ArcelorMittal

Steel Sheet Piles

Underground car parks

Fire resistance

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Aim of this brochure

This brochure provides assistance in the fire safety design of steel sheet piles to be used as permanent structural elements in underground car parks or roadworks (tunnels, underpasses, ...).

It summarises the efforts that have been made on this subject and the verification services provided by ArcelorMittal. Furthermore, it includes an easy-to-use verification procedure allowing a simplified assessment of the fire safety of the steel sheet pile structure at the pre-design stage.

Steel sheet piles as permanent structural elements

Steel sheet piles used as permanent structural elements in underground car parks and roadworks have a multiple role. They can:

(Fig. 1) Mercedes-Benz Car Park, Ghent, Belgium

- serve as a retaining wall during the excavation phase to support the horizontal pressures
- provide watertight containment for the excavation pit
- form the permanent outer structural wall
- carry parts of the vertical loads from the floors or even from the superstructure.

Thus, avoiding the need for a temporary retaining wall outside, the permanent sheet pile wall:

- maximises the available space, an important issue especially in urban areas
- shortens the construction time
- reduces the total cost of the building.

Economical steel solutions

The main benefit of using steel sheet piles as permanent structural elements for underground car parks and basements is the simplification of the construction sequence and the resulting substantial savings of cost and time.

Economical steel solutions without any protective measures can even be defined for structures subject to fire resistance requirements.

Steel sheet piles can easily be painted after completion of the works.

Verifications are usually confined mainly to the design at serviceability or ultimate limit states considering the temporary execution steps as well as the final situation, and focus on the most economical solution.

(Fig.2) Car Park in The Hague, The Netherlands

Specifics

Like any bearing pile, steel sheet piles can safely transmit vertical loads to the substratum through skin friction and toe resistance.

Structural connection of the floors and superstructure is easy with cast in-situ concrete corbels or capping beams.

Using the top-down method will even allow a further reduction in construction time, since temporary anchoring or propping of the retaining wall is not necessary.

Fire resistance of steel sheet piles

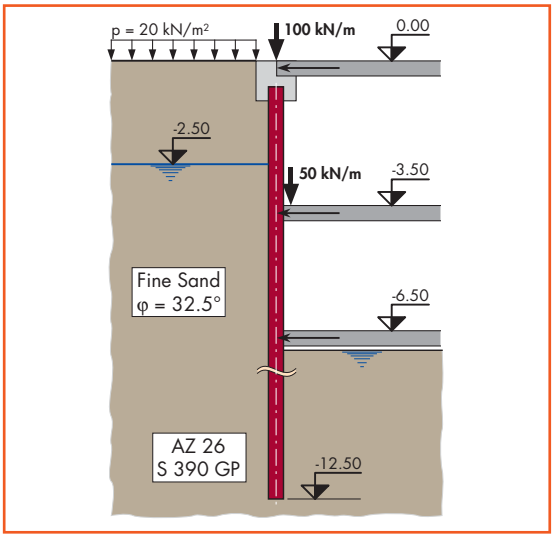
In most cases, the "Fire" load case does not have to be considered for temporary constructions.

However, for permanent structures, steel sheet pile solutions are often excluded right from the design stage due to unfounded prejudices or to a lack of know-how concerning fire safety in general or the particular behaviour of steel sheet piles under the effect of a possible fire event.

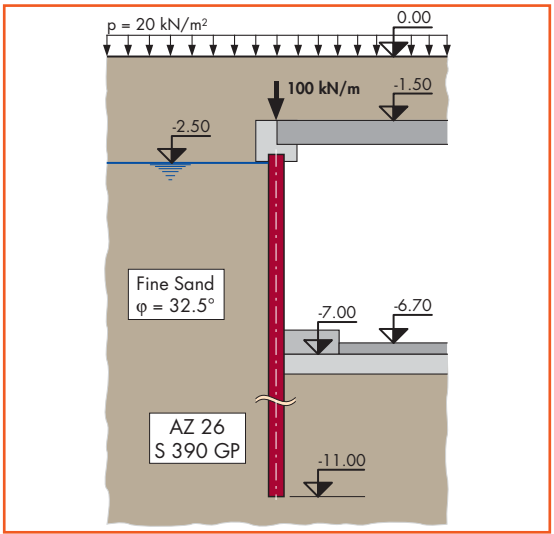
Arcelor has carried out extensive fire testing and numerical simulations focusing on the fire resistance of steel sheet piles and the effects of the surrounding soil.

Using the knowledge gained, the fire safety of steel sheet pile walls can be verified taking the following parameters into account:

- the thermal characteristics of the different soils
- different fire loads
- different protective measures



(Fig.3) Underground car park



(Fig.4) Road tunnel / underpass

General fire safety concepts

The overall purpose of fire safety is to reduce the risk of both life and property losses, the main concern being the safety of lives.

An appropriate fire safety concept is a package of active systems (i.e., fire detection, fire fighting) and passive systems (i.e., structural fire resistance, partitioning, etc).

(Fig.5) Car Park in Scheveningen, The Netherlands

Factors for assessing the probability of a major fire occurring include:

- the activity and combustible contents (fire load) of the building,
- the type of building,
- the active fire prevention.

Safety precautions may differ between different types of buildings in evaluating personal fire safety as a function of:

- density of human occupation
- occupant mobility
- size and number of storeys (escape time)
- limits on the spread of smoke to remote parts of building.

Active and passive protection measures

Possible protection measures include:

Active protection measures, like:
- fire and smoke detectors,
- automatic sprinklers,

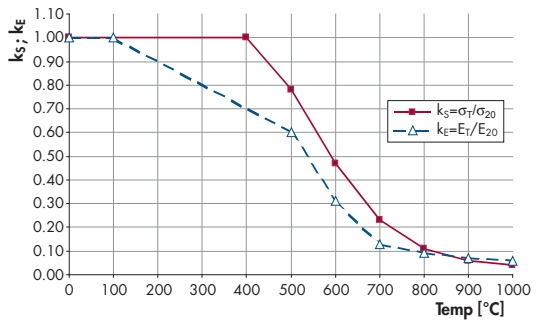
will normally limit the spread of fire and ensure that fire-fighting services are called to the scene as quickly as possible.

Passive protection measures are used to prevent the build-up of high temperatures in the load-bearing structural elements. These measures may include:

- specially applied protection materials (i.e., insulation boards, coating)
- natural passive protection of the steelwork by concrete fill or the surrounding soil

Designing structures for fire loads

According to the relevant standards, any structure subject to the risk of a possible fire event has to be designed taking the effects of such a fire into account.



(Fig.6) Thermo-mechanical characteristics of steel

Different aspects have to be considered:

- the effects of smoke development

Depending on the available combustibles and on the ventilation conditions, the fire compartment may be filled with toxic gases. In order to prevent intoxication and human losses, a certain amount of ventilation has to be achieved.

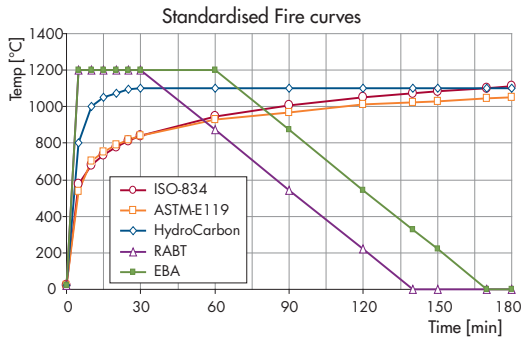
- the effects of high temperatures

Although steel will not burn, its mechanical properties will be strongly influenced by elevated temperatures. Thus, a thorough design of the structural elements is quite an important aspect.

Indeed, the mechanical properties of steel decrease with increasing temperature to about 10% of their nominal values for temperatures of 800°C.

Structural design is mainly based on standardised fire curves. However, consideration of natural fire loads on the basis of the available combustibles is gaining more widespread acceptance.

Standardised fire curves



(Fig.7) Standardised fire curves

The predominant fire resistance assessment methods all over the world are generally based on standardised temperature/time curves, such as ISO-834, ASTM-E119, Hydro-Carbon, RABT, EBA, etc.

The traditional definition of fire resistance is the time expressed in minutes that a structural element is able to support the design loading when exposed to the standard fire before a specific condition of failure is reached. Accordingly, the elements or structures are classified into fire resistance categories R30, R60, etc.

These standardised curves, however, do not describe natural fires in a realistic way.

A more rational approach to fire engineering design of buildings is based on the behaviour of a structure in a real or natural fire. Such design procedures have been progressively developed in recent years and are increasingly accepted by authorities in many countries.

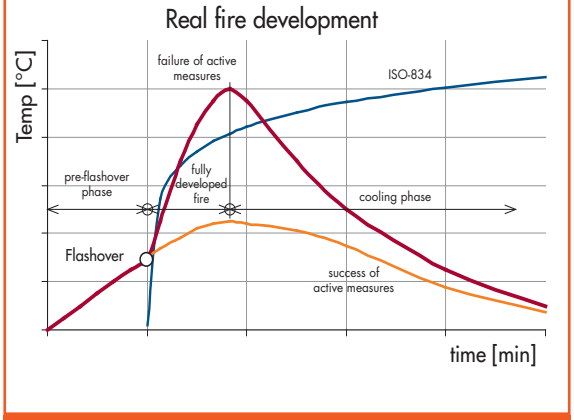
Factors influencing the severity of realistic fires

The intensity of a fire and the duration of the phases, as measured by the temperature/time curve of the gases in the fire compartment, depend on many parameters:

- the amount and distribution of combustible materials,
- the characteristics, i.e., the burning rate of these materials,
- the ventilation conditions of the room,
- the compartment geometry,
- the thermal properties of the walls and ceiling.

