SECURE WITH STEEL

FDS – SAFIR Interface

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OVERVIEW

3 problems have to be solved. Each of them is governed by different equations.

1. Fire development => Temperatures and flows in the compartment. It requires a 3D model.
2. Thermal response => Temperatures in the structural elements. A 2D model is generally sufficient.
   - Elements across the compartment.
   - Elements on the boundaries of the compartment.
3. Mechanical response => Behaviour of the structural elements.

LEVEL OF COUPLING

IN REALITY EVERYTHING IS COUPLED

2. Temperatures in elements

1. Compartment

3. Structural behaviour

LEVEL OF COUPLING

FIRE

- Convection and radiation to structural elements (1 to 2).

VELOCITY OF GASES

- Coefficients of convection (1 to 2).
- Dynamic pressure on walls, windows (1 to 3).

PRESSURE

- Static pressure on walls, windows (1 to 3).

LEVEL OF COUPLING

TEMPERATURE IN MATERIALS

- Thermal elongation of elements (2 to 3).
- Degradation of mechanical properties (2 to 3).
- Absorption of energy from the compartment (2 to 1).

PLASTICITY AND CRACKING IN ELEMENTS

- Generation of heat or heat leakage (3 to 2).
- Modification of thermal properties: k and c_p (3 to 2).

DISPLACEMENTS IN ELEMENTS

- Modification the flow of gases (3 to 1).
- Modification of the element thermal exposure (3 to 2).

Option 1: FULL COUPLING

ADVANTAGES

- All phenomena are taken into account.
- Exact results.
- General field of application.

ISSUES

1. A CFD software A must communicate with an FE software X.
    - Modifications have to be made in both codes.
    - Issues about different time steps must be addressed.
    - Will not work with a CFD software B or an FE software Y.

FULL COUPLING

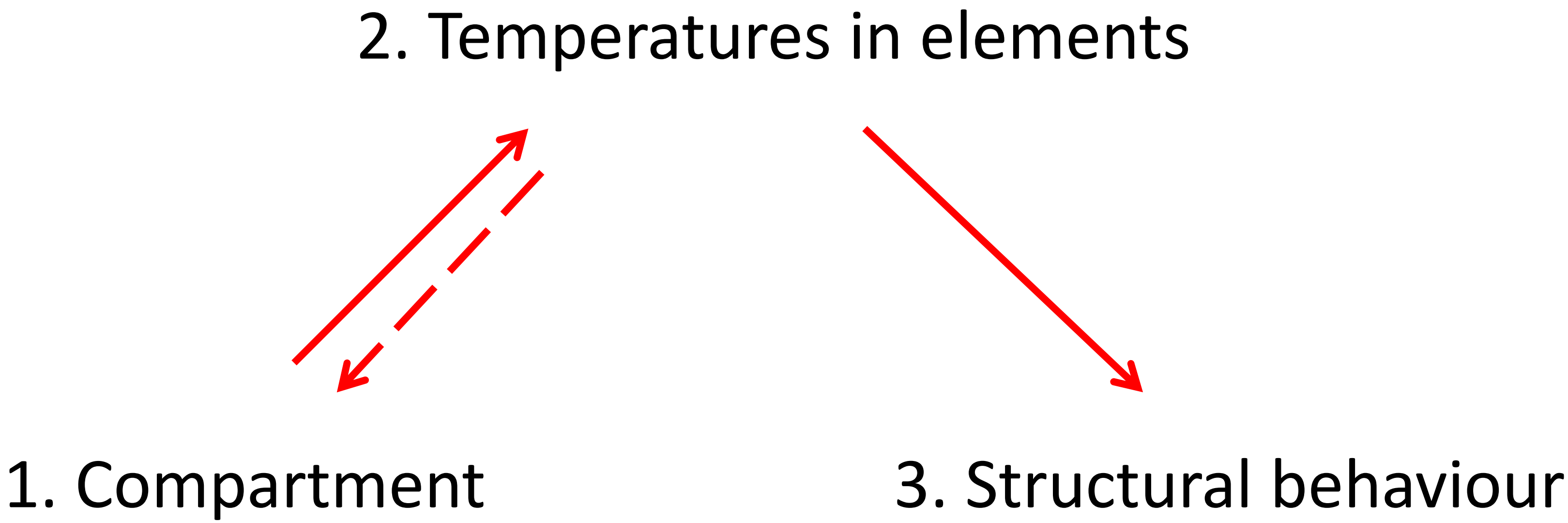
ISSUES

2. Each run requires a specialist in CFD and a specialist in FE (or someone who is specialist in both).

3. Capacity demand of the hardware and CPU time increases, especially during the debugging of the model.

4. If the structure must be changed (either because it does not satisfy the fire resistance requirement, or because the architect changes the project), everything has to be recalculated.

Option 2: WEAK COUPLING STRATEGY

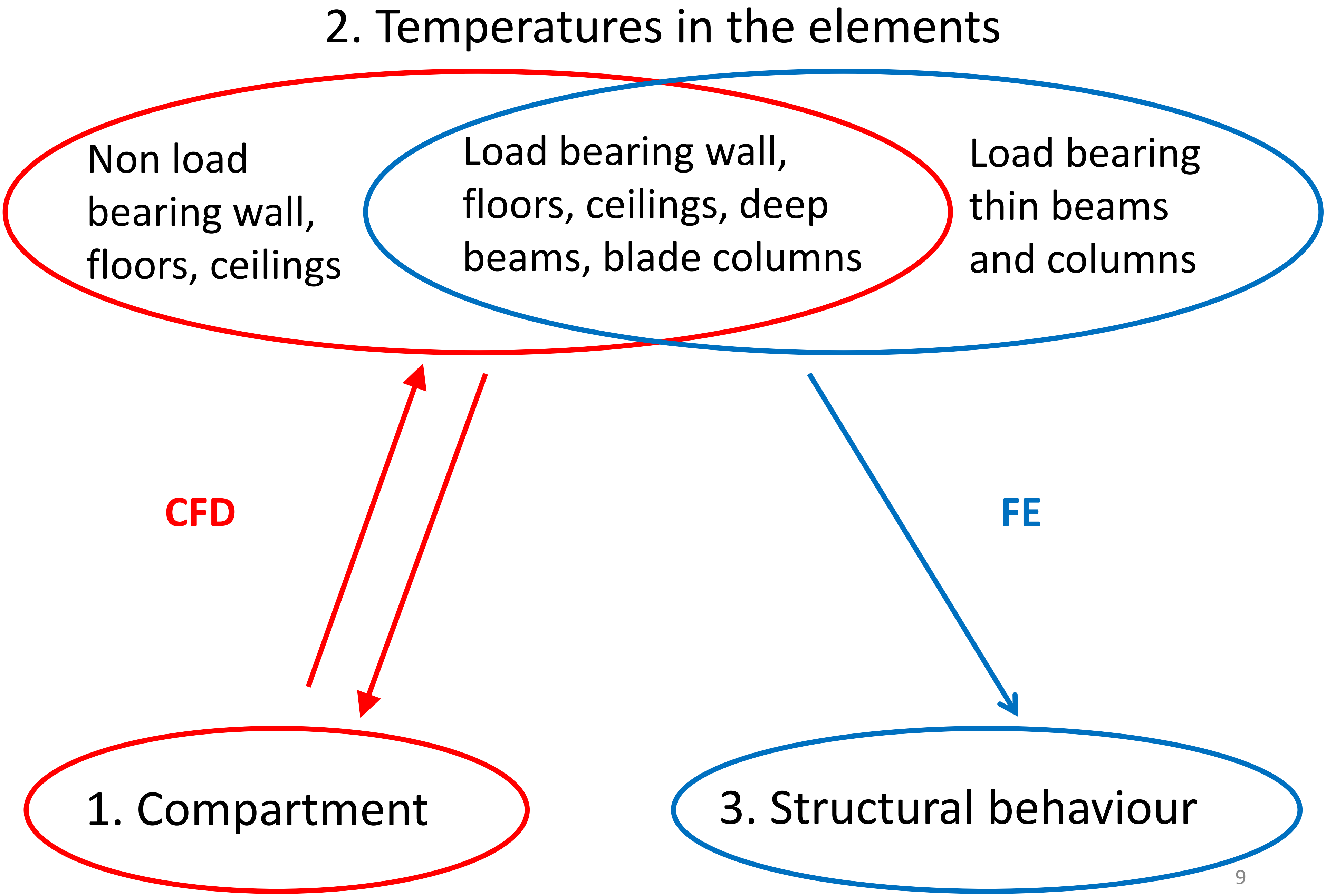


NOTE: Interaction 2 to 1

- It is complete if step 2 is performed by the CFD
- It is limited to the boundaries of the compartment(*) if step 2 is performed by the FE.

(*) plus eventual internal elements if they influence the mass and/or the heat flow,

WEAK COUPLING STRATEGY



WEAK COUPLING STRATEGY

ESSENTIAL FEATURES

1) The thin structural elements are not present in the CFD analysis, except for the boundaries of the compartment, possibly in an approximated manner.

2) The heat exchange to the boundaries of the compartment are considered in the CFD analysis.

3) The temperatures in load bearing elements are calculated by the FE software.

WEAK COUPLING STRATEGY

FDS

- Simulation of the fire development in the compartment

TRANSFER FILE

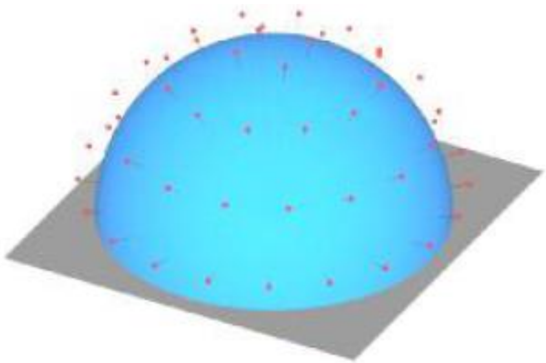
INFORMATION:

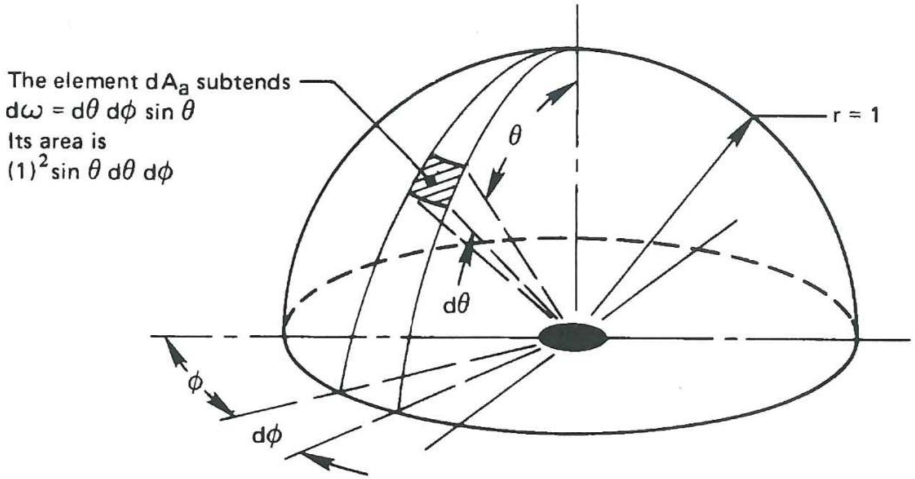
- Temperatures
- Convection factors
- Radiant intensities

SAFIR

- Thermal response
- Mechanical response

TRANSFERRED INFORMATION: Radiant intensities I





The flux received by surface will be computed by SAFIR on the base of the radiant intensities

$$dq = I d\omega \cos\vartheta \text{ where } d\omega = \sin\vartheta d\vartheta d\varphi$$

$$q = \int_0^{2\pi} \int_0^{\pi/2} I \sin\vartheta \cos\vartheta d\vartheta d\varphi$$

TRANSFERED INFORMATION: Radiant intensities

Radiant intensities from different directions are preferred to impinging radiant fluxes (or adiabatic surface temperatures) on predefined surfaces (with their direction) because the structural elements are not included in the CFD model and thus no information is available at that stage about the shape of the cross-sections.

