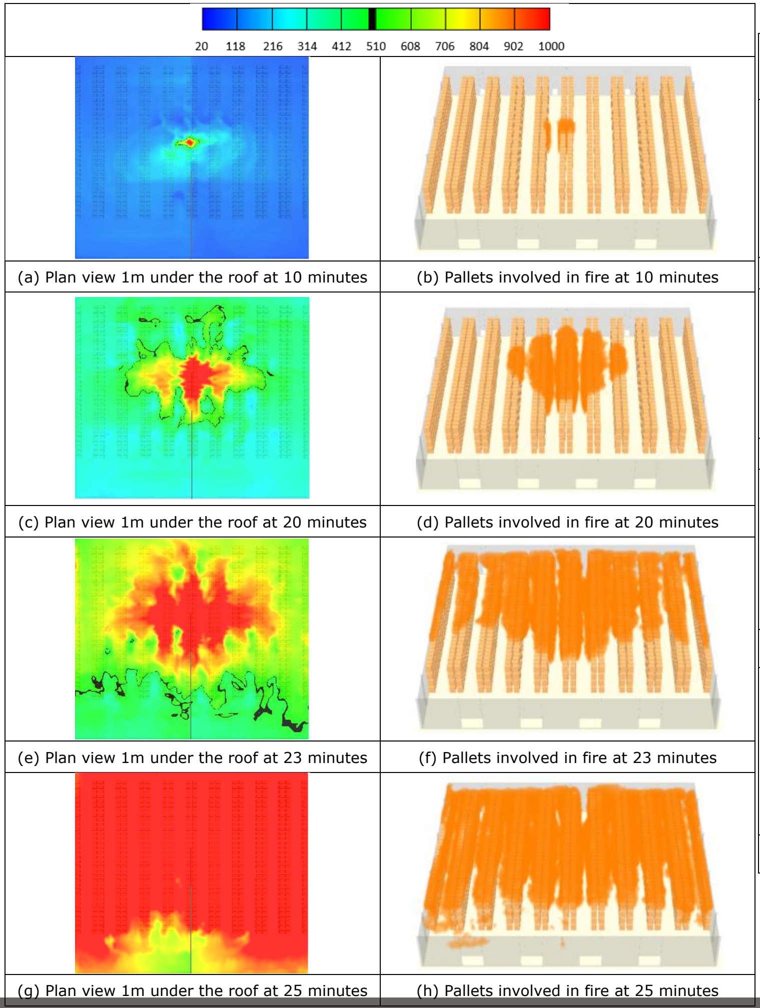
- **Fire scenarios W.4.1**
  - Thermal analyse



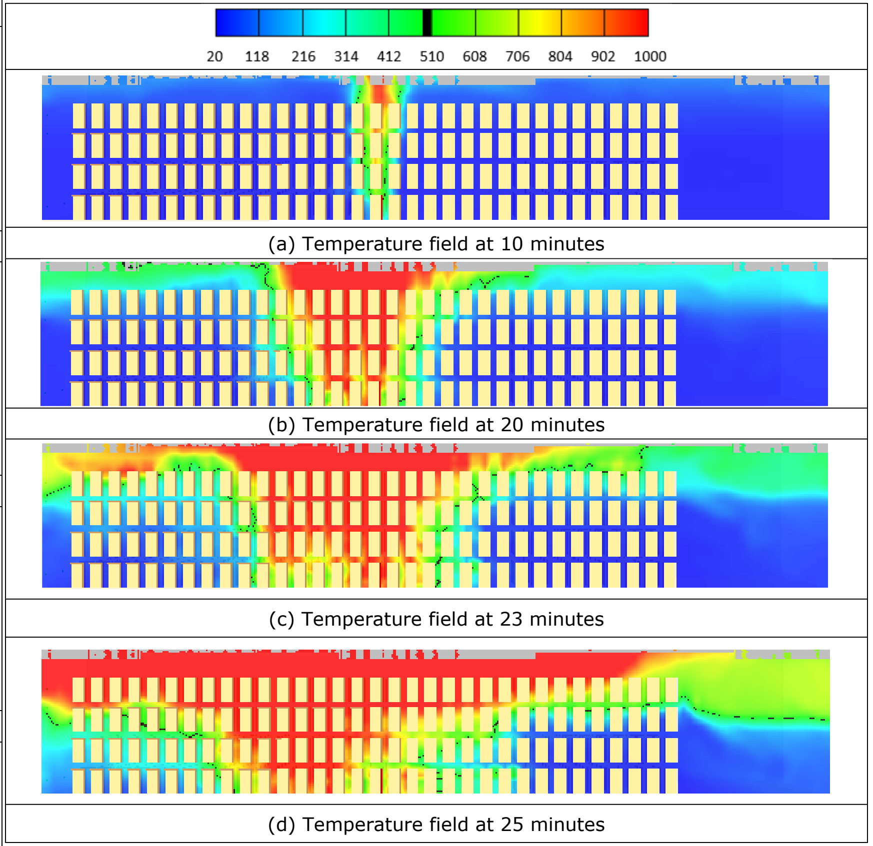
Parametric study on whole steel structures