Real fire development

In a natural fire, three different phases can be identified:



(Fig.8) Realistic fire development

- In the first phase, the combustible begins to burn; temperature varies from one point to another with significant gradients within the compartment, and there is a gradual propagation of the fire. In this first step, there is normally no risk of structural failure, although some local damage to contents may occur.

- In the second phase, the average temperature rises in the compartment; if it reaches about 300°C to 500°C, the upper layers are subjected to sudden ignition, called "flashover", and the fire develops fully. The transition from a local fire to a fully developed fire is an essential step in evaluating structural fire safety. After flashover, the gas temperature increases very rapidly to a peak value, often in excess of 1000°C, and becomes practically uniform throughout the compartment.

- In the third phase, the available combustibles begin to decrease and the gas temperature necessarily falls.

Fire load densities

The fire load is defined as the sum of all combustible materials of a compartment, expressed in [MJ] or in [kg] wood equivalent. It may be also expressed by the fire load density q_f in [MJ/m^2] or [kg/m^2], which is the ratio of total fire load to the floor area.

Characteristic values of the fire load density q_f for buildings according to EN1991-1-2, "Actions on structures exposed to fire" are:

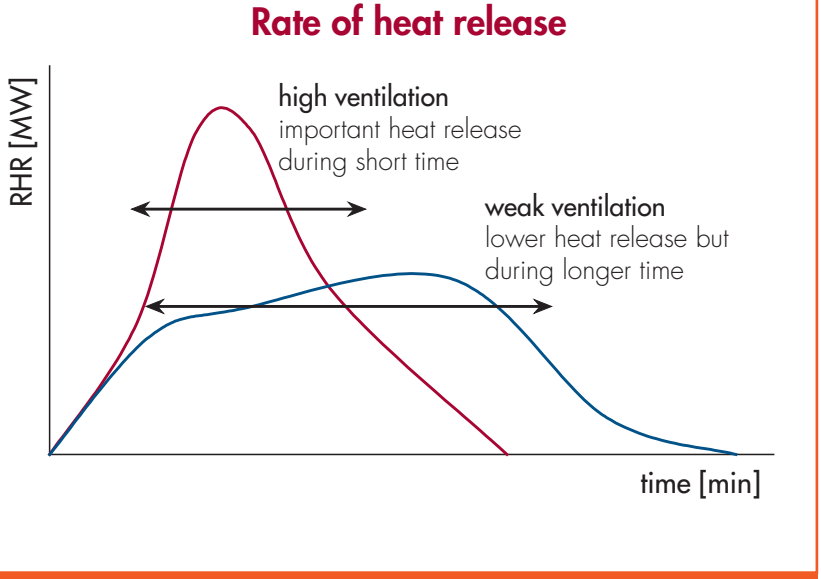
(Table 1) Characteristic values of fire loading q_f for buildings

Type of fire compartment	fire load density q_f [MJ/m^2]	
	mean	80% fractile
Dwellings	780	948
Hospitals	230	280
Hotels (bedrooms)	310	377
Libraries	1500	1824
Offices (standard)	420	511
Schools	285	347
Shopping centres	600	730
Theatres (cinemas)	300	365
Transport (public space)	100	122

Characteristic fire loads for cars are about 5000 to 7000 MJ.

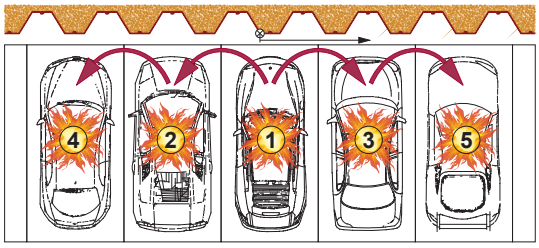
Rate of heat release (RHR)

The fire load defines the available energy but the gas temperature in a fire depends on the rate of heat release, which is governed by the available oxygen supply. The same fire load burning very quickly or smouldering can lead to completely different gas temperatures.

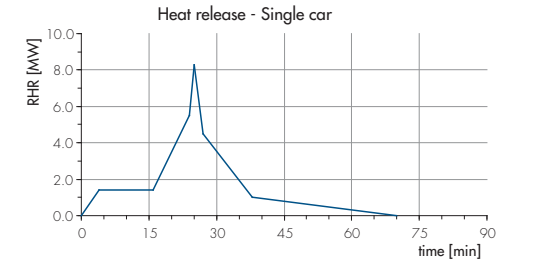


(Fig.9) Different rates of heat release

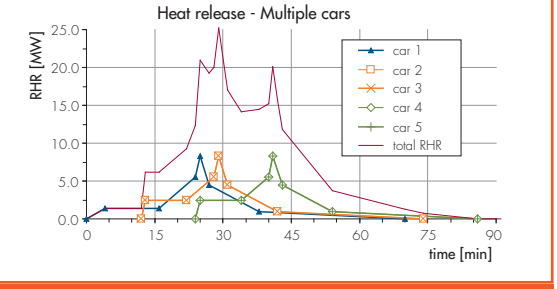
Simulation approach



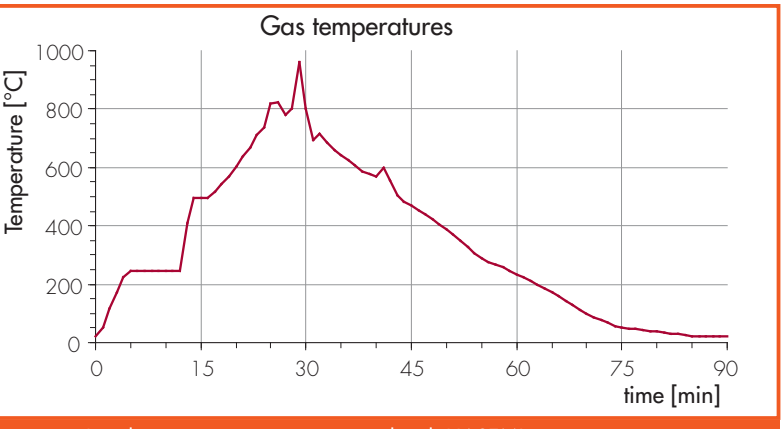
(Fig. 10) Plan view of car park and fire scenario



(Fig. 11) Standardised heat release curve



(Fig. 12) Heat release for multiple car fire scenario



(Fig. 13) Local gas temperatures computed with HASEMI

Calculation according to EN 1991-1-2 Annex C

This method (based on the heat flux according to the HASEMI method) gives the temperatures at the top level of the SSP wall as a function of the distance to the fire source, (see fig. 10) for a single or multiple car fire scenario.

The heat release of the different single cars is based on experimental curves, derived from several car burning tests performed in the frame of the ECSC project "Development of design rules for steel structures subjected to natural fires in closed car parks".

It is assumed that the fire starts in car 1 and may spread to the neighbouring cars 2 and 3 after 12 minutes and then to cars 4 and 5 after 24 minutes.

The Rates of Heat Release from the second and following cars have a slightly different increasing phase as they are already heated by the first car (see fig. 12).

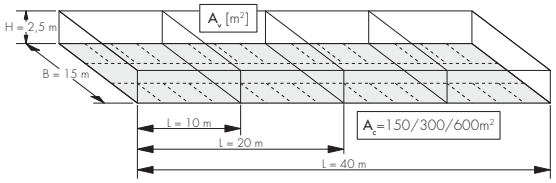
In cases where a sprinkler system is available, it could be considered that only 1 car is burning, as the sprinklers cool it down and avoid a spread over.

The calculation of the temperature distribution takes into account the location of the respective individual heat releases and the height of the compartment.

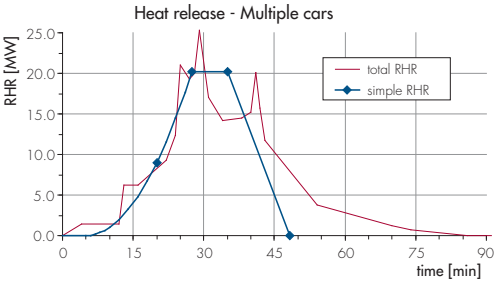
Influencing parameters for this curve are:

- the fire load of the single cars
- the numbers and position of the cars with respect to the SSP.
- the compartment height

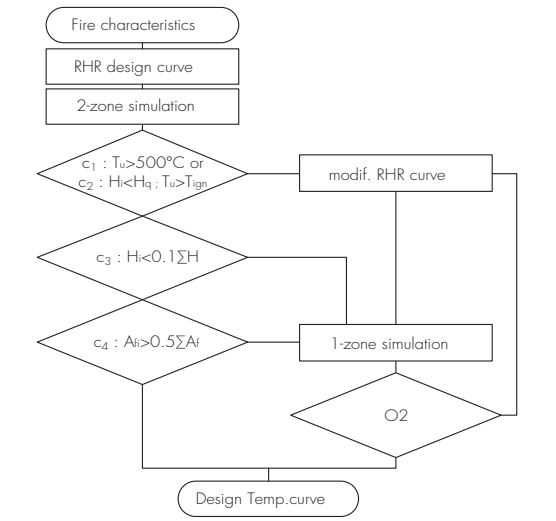
It shall be noted that the temperatures are calculated at the top level, just below the ceiling, and thus are safe sided.