Computing the fluxes at the surface of the structural elements within the FE software, at a stage when the shape of the section is known, allows taking into account possible shadow effects in concave sections.

WEAK COUPLING STRATEGY

ADVANTAGES

• The CFD calculation can be performed before and separately of the FE analysis.

• This strategy can be used with different combinations of CFD and FE software (only the format of the transfer file must be respected).

• Less demanding in terms of CPU and hardware.

• If *p* structures must be evaluated under *q* fire scenarios, only *q* CFD analyses must be performed, compared to *p·q* coupled analyses in a two-way coupling approach.

• By transferring radiant intensities rather than fluxes, shadow effects in concave sections can be considered,

WEAK COUPLING STRATEGY

LIMITATIONS

1.

The dimensions of the structural elements perpendicular to their longitudinal axis and

the displacements of the structural elements perpendicular to their longitudinal axis

must be small compared to the dimensions of the compartment

in order not to significantly influence the temperatures and the air flow around the elements.

WEAK COUPLING STRATEGY

Consequences:

i) a series of 2D thermal analyses for different sections along the structural elements rather than a unique 3D thermal analysis can be made.

ii) a 1x1 m^2 concrete columns in a 100 m^2 compartment must clearly be considered in the CFD model because it influences the mass and energy transfer in the compartment.

iii) This would also be the case for 1-meter deep concrete beams in a car park with a distance from the floor to the beams that is on the order of magnitude of 2 meters.

Q: How to represent a deep beam in a CFD model if the transfer file has to be written and used by SAFIR ?

A: By a thin vertical membrane.

Why ? Discussion.

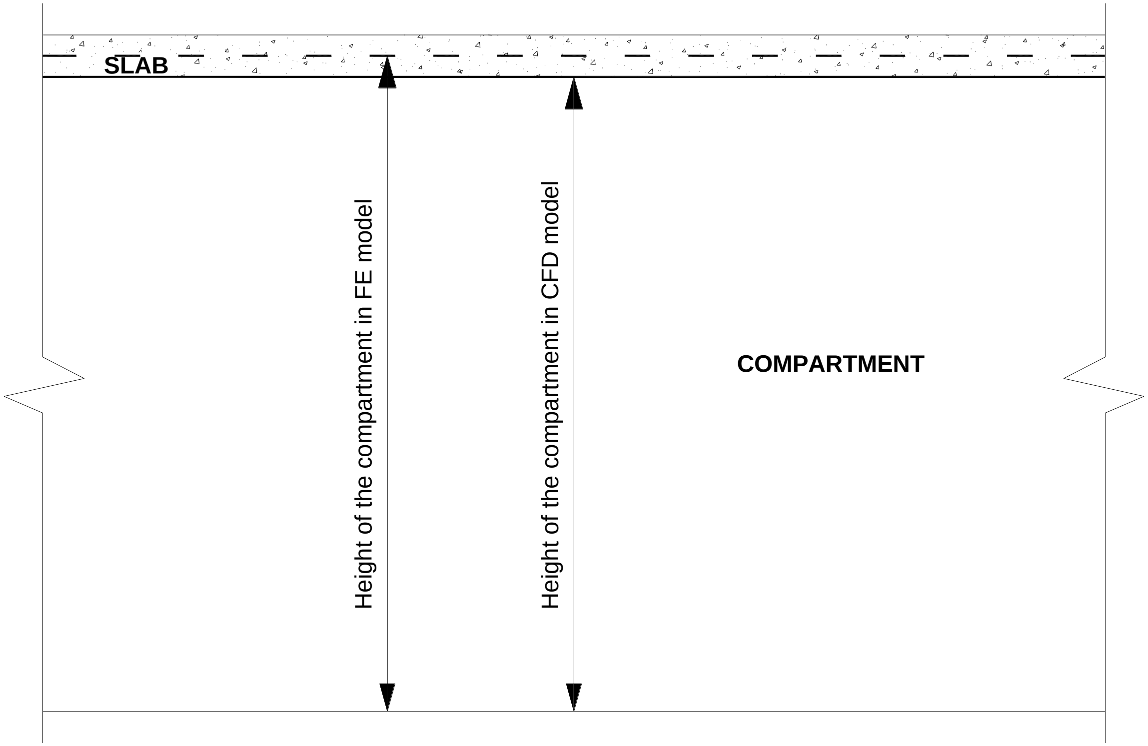
WEAK COUPLING STRATEGY

iv) Influence of air pressure variation on the structure must be limited (not OK for very flexible structures, e.g. membrane structures).

v) Floor systems designed according to the tensile membrane action exhibit very large displacements during the fire. These can influence the fire development and the fire exposure to the ceiling, especially if the floor to ceiling distance is small.

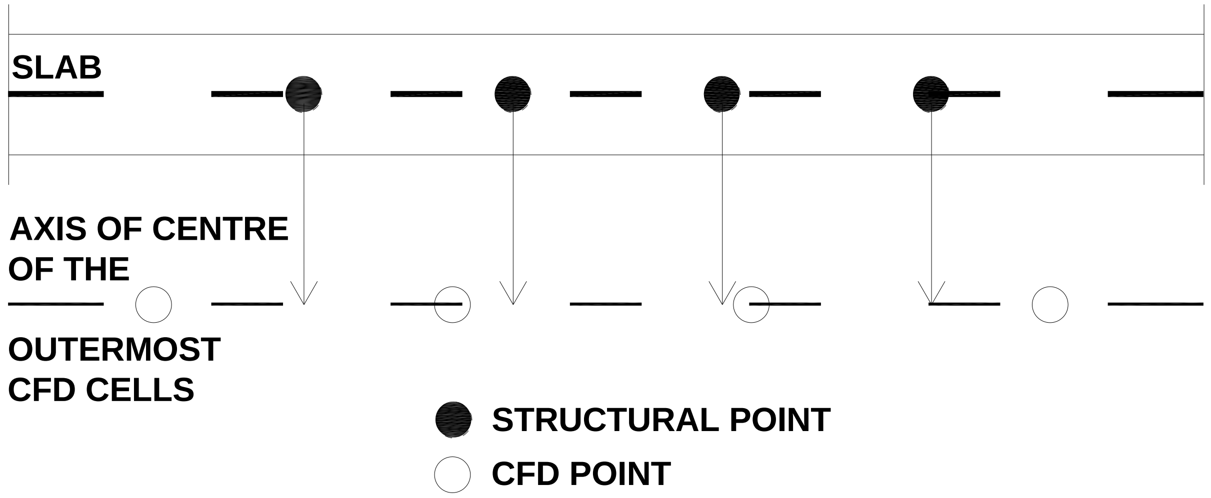
LIMITATIONS

2. Generally, in the CFD model the dimensions of a parallelipedic compartment correspond to the clear distances between opposite walls. However, in the FE model a slab is generally modelled in correspondence to its centreline.

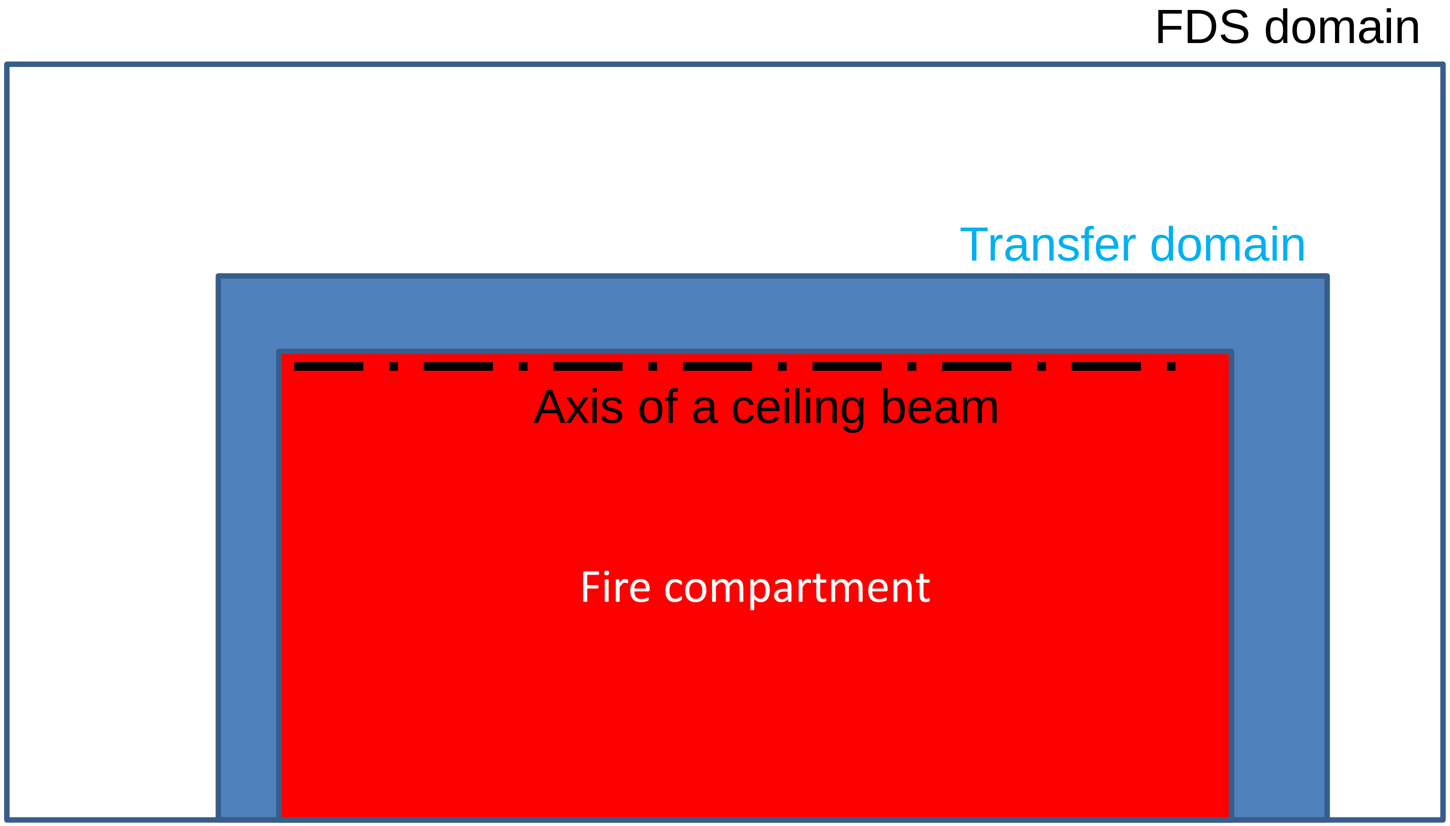


WEAK COUPLING STRATEGY

In this methodology, any structural points located outside the CFD domain for the reason described above is moved to the closest position in the CFD.