➢ Fire scenarios W.2.3

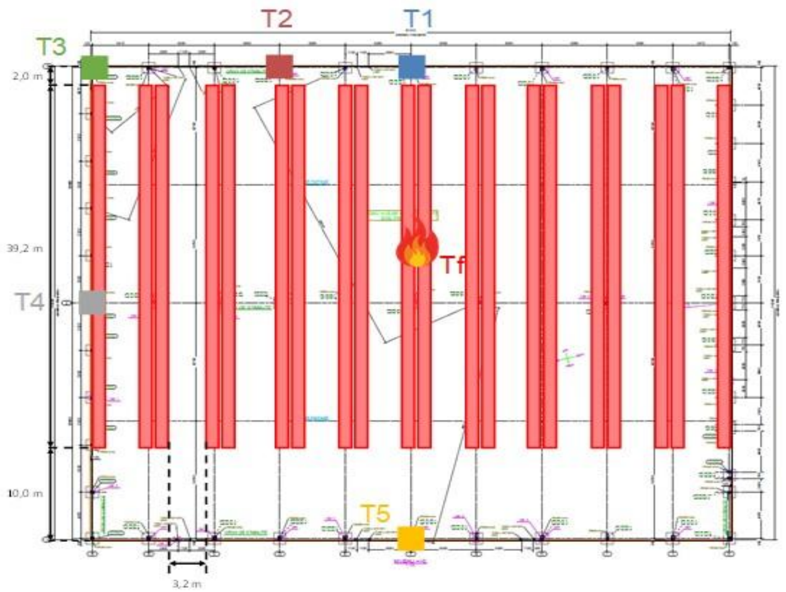
❖ Fire development

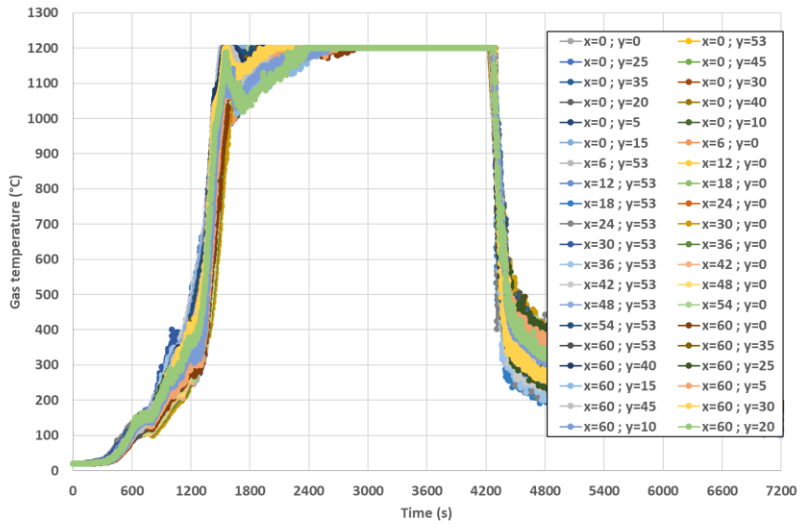


(a) Plan view 1m under the roof at 10 minutes
(b) Pallets involved in fire at 10 minutes
(c) Plan view 1m under the roof at 20 minutes
(d) Pallets involved in fire at 20 minutes
(e) Plan view 1m under the roof at 23 minutes
(f) Pallets involved in fire at 23 minutes
(g) Plan view 1m under the roof at 25 minutes
(h) Pallets involved in fire at 25 minutes