(Fig.14) Modelling for OZONE



(Fig.15) Simplified RHR for OZONE calculation



(Fig.16) Calculation approach of OZONE

Simulation with OZONE V2.2

OZONE is a two zone calculation model that gives gas temperatures in both the hot and cold layers (available on ArcelorMittal's homepage free of charge).

This simulation takes into account the total fire as well as the compartment properties with the ventilation conditions.

The simulation is based on a simplified RHR curve with the same fire load as the HASEMI calculation for the 5-car fire scenario.

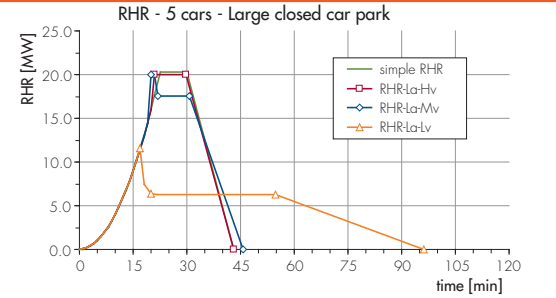
OZONE takes into account the ventilation conditions (c_1, c_2, c_3, c_4) of the fire compartment and defines the possible heat release accordingly.

Parametric calculations

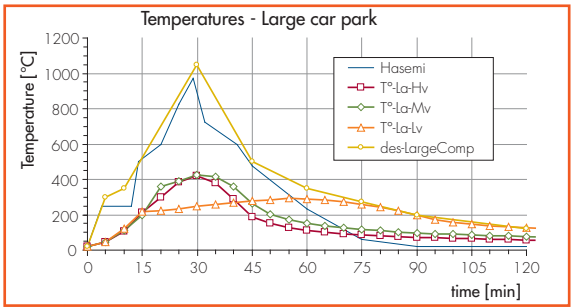
Number of burning cars: 5

(Table 2) Ventilation conditions for closed car parks

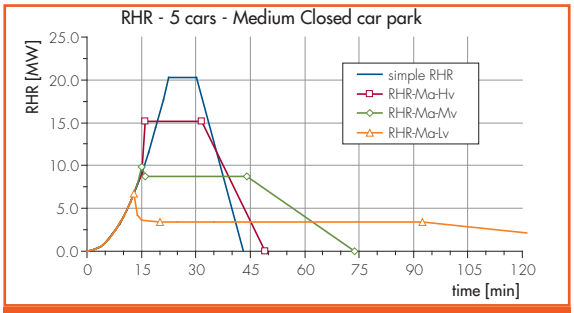
			Ventilation conditions		
			low ventilation 10 m³/m²/h	medium ventilation 35 m³/m²/h	high ventilation 60 m³/m²/h
			Lv	**Mv**	**Hv**
Compartment Area A_c	total 8 cars 150 m²	**Sa**	0.4 m³/s	1.5 m³/s	2.5 m³/s
	total 16 cars 300 m²	**Ma**	0.8 m³/s	2.9 m³/s	5.0 m³/s
	total 32 cars 600 m²	**La**	1.7 m³/s	5.8 m³/s	10.0 m³/s



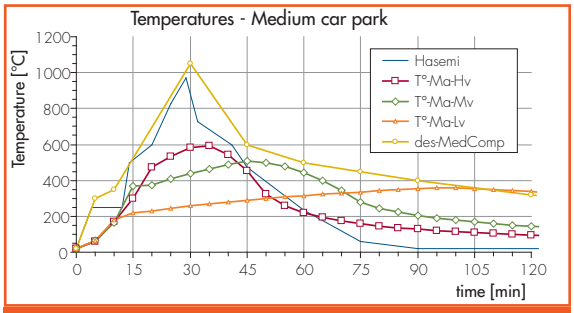
(Fig.17) Heat release in large car parks



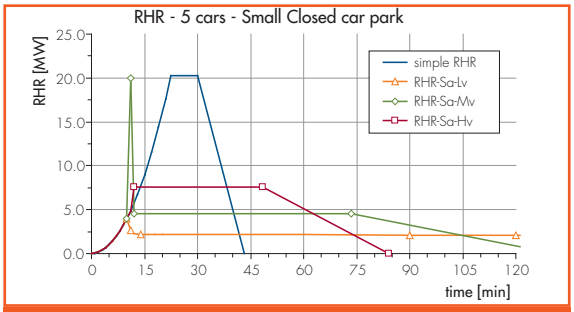
(Fig.18) Temperatures in large car parks



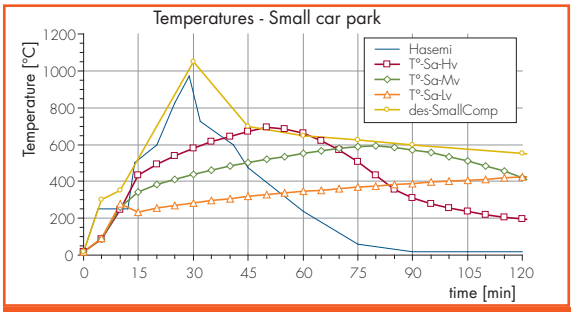
(Fig.19) Heat release in medium sized car parks



(Fig.20) Temperatures in medium sized car parks



(Fig.21) Heat release in small car parks



(Fig.22) Temperatures in small car parks

Note: most standards specify a minimum ventilation for closed car parks of about 10 $m^3/m^2/h$ which is considered here as low ventilation (Lv curves in the following figures).

From fig. 17 it can be clearly seen that for low ventilation conditions the heat release will be less than 50% of the initial design values, however, the fire duration will be doubled.

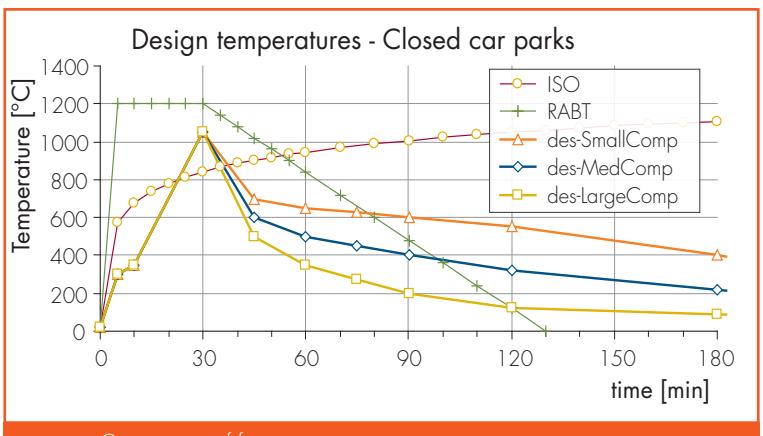
From fig. 18 it can be seen that the calculated mean temperatures in the closed fire compartment are quite lower than for fires in open car parks with full ventilation during the first hour approximately.

Only after about 45-70 minutes (depending on the ventilation conditions and the compartment size), the temperatures in the closed fire compartment will be higher than those in the open compartment.

A safe sided approach for the definition of design temperatures will be to consider the temperatures from open compartments in the first phase and the temperatures from enclosed compartments in the second phase.

From these figures, it appears that the heat release is also governed by the size of the fire compartment.

Safe-sided natural fire curves



(Fig.23) Comparison of fire curves

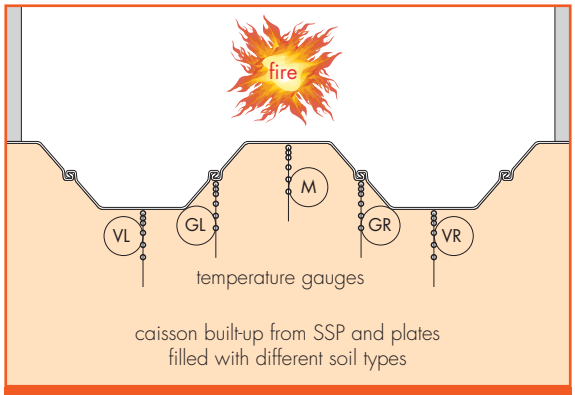
Calculation of gas temperatures for realistic fire loads.

For any verification of steel sheet pile structures in enclosed car parks where natural fire design will be accepted, one of the three design fire curves shown will be applied.

In comparison with the standardised curves, both the fire development and extinction phases can be observed to be considered in a more realistic way, but are still safe sided.

Analysis of thermal properties of soils by fire tests

A series of fire tests has been carried out at the laboratories of the MSM department at the University of Liège, Belgium.



(Fig.24) Schematic test set-up

The aims of these tests were to determine, experimentally, the temperature flow in the steel sheet pile and in the soil and to define the thermal characteristics of the soil for use in FE-simulations.

Test set-up

The tests were carried out using a test furnace, the front side of which was closed by the test specimen.
The test specimen consisted of a caisson built up from PU 6-sheet piles and plates and filled with different soil types with different water contents.
A series of 4 tests was carried out:

Test N°	Soil	Water content
1	Clay	Dry / moist
2	Clay	Saturated
3	Sand	Dry / moist
4	Sand	Saturated

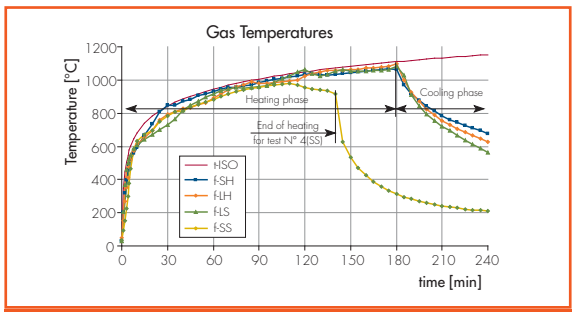
(Fig.25) Test furnace opened after the test

Fire curve

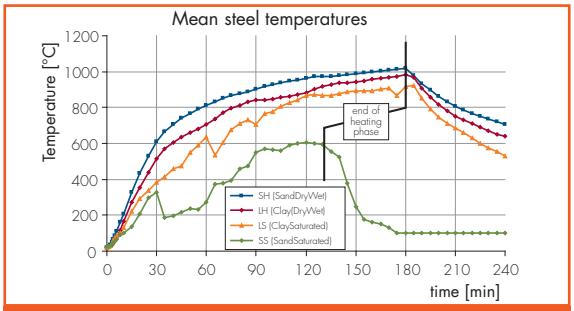
The heating of the oven was controlled in such a way as to simulate a fire curve according to ISO-834 up to a fire duration of 3 hours, except for the tests with saturated sand, where the heating control could not be maintained due to a shortage of gas supply.