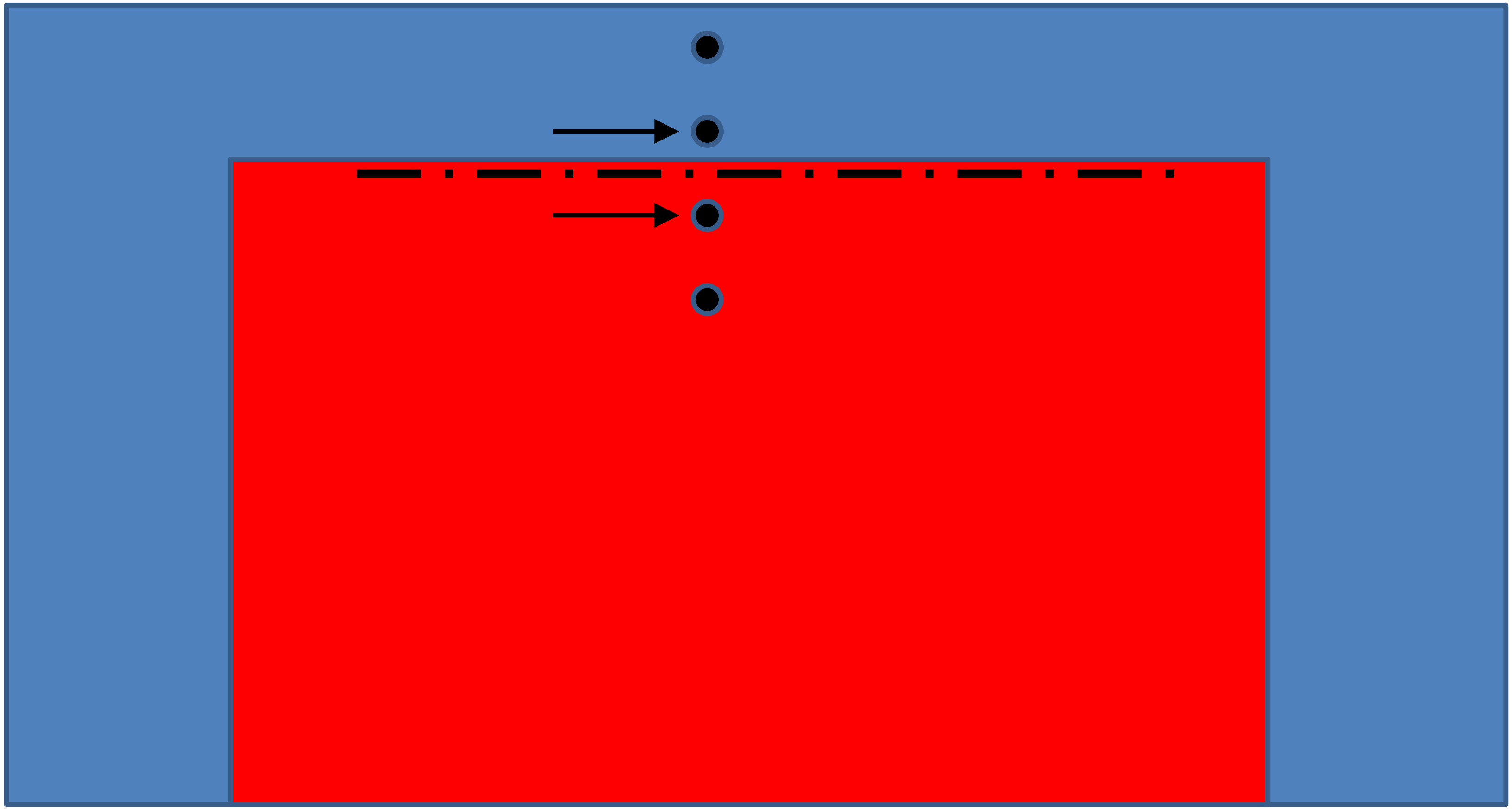


Here is the description of a possible error if the FDS domain extends outside the fire compartment.



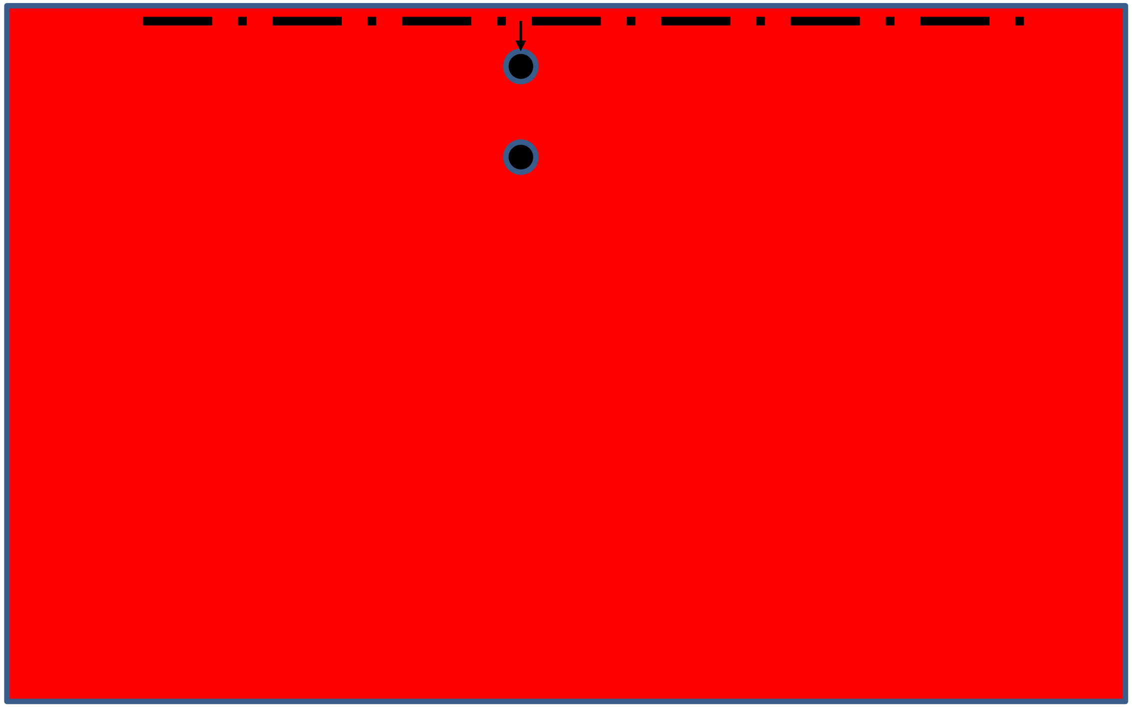
WEAK COUPLING STRATEGY

If the transfer domain extends outside the fire compartment, interpolation in the vertical direction can occur between meaningless points.



WEAK COUPLING STRATEGY

It is preferable to limit the transfer domain to the inside surface of the fire compartment and allow eventual projections of the PoI of the beam to the nearest points in the transfer domain..



WEAK COUPLING STRATEGY

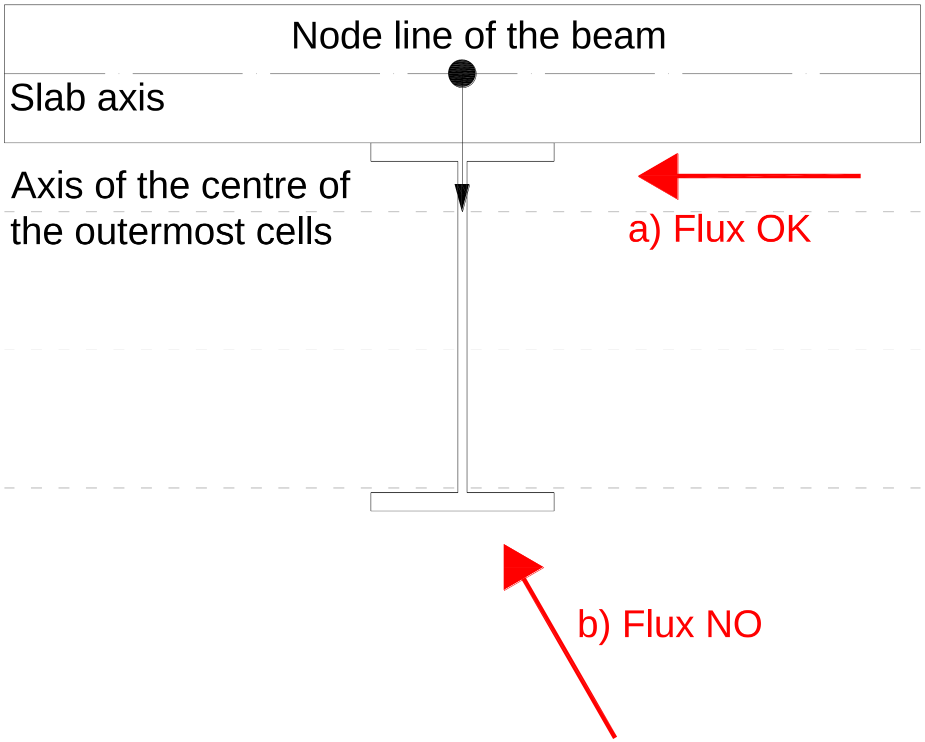
LIMITATIONS

3. Because the size of the structural elements perpendicular to their longitudinal axis is small, the flux at all boundaries of a section are computed as if this boundary would be positioned in space on the node line of the beam finite element.