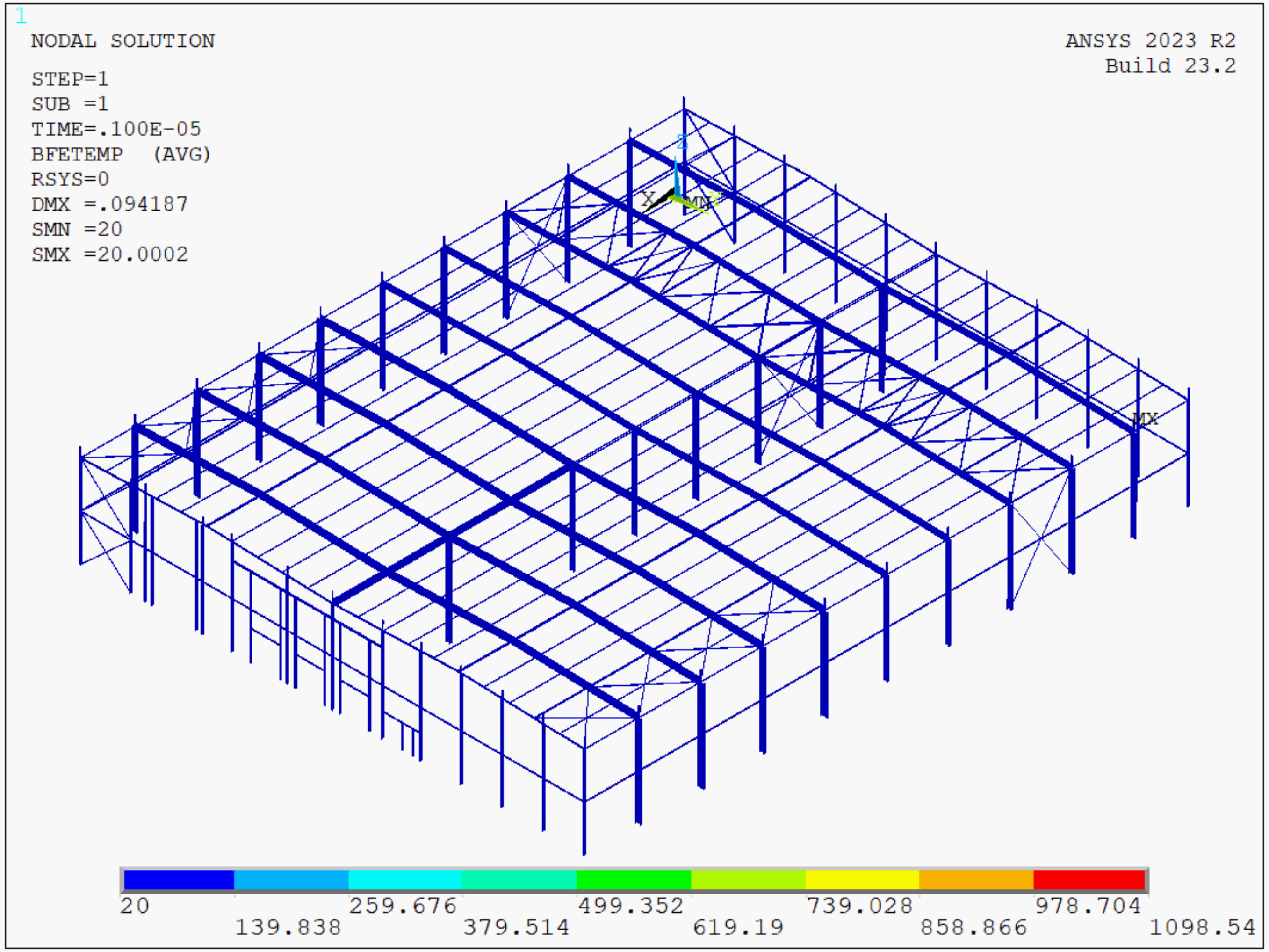
(a) Temperature field at 10 minutes
(b) Temperature field at 20 minutes
(c) Temperature field at 23 minutes
(d) Temperature field at 25 minutes