Fig. 26 shows the temperatures in the furnace in comparison with the relevant standard curve.

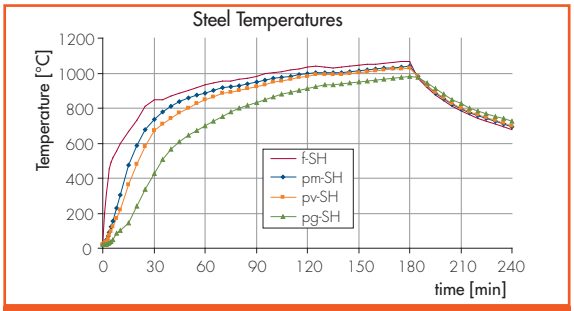
The temperatures were recorded in the heating phase as well as in the cooling phase up to 6 hours (360 min).



(Fig.26) Measured gas temperatures in the furnace



(Fig.27) Comparison of measured steel temperatures for the different tests



(Fig.28) Measured temperatures on steel for test N°3 (Sand Dry/moist)

(Fig.29) Temperature gauges in the soil body

Temperatures measured on steel

A series of 9 temperature gauges was disposed on the steel surface at different locations.

The influence of soil type and water content on the steel temperatures is quite substantial, as shown by fig. 27.

The temperature in the steel may differ by up to 200°C due to the concave/convex shape of the sheet pile and to the different steel thickness. The highest temperatures can be measured at the outer fibre (PM series, cf. fig. 28) and the lowest temperatures at the location of the interlocks (high massivity).

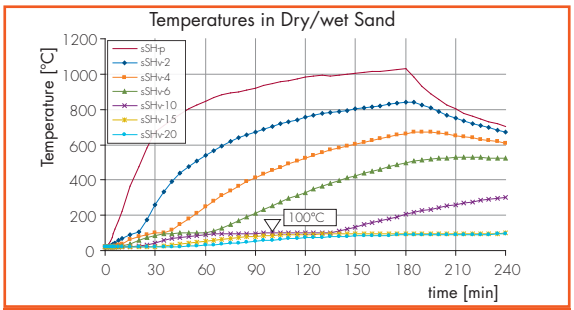
Temperatures measured in the soil

A total of 30 temperature gauges in 5 series of 6 gauges were placed in the soil body to record the temperatures at different distances (2, 4, 6, 10, 15 and 20 cm) from the sheet pile.

The temperature gradient is quite regular for non-saturated soils as shown in fig. 30.

The temperature evolution is governed by the water content of the soil.

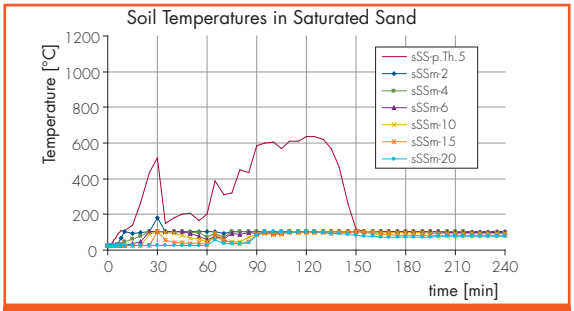
It can be seen from the figure that the heating in the different locations is delayed at 100°C due to the energy input required to evaporate the residual water.



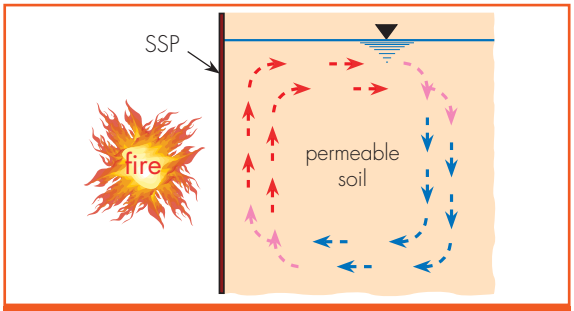
(Fig.30) Temperatures measured in the soil for test N°3 (Sand Dry/moist)

Influence of water in permeable soils

For saturated sand, it can be observed that the heating of the steel is not regular due to the development of a water flow inside the soil body (fig. 32), and that the heating is considerably reduced.



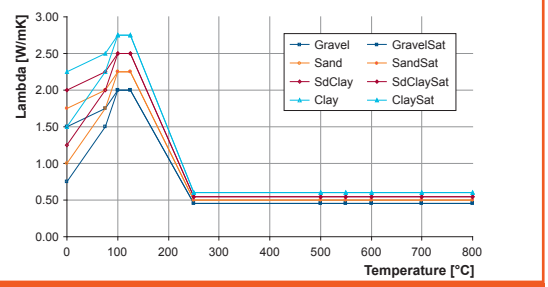
(Fig.31) Temperatures for test N°4 (Sand Saturated)



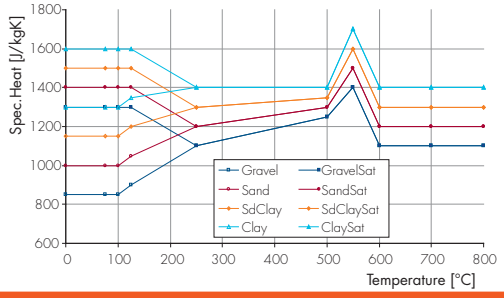
(Fig.32) Induced water flow in permeable soils caused by temperature gradient

Calibration of thermal properties of soils

A series of extensive FE-simulations (back-calculation of tests) allowed for a calibration of the thermal properties (fig. 33 & 34) of some typical soils.



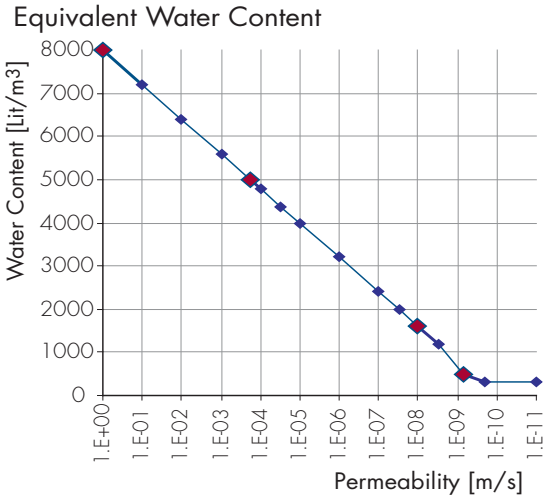
(Fig.33) Thermal conductivity



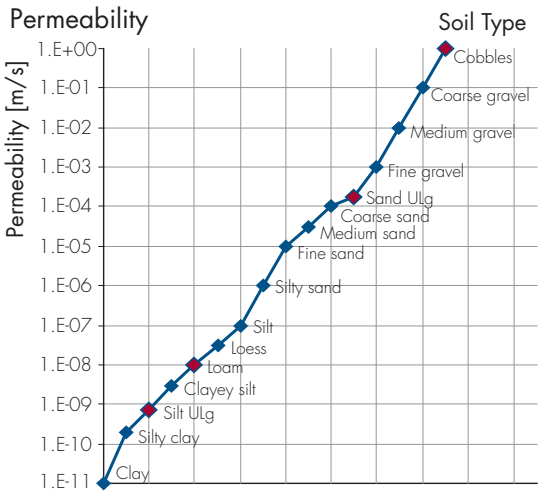
(Fig.34) Specific heats

Effects of the water content

In order to take into account the water flow (fig. 32) the calibration allowed to define equivalent water contents as a function of the permeability of the soils (fig. 35 & 36)



(Fig.35) Equivalent water contents for calculation



(Fig.36) Permeability of soils

Parametric temperature calculations in the sheet piles

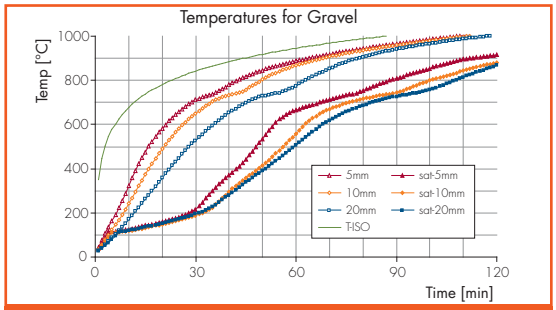
Matrix of parameters

Fig. 37 - Fig. 44 show the mean temperature in the steel for different parameters:

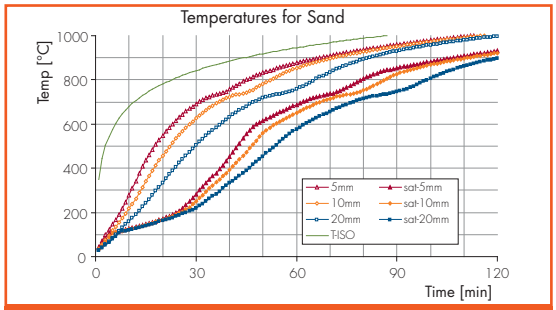
4 types of soils	2 water contents	3 steel plate thicknesses	2 fire curves
Gravel Sand Silt Clay	dry/wet saturated	5 mm 10 mm 20 mm	ISO-834 NatFire

For cohesive soils, the effect of the water content is less important than for sandy soils, due to the lower permeability.