WEAK COUPLING STRATEGY

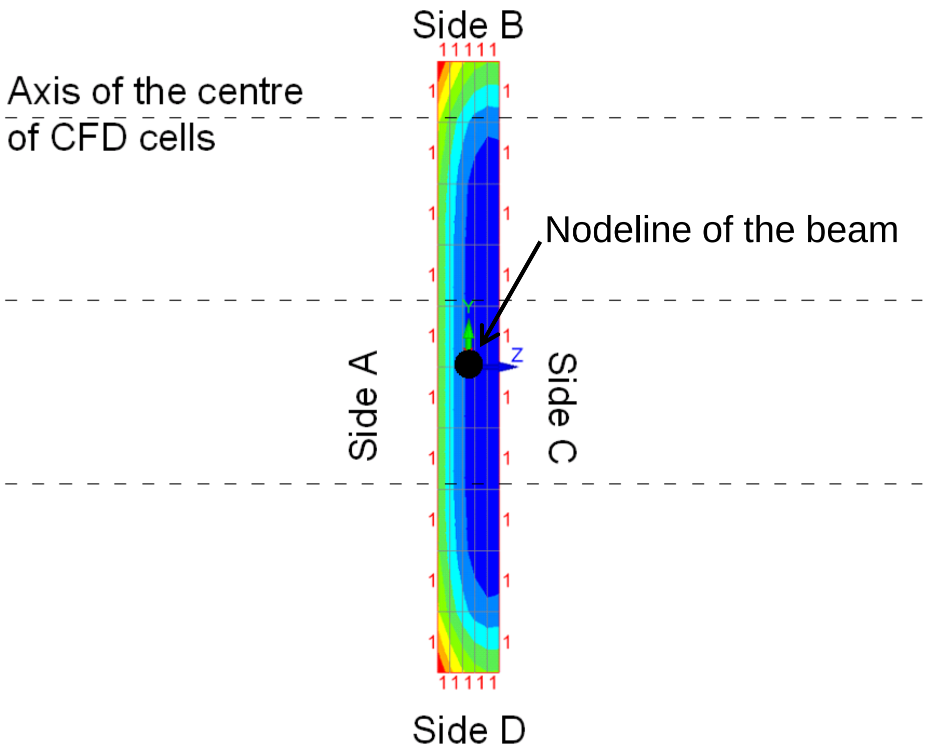
This implies:

i) if the node line of a composite beam element is at mid level of the slab, the flux will be evaluated for all boundaries at the nearest grid point of the CFD domain



If the flux is a jet stream parallel to the ceiling, this assumption is on the safe side. Conversely, if the flux has predominant direction from bottom to top this assumption may not be safe anymore.

ii) All faces of the elements constituting the contour of a beam section having the same orientation (excluding any shadow effects) receive the same flux

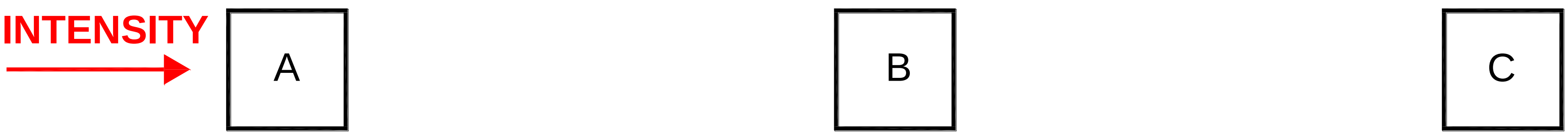


Hence, all boundaries of Side A receive the same flux. The same occurs on the other 3 sides.

LIMITATIONS

4. Since the structure is not included in the CFD model, the effect of shielding from any structural elements on others cannot be detected.

NO SHIELDING EFFECT ON COLUMN B AND C DUE TO COLUMN A



NOTE

For the same reason, a H section made of shell elements will not be able to detect any shadow effects; the use of shell elements for modelling beam members is not recommended.

LIMITATIONS

5. Irrigated structures in which water is circulating in order to keep the temperature of the structure within acceptable limits cannot be neglected because they may contribute in evacuating important amount of energy from the compartment.

HOW IT WORKS

1. The CFD specialist and the FE specialist must agree on a common system of coordinates. This is VERY important and yet too often neglected.
2. The CFD specialist makes his CFD model without considering the structural elements across the compartment. He refines the CFD grid where required by the fire.

   Note:

   1) He must ask to the FE specialist what is the extend of the transfer domain that is required. It is not necessarily that the transfer domain covers the whole FDS domain.
   2) In FDS7, several transfer domains can be written from the same CFD analysis.
3. He runs FDS7 that will write information in one or several transfer files according to a well defined and standardised format. These results describe the thermal environment in the transfer domains(s).

HOW IT WORKS

4. The FE specialist makes his structural model without considering the fire. He refines the grid where required by the structure.

5. The FE software reads the results from the transfer file(s) and uses them to calculate the temperatures in the structural elements.

6. Based on the temperatures in the elements, the FE software calculates the structural behaviour.

TRANSFER FILE

1. The information is written at given time steps chosen by the CFD specialist.

2. The information is written in one or several subdomains of the fds domain (called the transfer domains) defined by the CFD specialist. The distance between points in the transfer domain is chosen by the CFD specialist; it may be different from the grid of the CFD domain (eg. 10 cm for the cells in the CFD analysis and 30 cm used in the transfer file).

TRANSFER FILE

3. The information that is written in the transfer file at each point and each time step is:
   - The temperature of the air (used for convective exchanges)
   - The coefficient of convection (function of the air velocity, used for convective exchanges). If the F.E. is SAFIR, the coefficient of convection written in the transfer file is not taken into account. Its constant value is assigned by the user when declaring the material properties in the SAFIR input files of the thermal analysis. This is because the coefficient of convection computed by FDS is based on gas velocities that neglect the presence of the structural elements.

TRANSFER FILE

- The radiant intensities for a given number of directions (e.g. 104 directions, 6 directions is far too poor).
  When dealing with sections that entail shadow effects (e.g. H sections), at least 72 directions are recommended.

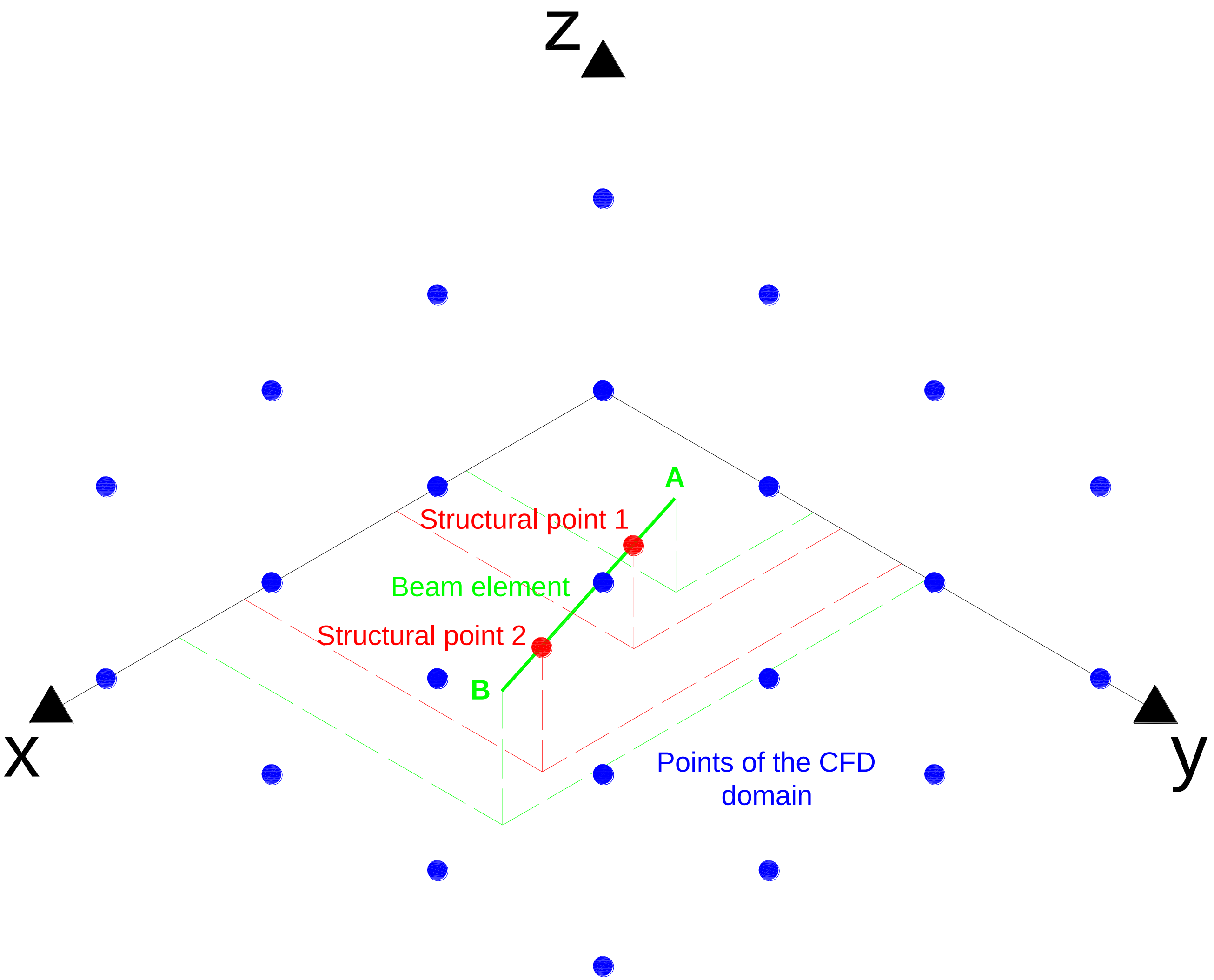
INTERPOLATION

Because the information is given at certain time steps, at certain locations in the space, and for certain directions, a three level interpolation must be performed by the FE software.