Parametric study on whole steel structures

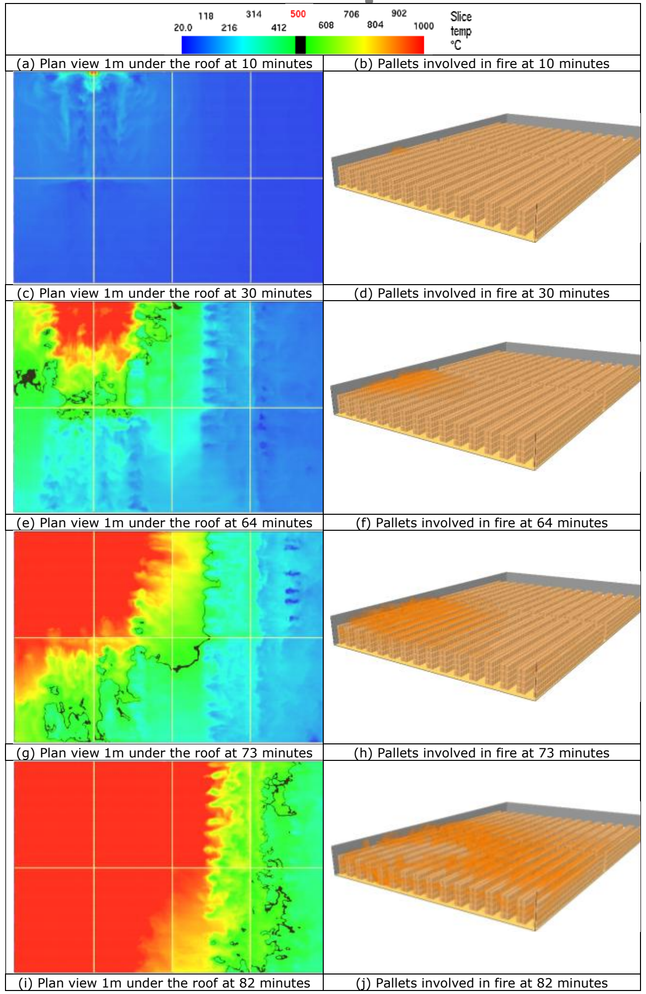
- **Fire scenarios W.2.3**
  - Thermal analysis