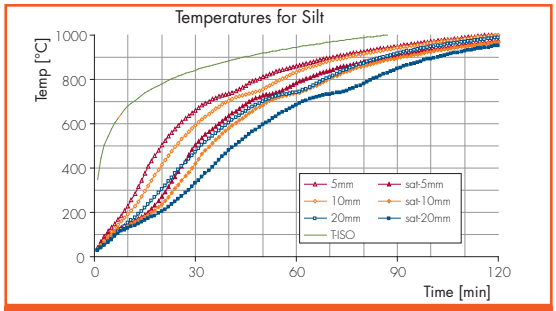
Temperatures in the sheet piles - Fire acc. ISO-834



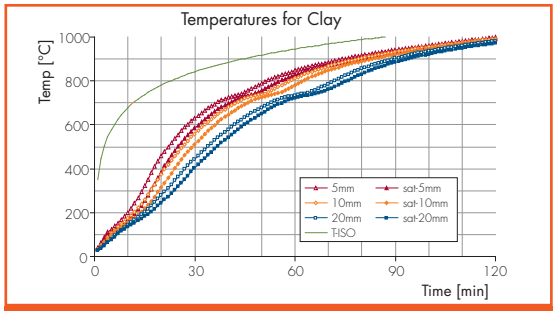
(Fig.37) Steel temperatures for ISO-fire Gravel (wet/saturated)



(Fig.38) Steel temperatures for ISO-fire Sand (wet/saturated)



(Fig.39) Steel temperatures for ISO-fire Silt (wet/saturated)

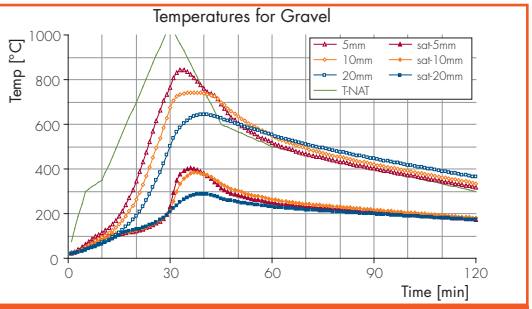


(Fig.40) Steel temperatures for ISO-fire Clay (wet/saturated)

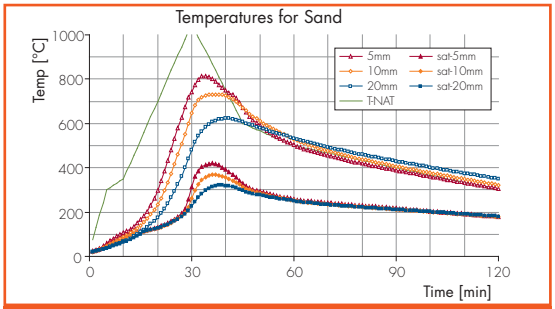
Temperatures in the sheet piles - Natural Fire

The following figures have been derived from the design fire curve as defined for a medium-sized fire compartment (cf. fig. 23).

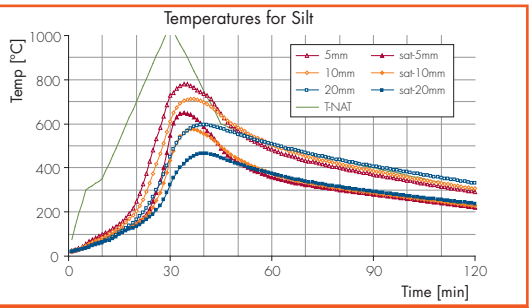
As the maximum temperatures will be obtained after 30-45 minutes, the slight differences for the fire curves in the extinction phase have no impact on the fire resistance of the structure.



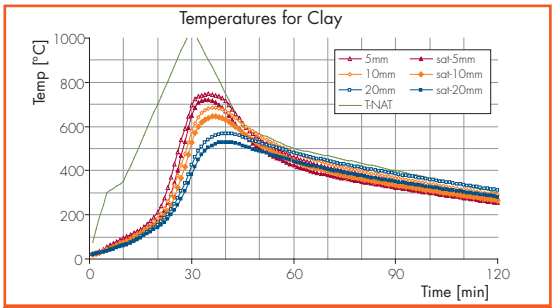
(Fig.41) Steel temperatures for NAT-fire Gravel (wet/saturated)



(Fig.42) Steel temperatures for NAT-fire Sand (wet/saturated)



(Fig.43) Steel temperatures for NAT-fire Silt (wet/saturated)



(Fig.44) Steel temperatures for NAT-fire Clay (wet/saturated)

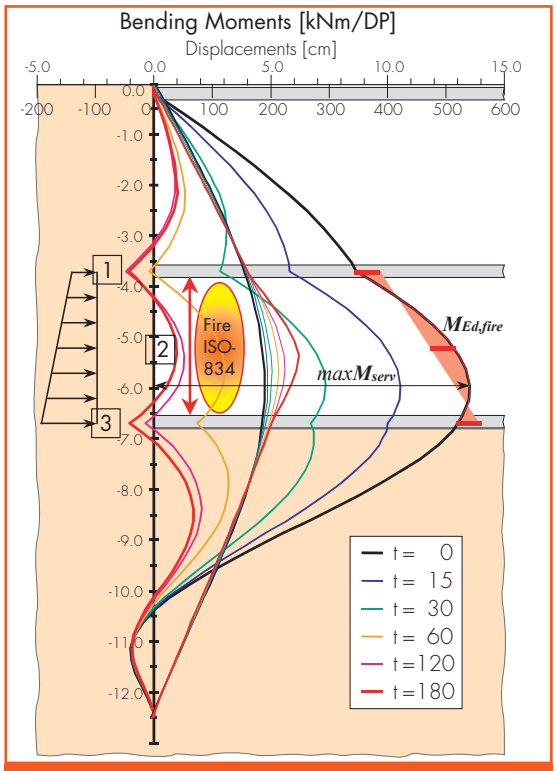
For a simplified verification of the fire safety of a steel sheet pile structure, the maximum steel temperature may be interpolated

from Fig. 37 - Fig. 40 for a fire curve according to ISO-834, or
from Fig. 41 - Fig. 44 for a natural fire curve.

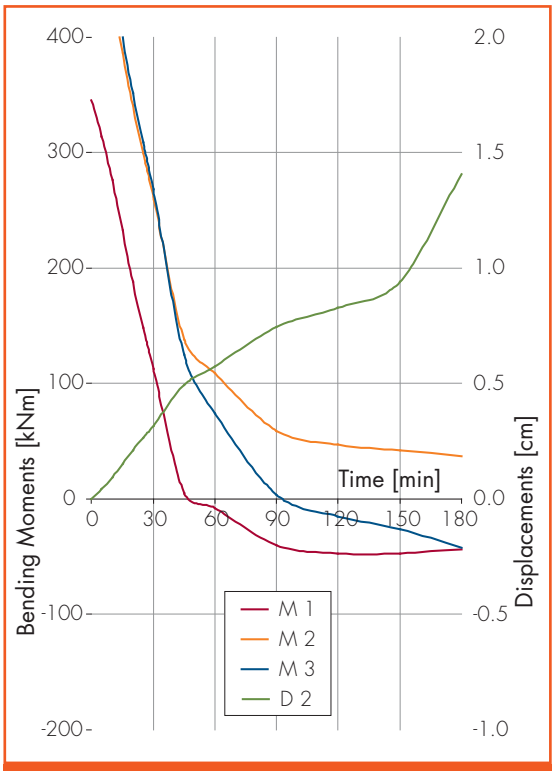
Moment redistribution in a steel sheet pile structure

Generally, the design of a steel sheet pile section is governed by the maximum bending moment at the service stage or possibly during an intermediary construction stage.

For a sheet piling structure, the bending moment shape is generally not characterised by (negative) hogging moments at the fixed supports.



(Fig.45) Moment redistribution in a SSP wall



(Fig.46) Moment redistribution in a SSP wall

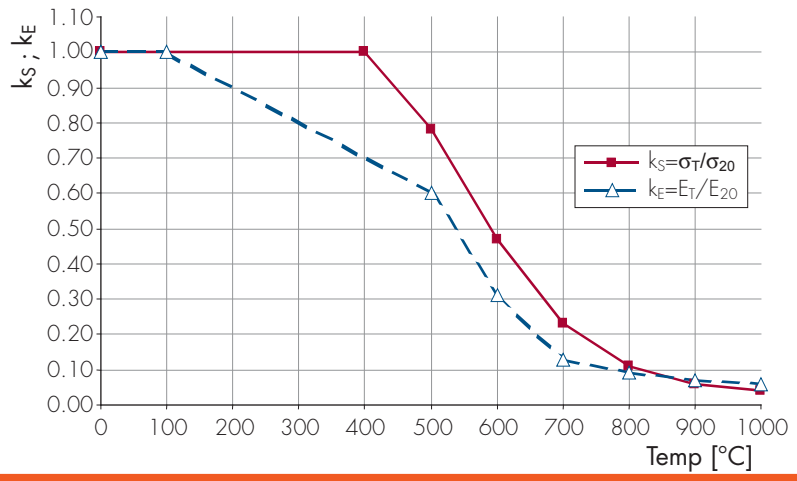
Hence, for such hyperstatic structures, local plastification with a resulting redistribution of moments could allow an increase in the maximum loading or a decrease in the cross sectional resistance.