1. A Cartesian interpolation in space to have the information at the locations that are relevant for the structure.

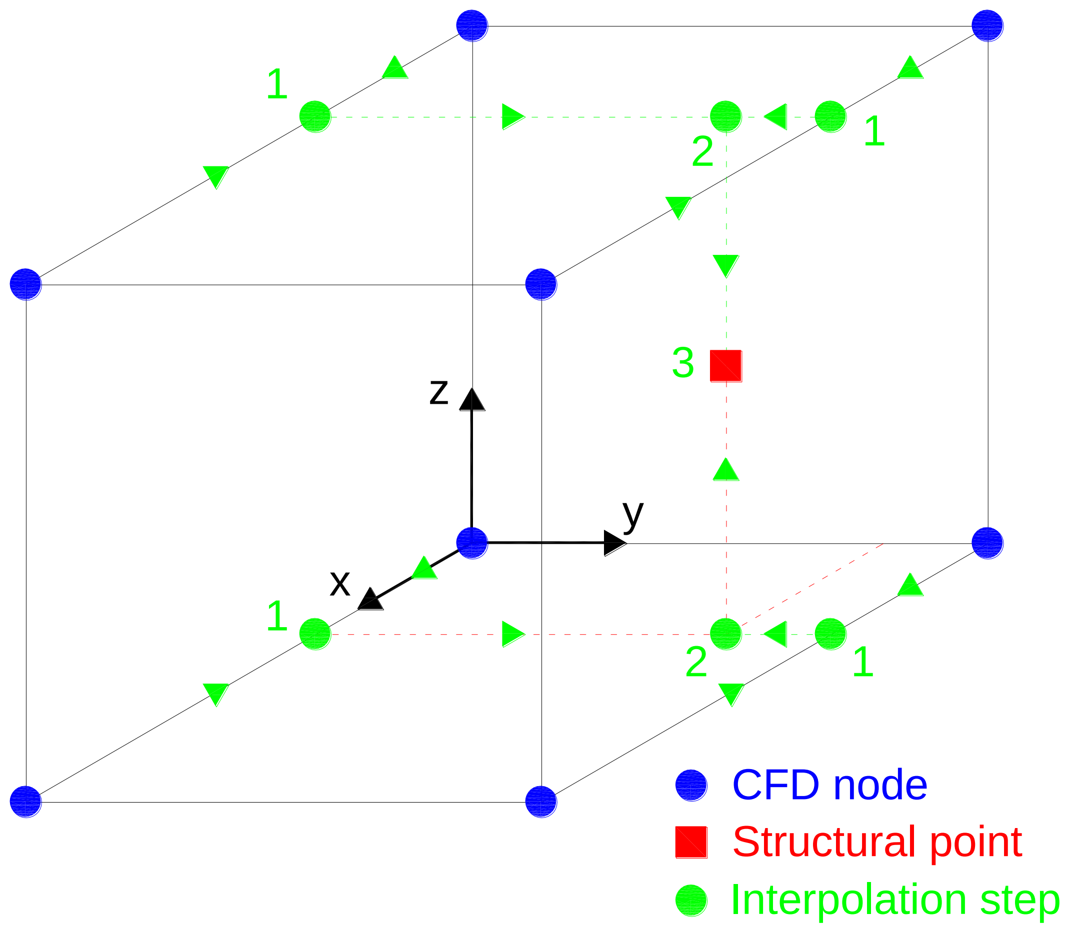
CARTESIAN INTERPOLATION

General representation of the scenario being analysed



CARTESIAN INTERPOLATION

A trilinear interpolation has been implemented



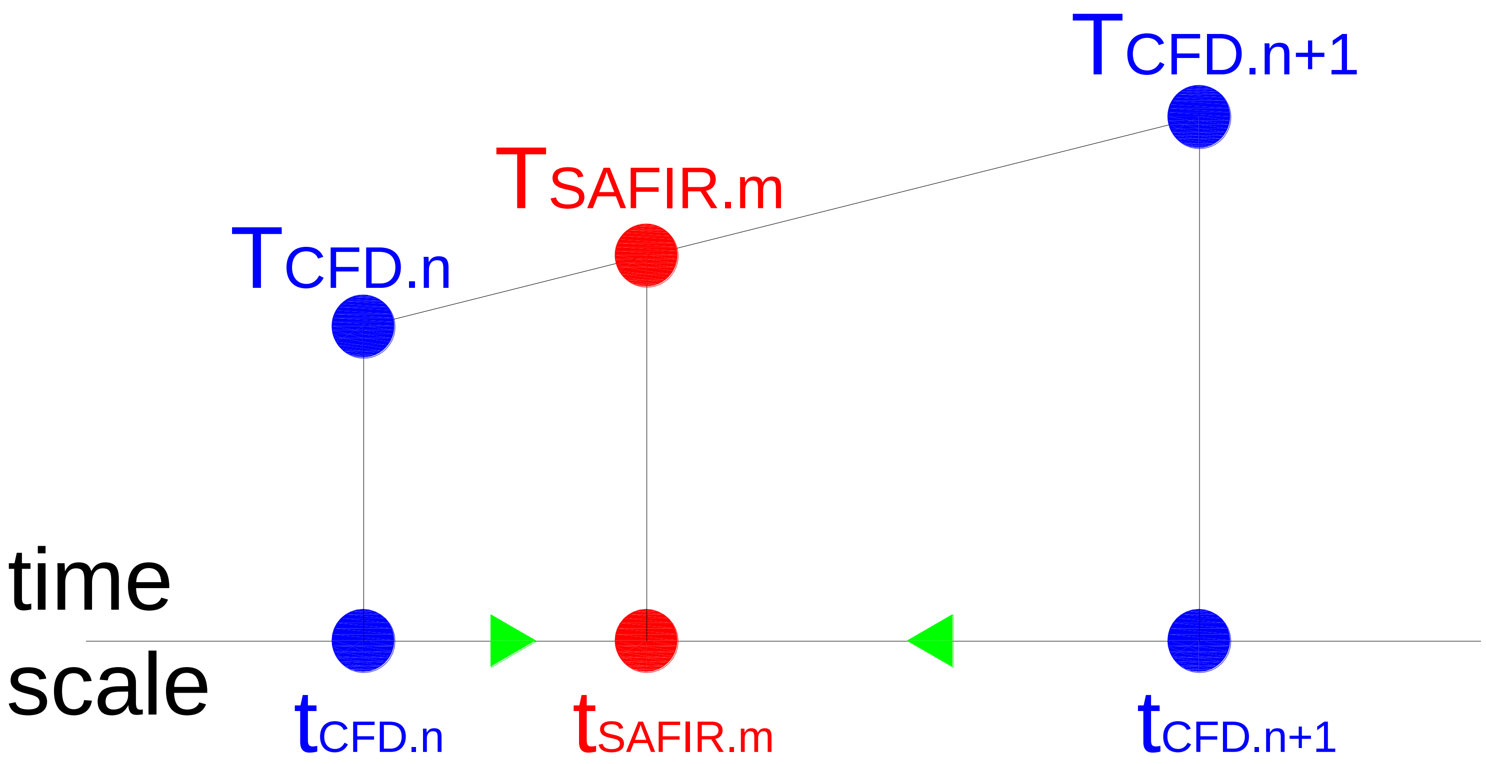
INTERPOLATION

Because the information is given at certain time steps, at certain locations in the space, and for certain directions, a three level interpolation must be performed by the FE software.

1. A Cartesian interpolation in space to have the information at the locations that are relevant for the structure.
2. Interpolation in time to have the information at the time step that are relevant for the structure.

TIME INTERPOLATION

A linear interpolation has been implemented



INTERPOLATION

Because the information is given at certain time steps, at certain locations in the space, and for certain directions, a three level interpolation must be performed by the FE software.

1. A Cartesian interpolation in space to have the information at the locations that are relevant for the structure.
2. Interpolation in time to have the information at the time step that are relevant for the structure.
3. Interpolation in spherical coordinates to have the radiant intensities in the appropriate directions on the surface of the structure.

SPHERICAL INTERPOLATION

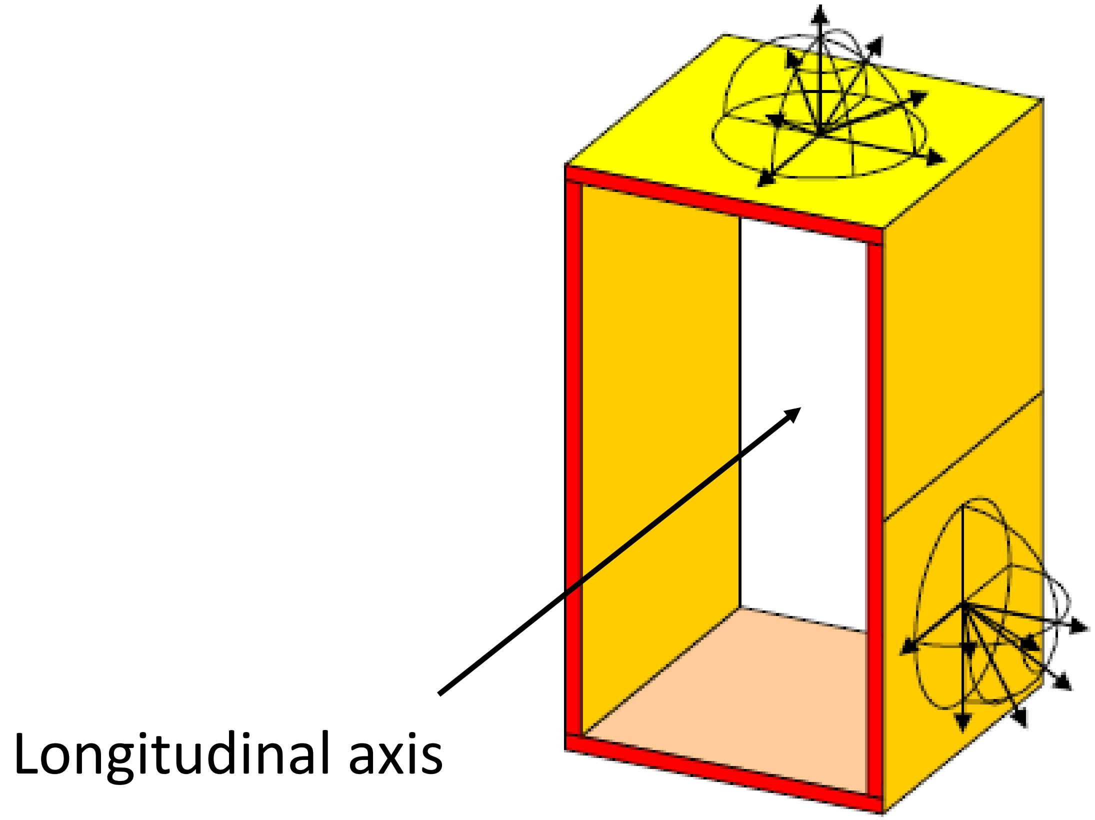
Generally, the directions of the radiant intensities required for numerical integration on the surface of the structural elements are not the directions in which the intensities are given by the CFD software (consider, for example, diagonals of truss girders).

As a consequence, rotations of axes may be required to find the surface system of coordinates taking into account:

- the direction of the longitudinal axis.
- the shape of the cross-section.

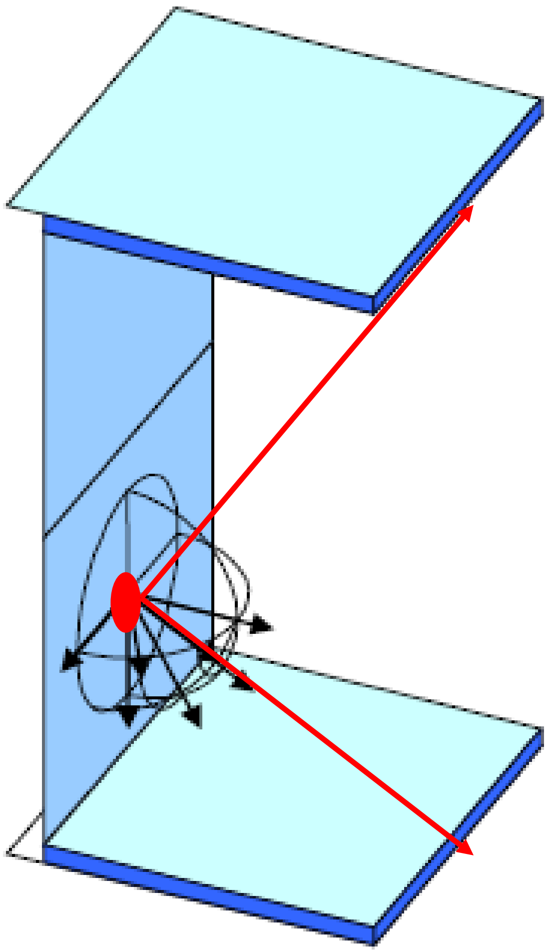
CONVEX ELEMENT

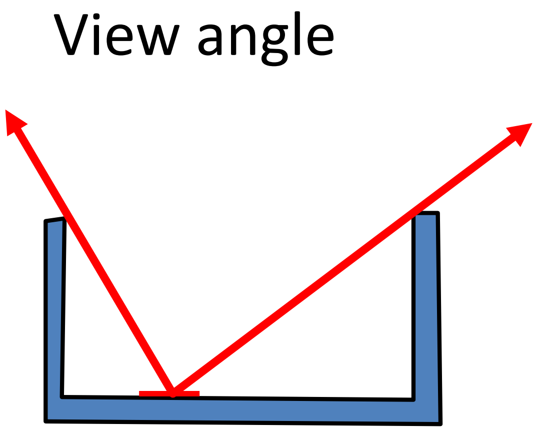
Integration on a complete hemisphere



CONCAVE ELEMENT

Integration on “clear sky”