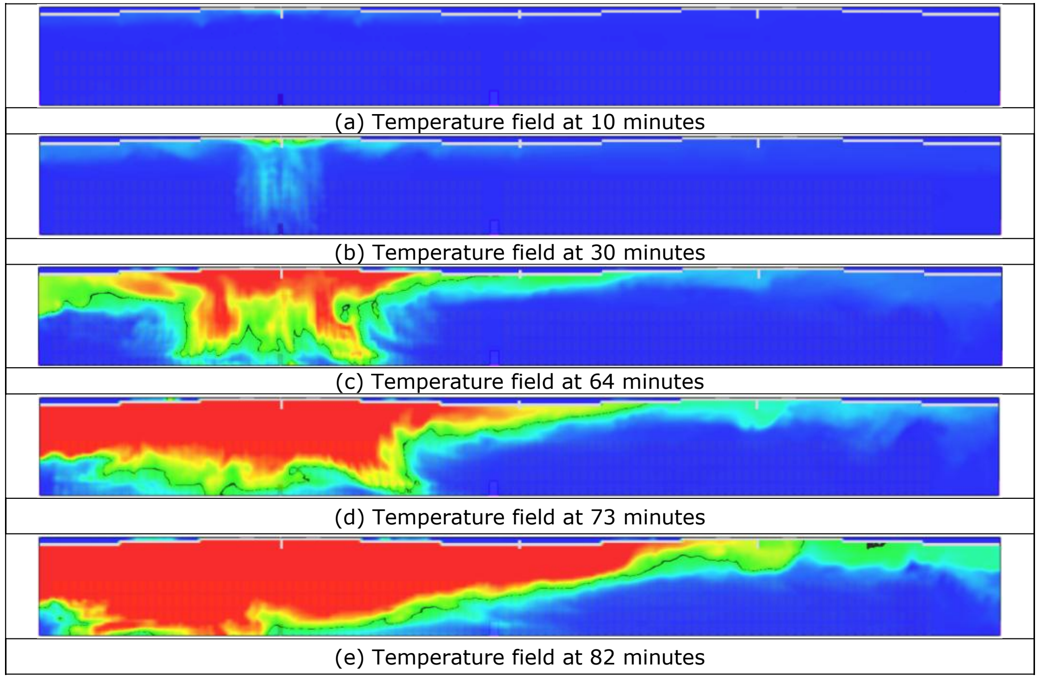


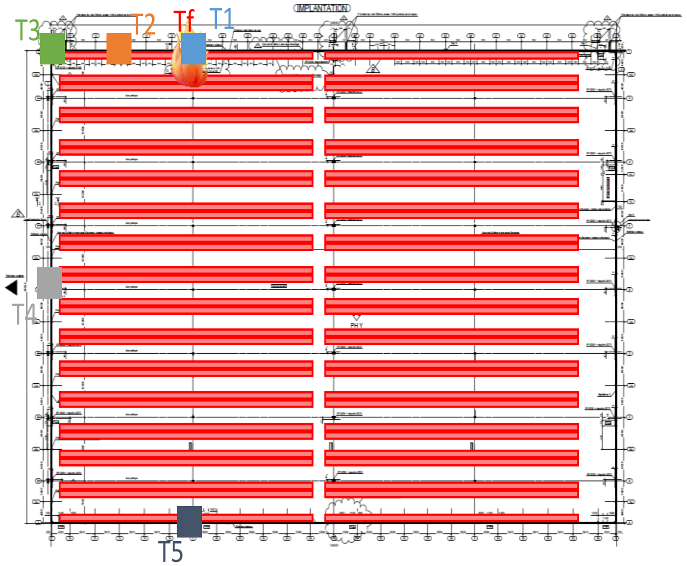
Parametric study on whole steel structures

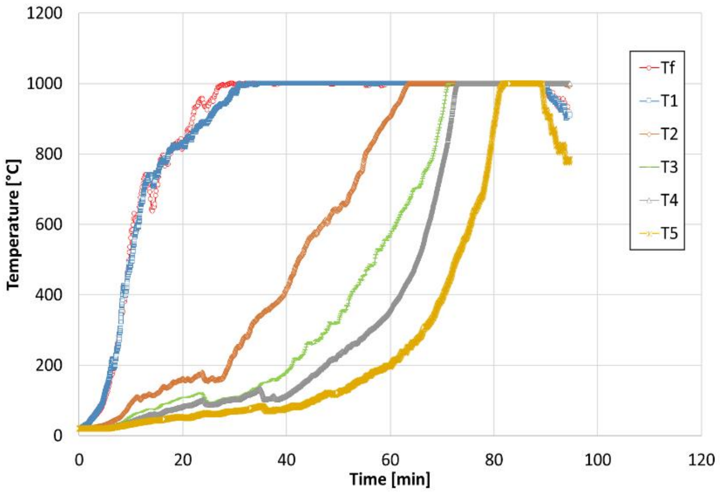
➢ Fire scenarios W.4.1

❖ Fire development









Parametric study on whole steel structures

- **Fire scenarios W.4.1**
  - Thermal analysis