There is an advantage associated with this ability, because during a fire event, as a consequence of increasing temperatures, the cross sectional resistance will decrease without necessarily losing overall stability.

The ultimate state will be reached if both the hogging and sagging moment $M_{Ed,fire}$ equal the moment resistance $M_{Rd,hot}$. Moment $M_{Ed,fire}$ depends on the earth and water pressures involved.

Thermo-mechanical properties of structural steel

The mechanical properties of steel will decrease with increasing temperature according to the following figure.



(Fig.47) Thermo-mechanical steel characteristics

This leads to a loss of cross-sectional resistance at elevated temperatures:

$$M_{Rd,Hot} = W_{pl} \times f_y \times k_s$$

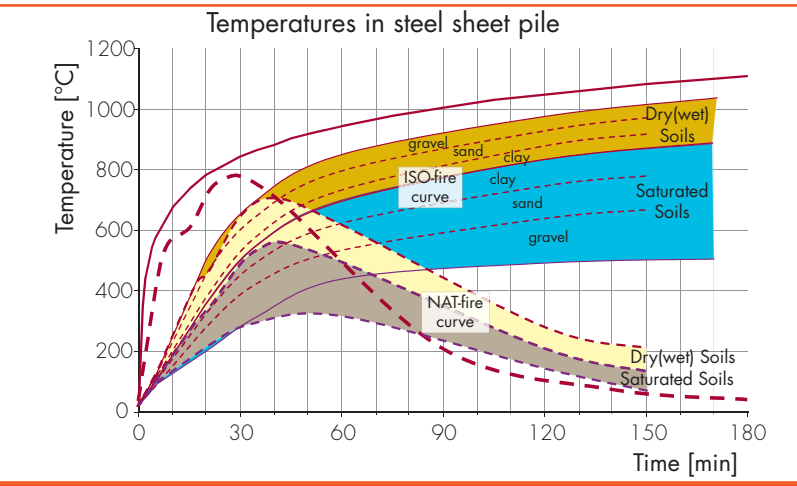
Soils characteristics and fire curve

The thermal properties of the materials and the partial heat absorption by soil leads to a reduction and delay in the heating-up of steel sheet pile.

The influence of soil type and water content (especially for saturated soils) is considerable.

However, it shall be noted that for any type of natural fire, temperatures will be lower than those for the ISO curve.

Note: this figure is only a rough estimation; see Fig. 37 - Fig. 44 for greater accuracy.



(Fig.48) Temperatures in steel sheet piles

Computing structural behaviour during a fire event

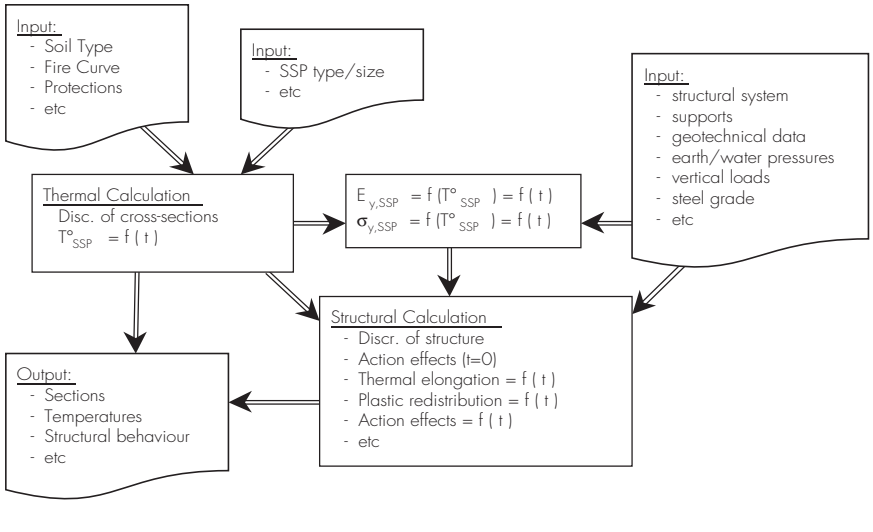
ArcelorMittal's engineers can provide assistance in verifying the fire resistance of your steel sheet pile structure, taking into consideration:

- your basic solution and retaining wall calculations
- additional loads, especially vertical loads from intermediate floors and superstructure
- different fire scenarios, i.e., standard fire curves (ISO, HydroCarbon, ...) or a natural fire curve
- possible protection measures

This will allow them to propose safe and economical steel solutions.

Detailed calculation with SARI

Calculation approach



(Fig.49) Calculation approach

Required input

In order to allow our technical staff to verify the fire resistance by calculation, the following project information is required:

SSP:	section type and steel grade length
Structure:	all relevant levels: head and toe level of SSP floor levels, temporary anchors / strut levels (if applicable) vertical loads from floors, superstructure, …
Soil:	levels of soil layers, water, … characteristic geotechnical data: soil type, friction angle, cohesion, permeability, …

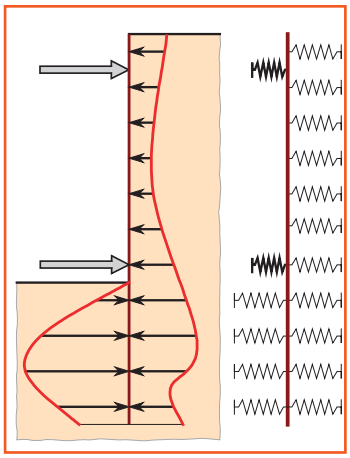
(Table 3:) Verification of the fire safety of a SSP structure

Retaining wall calculation

Subgrade Reaction Model

Interaction of:

- Structural Steel
- Geotechnics



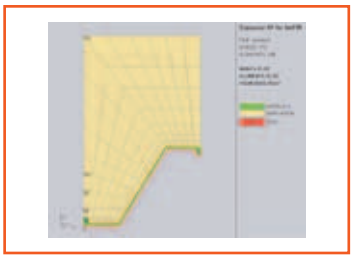
Specific data

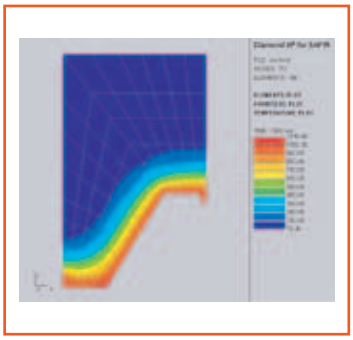
Input of missing data:

- Steel grade
- Protections
- Thermal soil characteristics
- Vertical loads
- Fire scenario

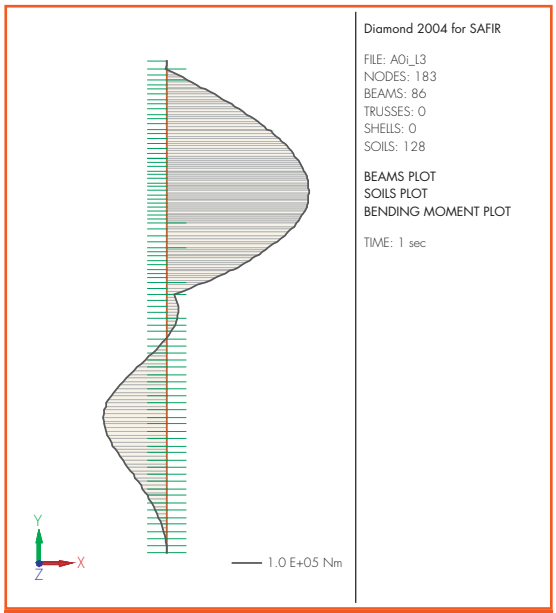
SAFIR Calculation

Discretisation	Structure: beam elements Cross section: finite elements (U and Z-sections)
Thermal calculation	FE-model For each different section = f(SSP, protection, soil, water,…)
Structural calculation	Beam model. Consideration of: • Subgrade reaction pressures • Vertical loads • Thermo-mechanical laws for SSP
Results	• Sections • Structure • Temperatures • Structural behaviour during fire event

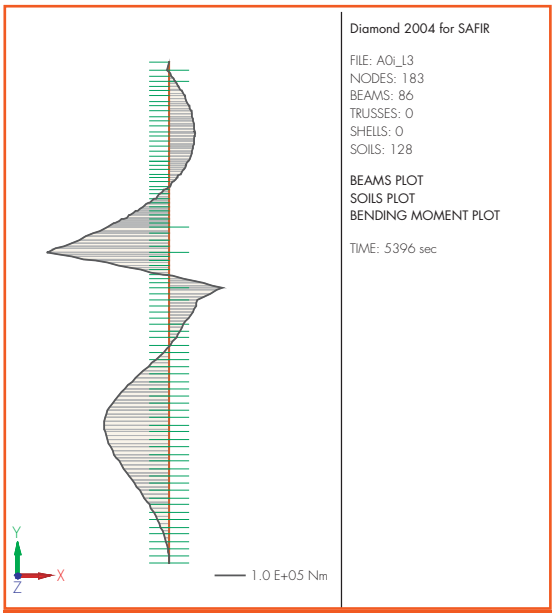




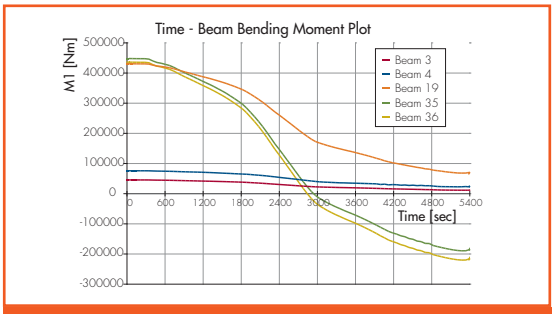
Results from an example computed with SARI