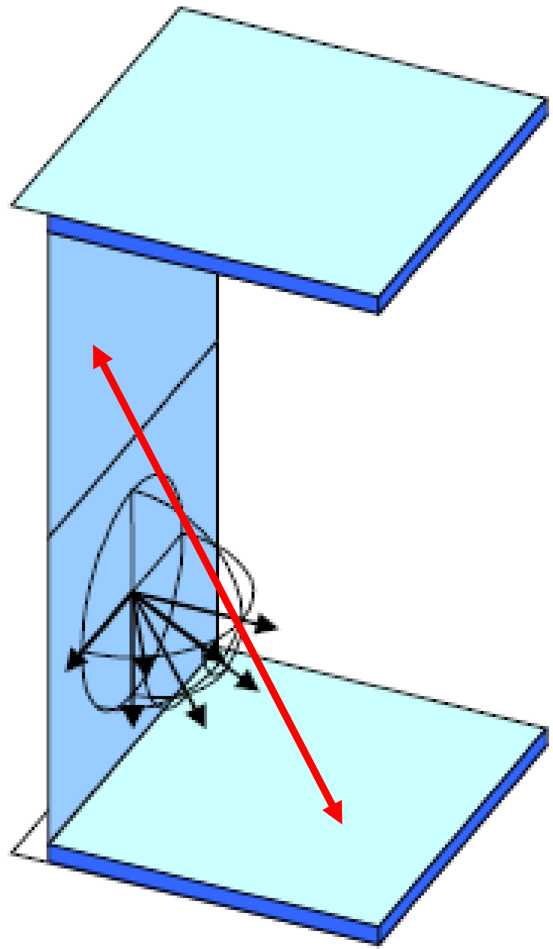


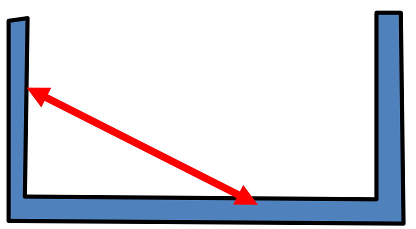


SPHERICAL INTEGRATION

CONCAVE ELEMENT

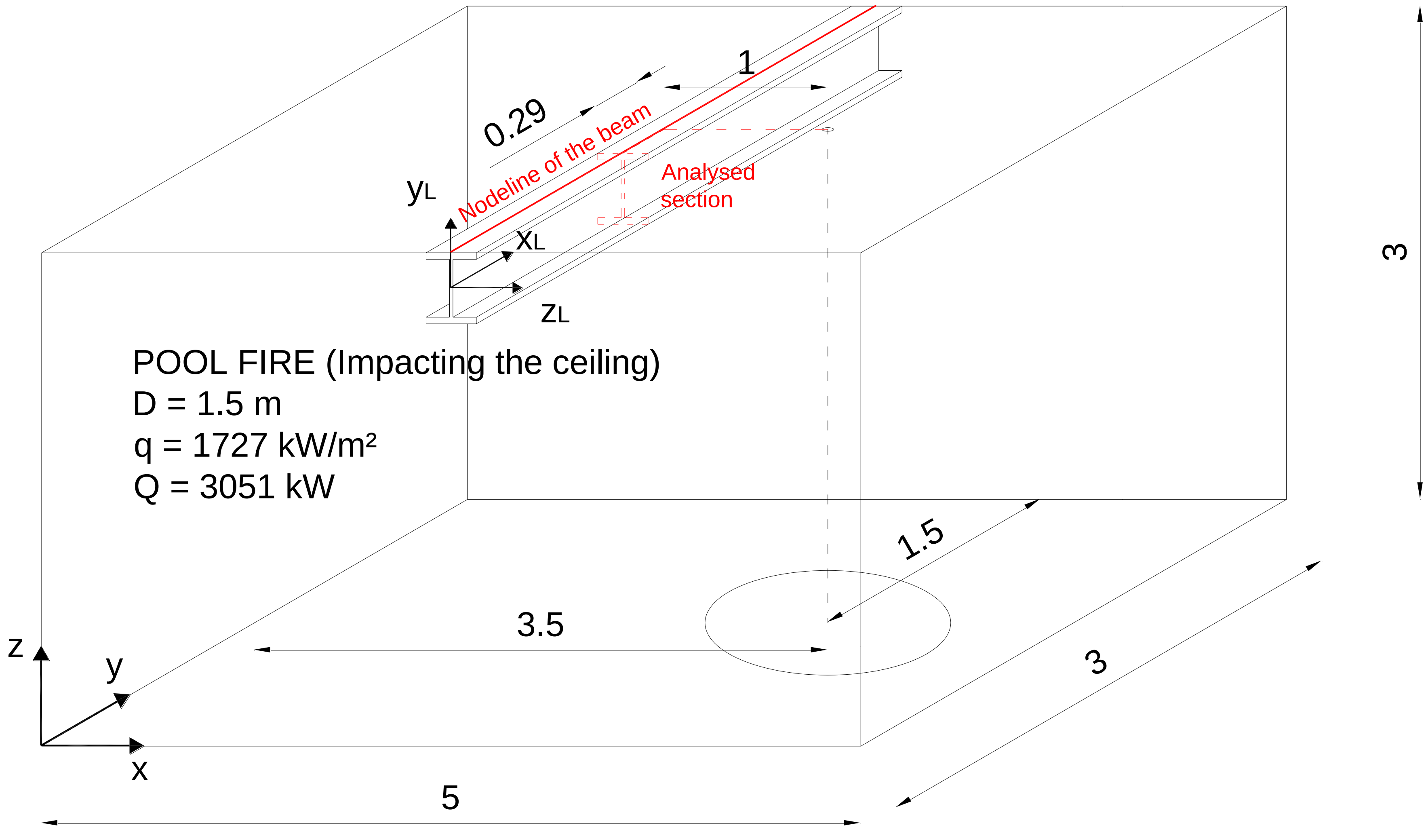
Note: radiation between boundaries of the section is not considered.





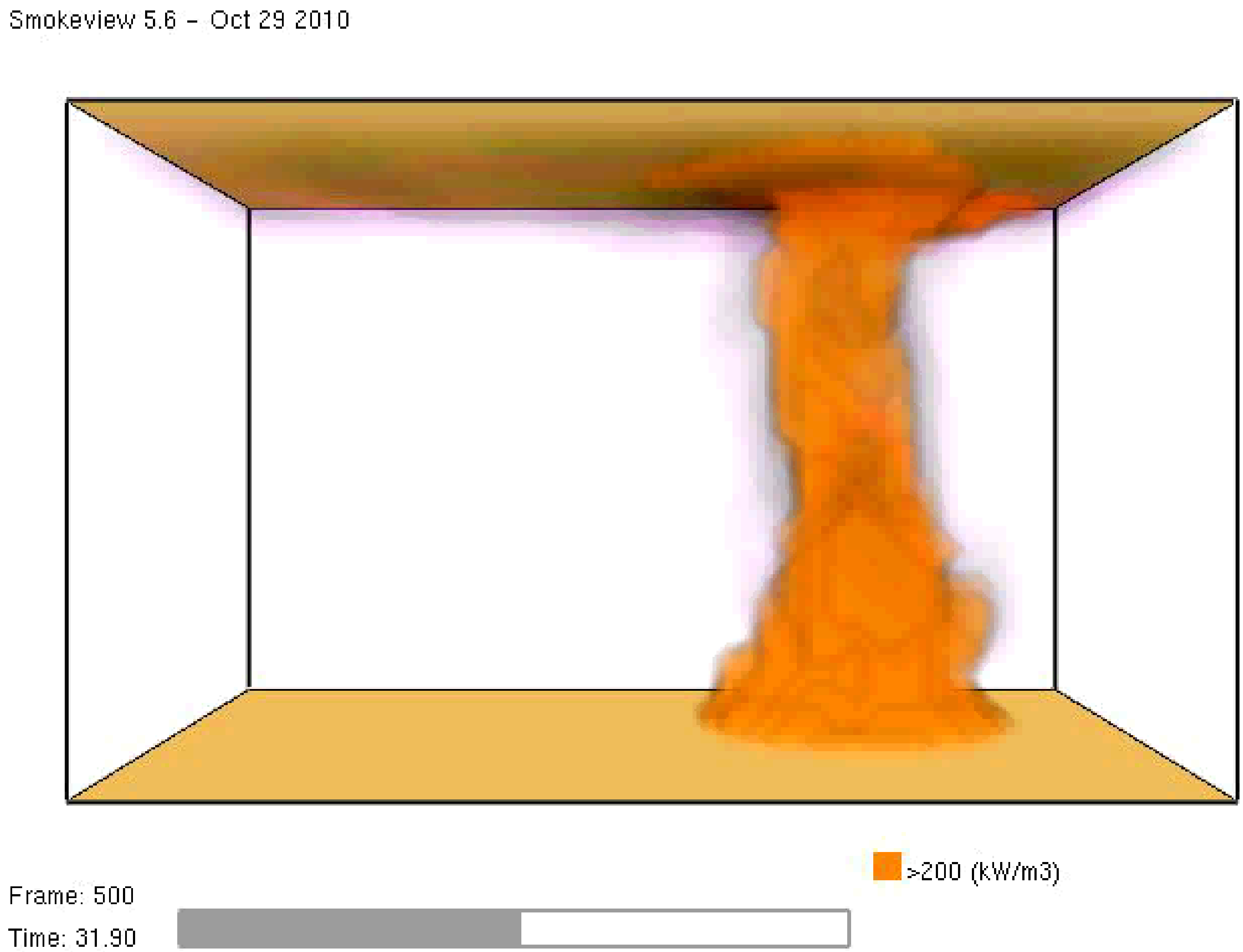
EXAMPLES: Compartment pool fire (FDS vs. HASEMI)