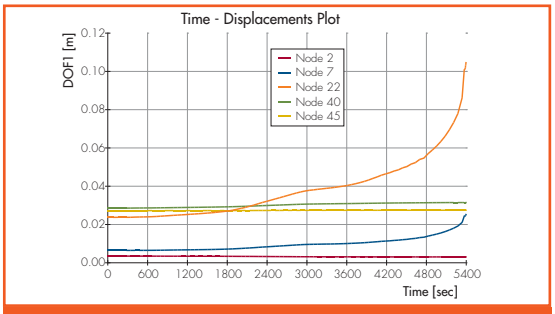
(Fig.50) Bending moments at service stage



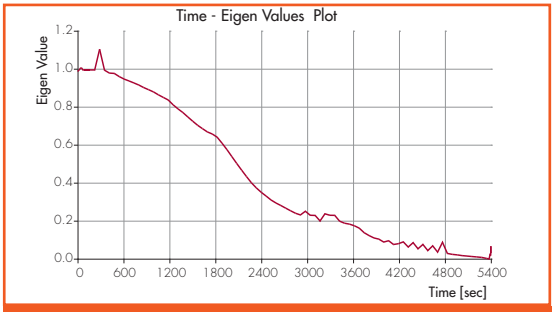
(Fig.51) Bending moments after redistribution



(Fig.52) Evolution of bending moments during fire event

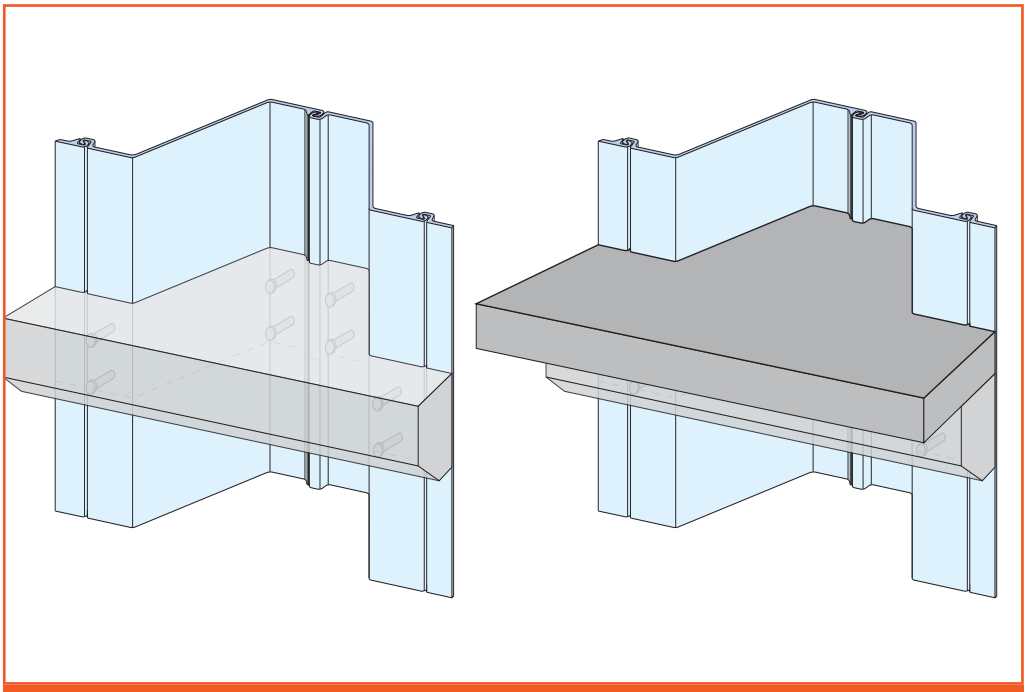


(Fig.53) Evolution of displacements during fire event

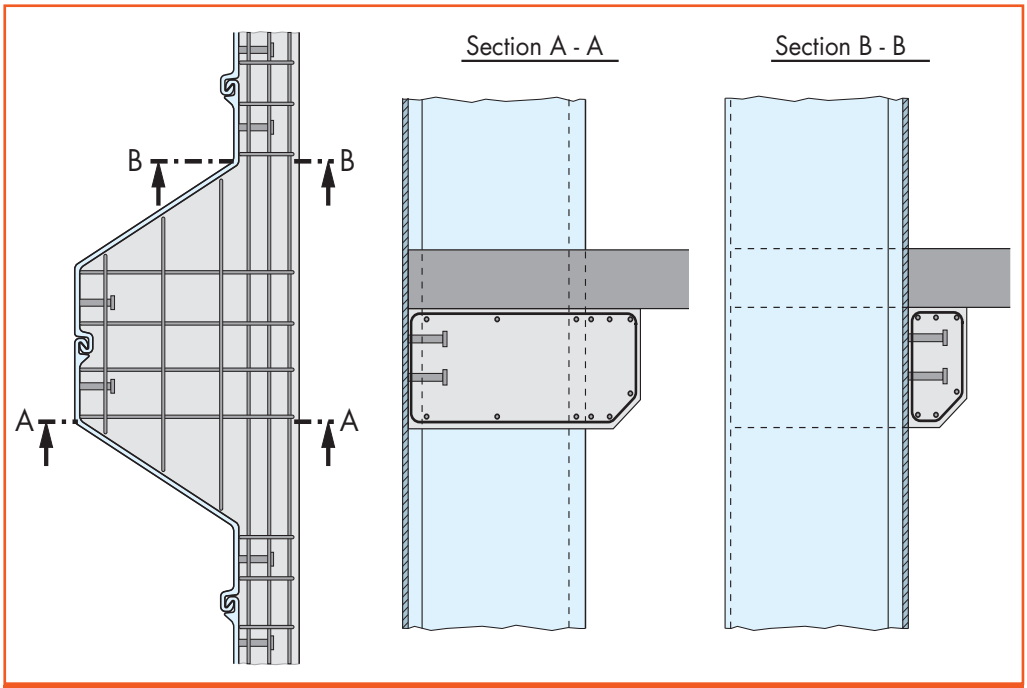


(Fig.54) Rigidity of system

Possible connection detail of intermediate floors



(Fig.55) Schematic view of floor connection



(Fig.56) Connection details: concepts

Improvement of the fire resistance

Protection measures to improve the fire resistance in case of high axial loading include:

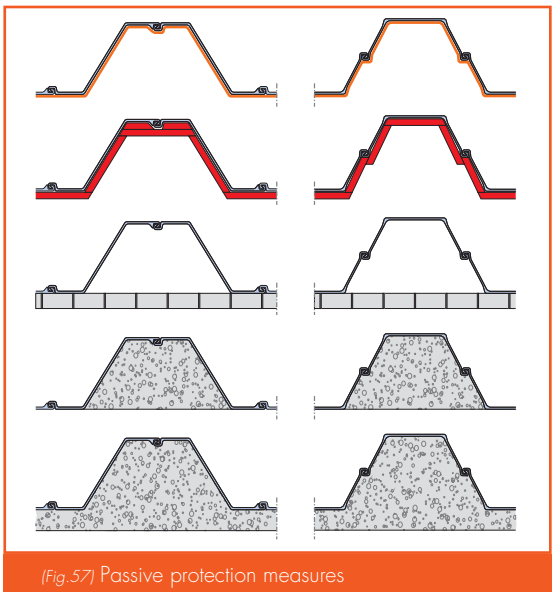
a) protective coating (intumescent paintings or sprays)
b) insulating panels
c) masonry
d) concrete fill of the SSP inner pans
e) complete concreting

The fire verification calculations with the software SARI can take these protective measures into account.

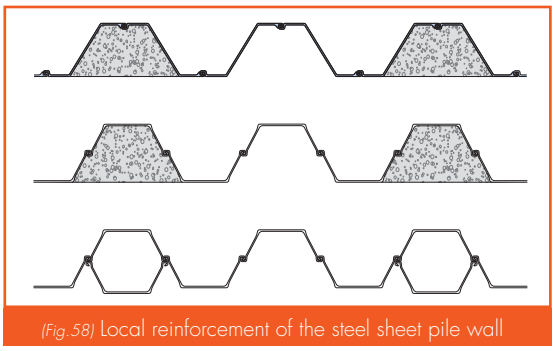
Alternatively, the sheet pile wall could be protected locally only, in that any x-th pile is being reinforced by concrete fill or as a box pile.

In case of a fire event, the non-protected piles will be considered only with respect to bending from horizontal pressures.

However, these reinforced piles will have to resist both the bending and the total vertical loads.