GEOMETRY



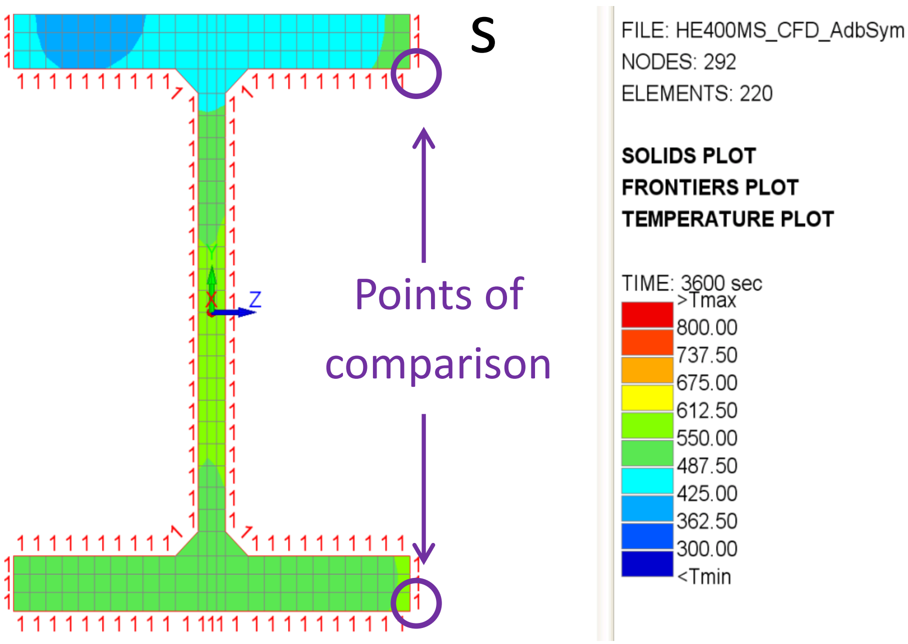
EXAMPLES: Compartment pool fire (FDS vs. HASEMI)

SIMULATION IN FDS

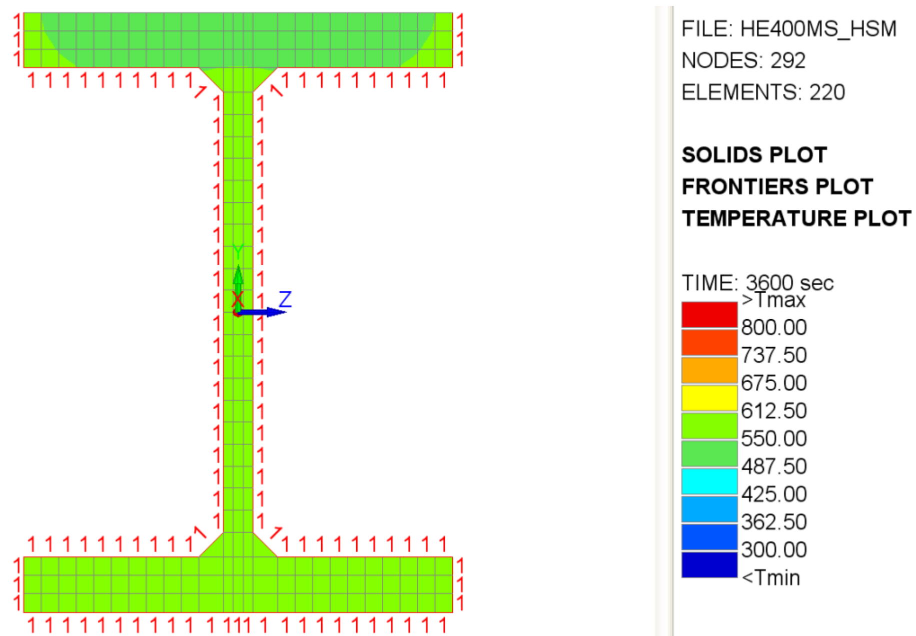


RESULTS

FDS – SAFIR @ t = 3600 s



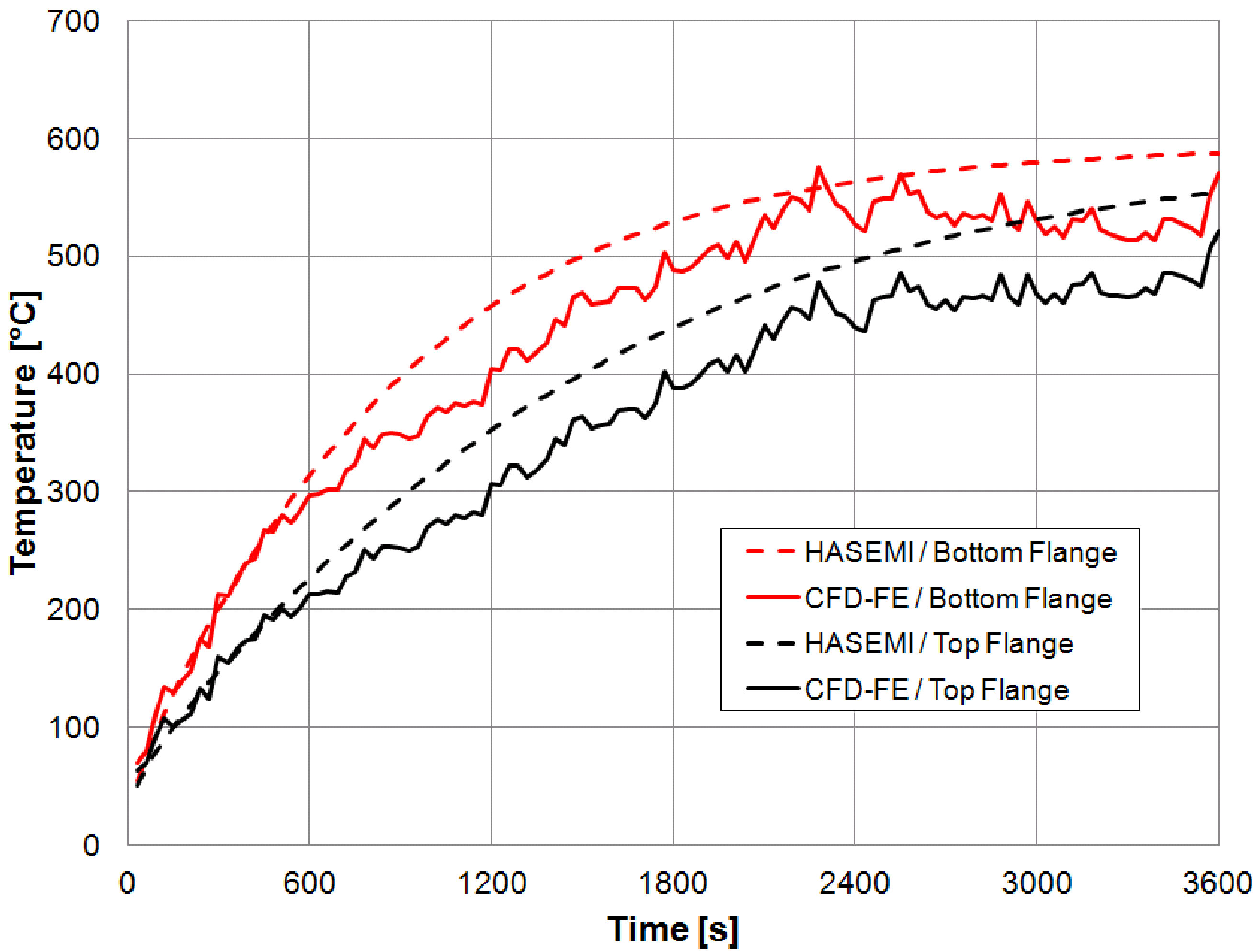
HASEMI @ t = 3600 s



Adiabatic conditions at the top upper flange

RESULTS

Comparison in terms of temperature



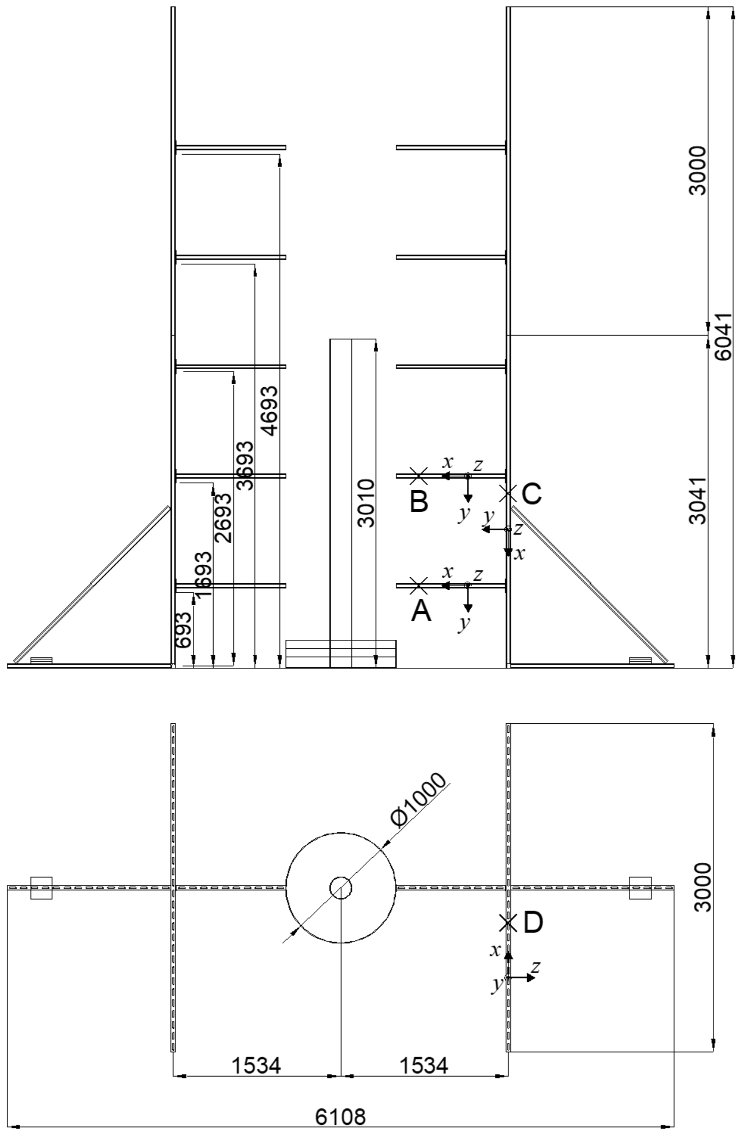
EXAMPLES: Rack analysis

LOCAFI Project

The LOCAFI research project dealt with the problem of columns engulfed in a fire source and the assessment of the real effect of the emissivity of flames.