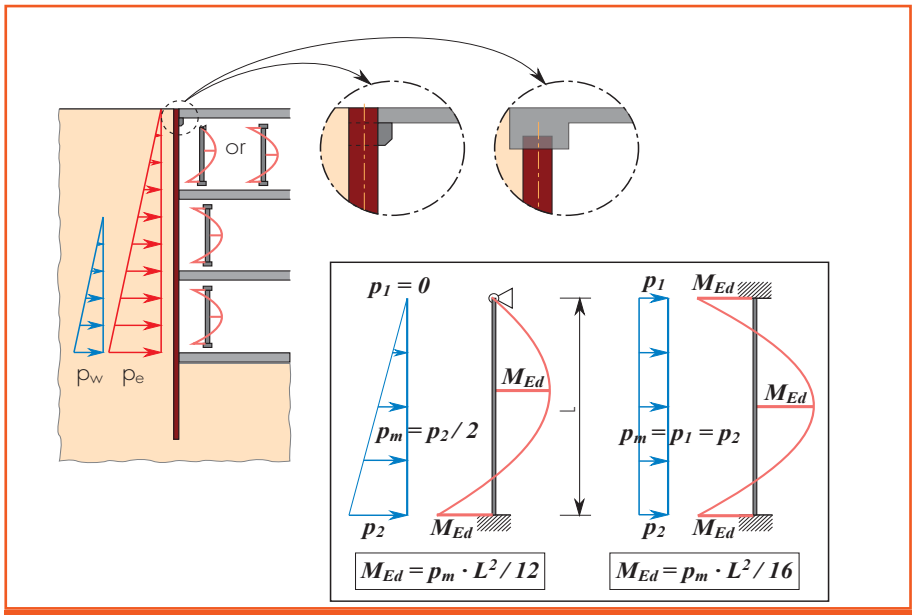


(Fig.57) Passive protection measures



(Fig.58) Local reinforcement of the steel sheet pile wall

Simplified verification procedure



(Fig.59) Equivalent system for simplified verification

Step 1

Determine:

- the relevant earth and water pressures (this earth and water pressures may be the result of a previous cold analysis using a limit earth pressure method, a subgrade reaction model or a finite element method) for the considered floor level:

$$P_1 = P_{w1} + P_{e1} \quad \text{and} \quad P_2 = P_{w2} + P_{e2}$$

- the mean pressure: $P_m = \dfrac{P_1 + P_2}{2}$

- the factor β: $\beta = \dfrac{P_1}{P_2}$

Step 2

Determine the bending moments acting at ultimate limit state: $M_{Ed} = \dfrac{P_m \cdot L^2}{k}$

where:	$k = \dfrac{12}{1+0.03 \cdot \beta}$	$k = \dfrac{16}{1+0.025 \cdot (1-\beta)^2}$
for:	Free rotation at top level	Fixed support at top level

Step 3

Determine the axial load ratio: $n = \frac{N_{Ed}}{N_{pl}}$ and the relative slenderness: $\overline{\lambda} = \sqrt{\frac{N_{pl}}{N_{cr}}}$

where: N_{Ed} = acting axial load

$N_{pl} = A \cdot f_y$ — A = cross sectional area of sheet pile; f_y = yield stress

$N_{cr} = \frac{EI \cdot \pi^2}{L_b^2}$ — EI = rigidity of sheet pile; L_b = buckling length

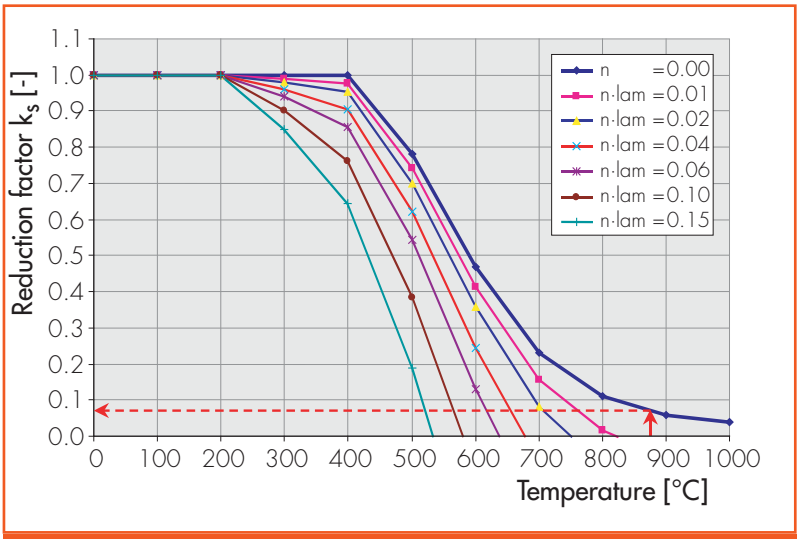
Step 4

Determine the maximum temperature in the sheet pile section from one of the figures (see Fig. 37 - Fig. 44). The figures show the steel temperatures for different soils and water contents.

Step 5

With $n \cdot \overline{\lambda}$, determine the strength reduction factor k_s as a function of the temperature.

Note: The proposed verification method is applicable for continuous Z- and U-sections.



(Fig.60) Reduction factor for elevated temperatures

Step 6

Verification of the design moment resistance.

The design moment resistance in the hot SSP-section can be defined as:

$M_{Rd,Hot} = W_{Pl} \cdot \sigma_{red}$

with: $\sigma_{red} = f_y \cdot k_s$ => $M_{Rd,Hot} = W_{Pl} \cdot f_y \cdot k_s$

And it shall be verified: $M_{Ed,0} \leq M_{Rd,Hot}$

Example 1: ISO-834 Fire, R90

Given the following data:

Section: **AZ 26** in **S 355 GP**
A = 198 cm²/m
I_y = 55510 cm⁴/m
W_{pl} = 3059 cm³/m
Soil: Saturated Silt, below the water table
Location: second underground floor with L = 3.20 m => L_b = 1.60 m
Axial load: N_{ed} = 350 kN/m

Earth and water pressures:

$p_1 = p_{w1} + p_{e1} = 25kN/m^2$ $\quad p_2 = p_{w2} + p_{e2} = 50kN/m^2$

Step 1

$$p_m = \frac{p_1 + p_2}{2} = 37.5 kN/m^2 \qquad \beta = \frac{p_1}{p_2} = 0.50$$

Step 2

$$k = \frac{16}{1 + 0.025 \cdot (1 - \beta)^2} = 15.9 \qquad M_{Ed} = \frac{p_m \cdot L^2}{k} = 24.15 kNm/m$$

Step 3

$$N_{pl} = A \cdot f_y = 7029 kN/m \qquad N_{cr} = \frac{EI \cdot \pi^2}{L_b^2} = 449418 kN/m$$

$$\overline{\lambda} = \sqrt{\frac{N_{pl}}{N_{cr}}} = 0.125 \quad => \quad n = \frac{N_{Ed}}{N_{pl}} = 0.05 \qquad n \cdot \overline{\lambda} = 0.006$$

Step 4

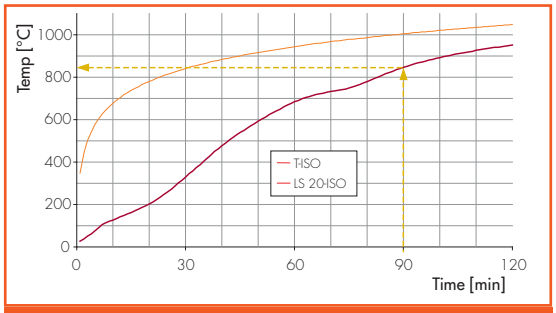
For a required Fire resistance F90 acc. ISO-834
=> maxT ≈ 850 °C

Step 5:

Reduction factor: $k_s \approx 0.04$

Step 6:

Verification:
$M_{Rd,Hot} = W_{Pl} \times f_y \times k_s = 43$ kNm/m
$> M_{Ed} = 24$ kNm/m



(Fig.61) Temperature - time curve, ISO-834 fire

Example 2: Natural Fire

Given a section **AZ 13** in **S 355 GP** with
A = 137 cm²/m
I_y = 19700 cm⁴/m
W_{pl} = 1528 cm³/m
with the same horizontal and axial loading.

Step 3

$$N_{pl} = A \cdot f_y = 4863 kN/m \qquad N_{cr} = \frac{EI \cdot \pi^2}{L_b^2} = 159494 kN/m$$

$$\overline{\lambda} = \sqrt{\frac{N_{pl}}{N_{cr}}} = 0.175 \quad => \quad n = \frac{N_{Ed}}{N_{pl}} = 0.07 \qquad n \cdot \overline{\lambda} = 0.013$$

Step 4

For a Natural fire => max T ≈ 575°C

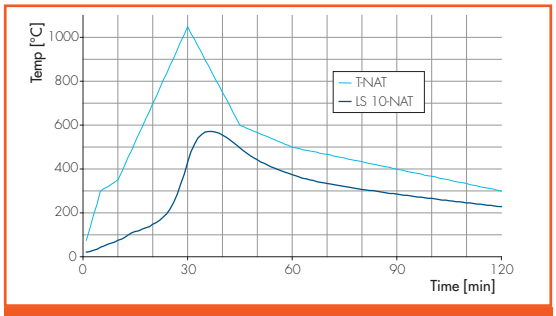
Step 5

Reduction factor: $k_s \approx 0.50$

Step 6

Verification:

$M_{Rd,Hot} = W_{Pl} \times f_y \times k_s = 270$ kNm/m
$>> M_{Ed} = 24$ kNm/m



(Fig.62) Temperature - time curve, Natural fire

ArcelorMittal Commercial RPS S.à r.l.
Sheet Piling

66, rue de Luxembourg
L-4221 Esch-sur-Alzette
Luxembourg

T +352 5313 3105
F +352 5313 3290
E sheetpiling@arcelormittal.com
www.arcelormittal.com/sheetpiling

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