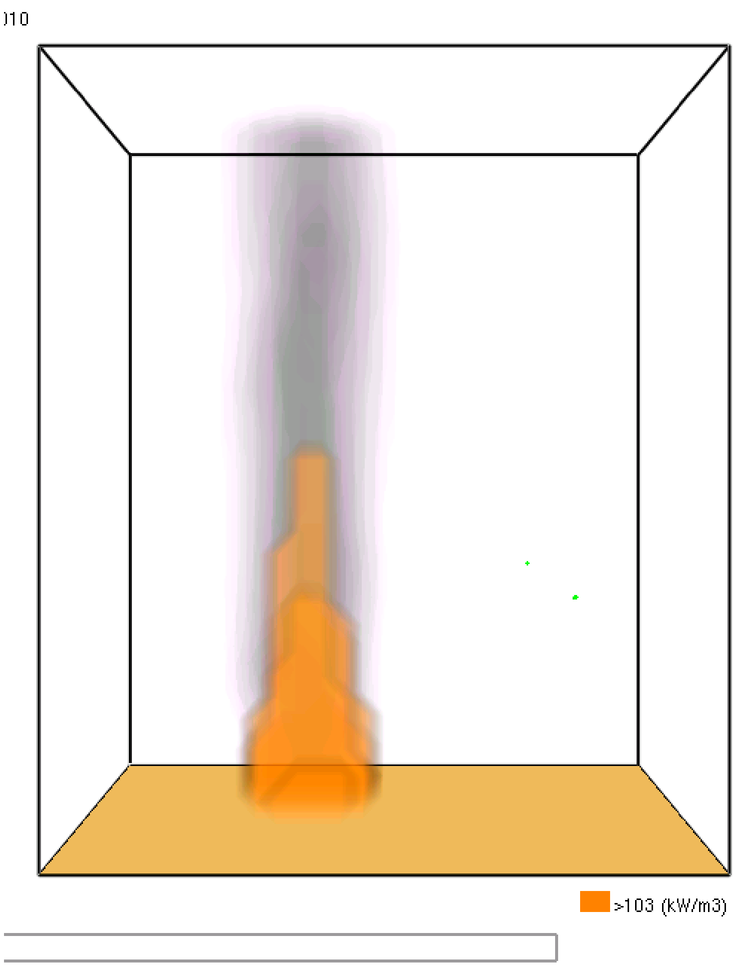
For this purpose, pool fire tests were performed and in order to measure temperatures at different heights, an instrumentation set-up was designed.

LOCAFI Project



Instrumentation set-up

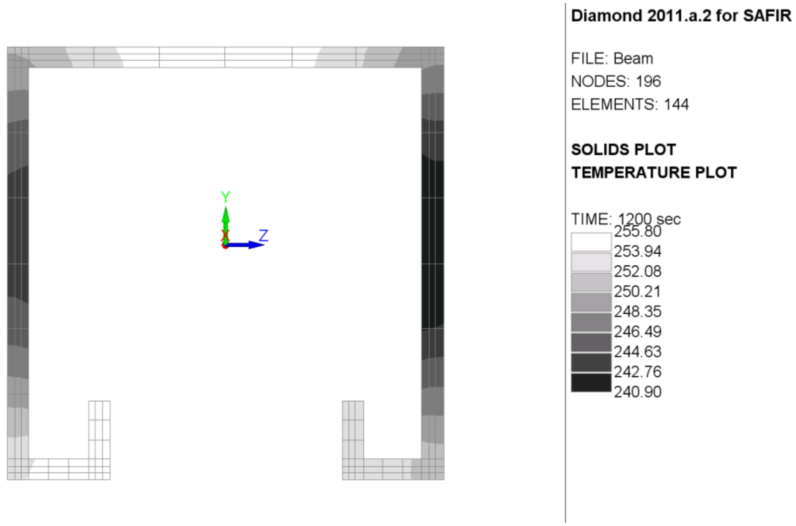
LOCAFI Project



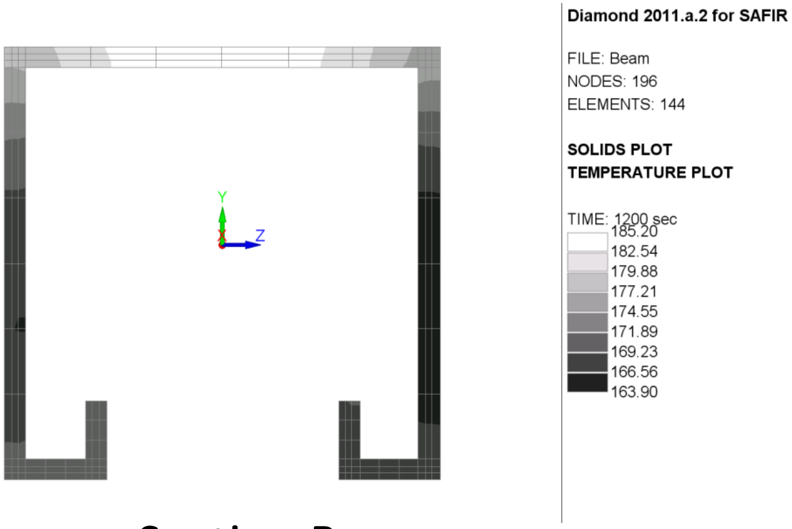
EXAMPLES: Rack analysis

LOCAFI Project

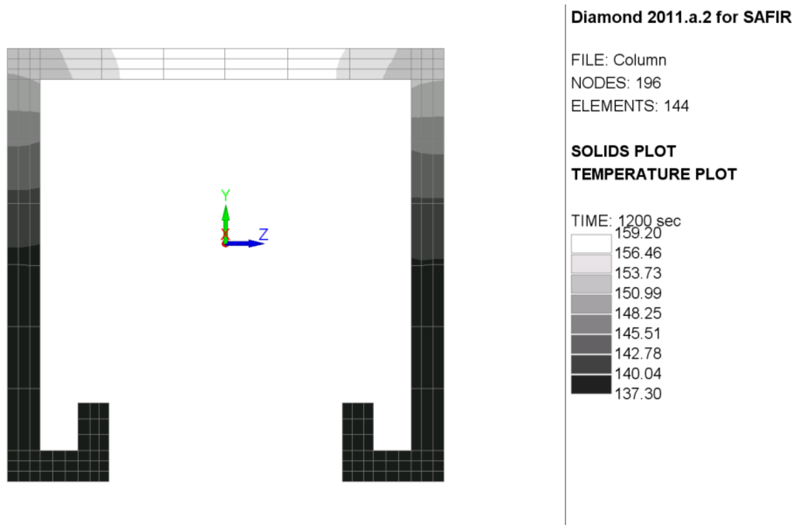
Results of thermal analysis



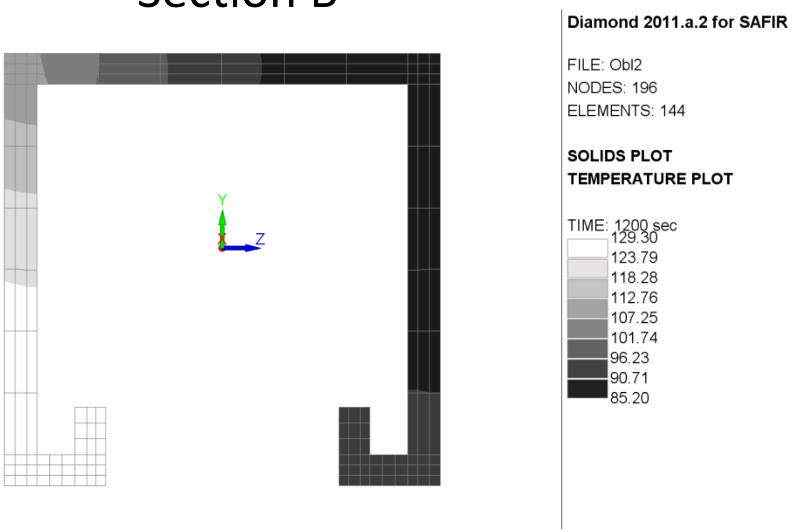
Section A



Section B



Section C

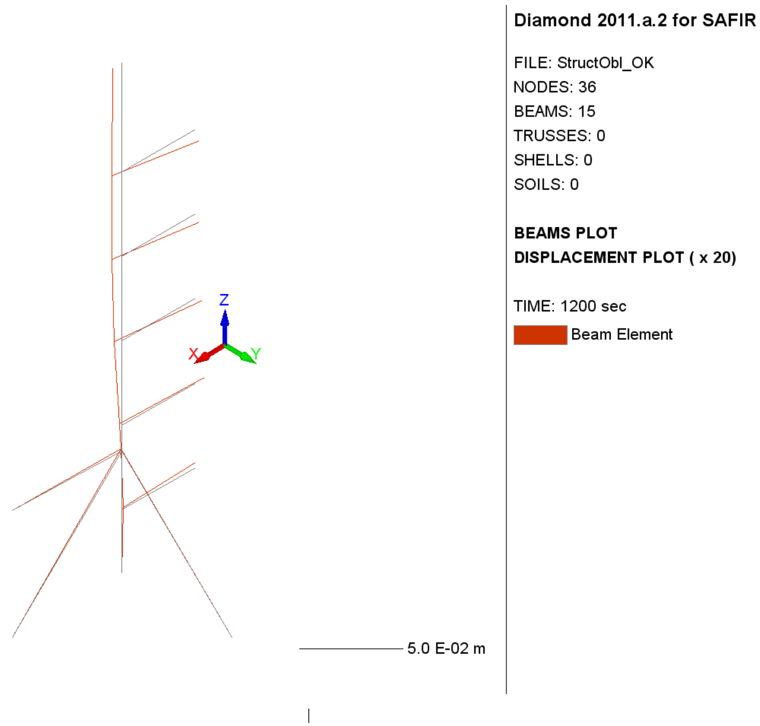


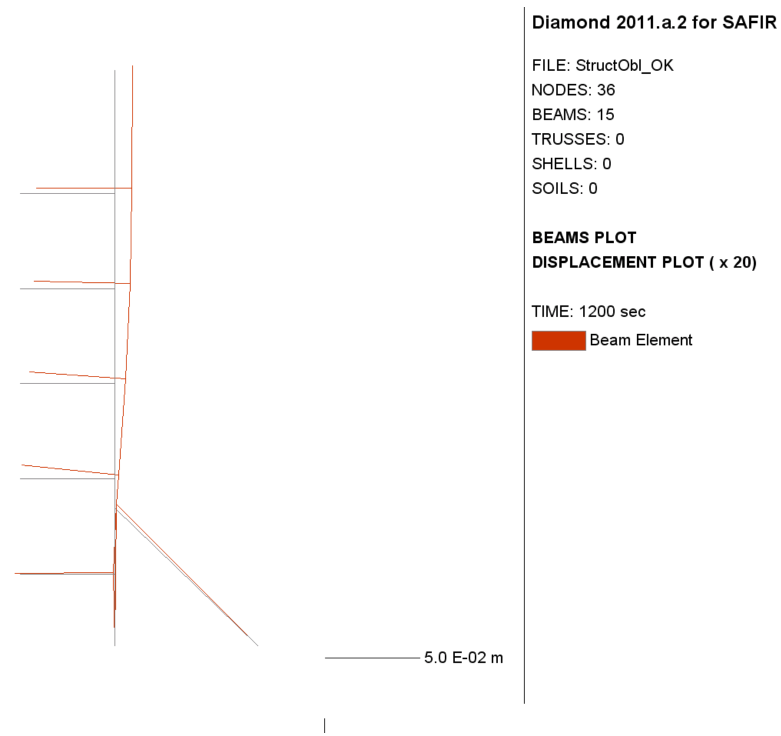
Section D

EXAMPLES: Rack analysis

LOCAFI Project

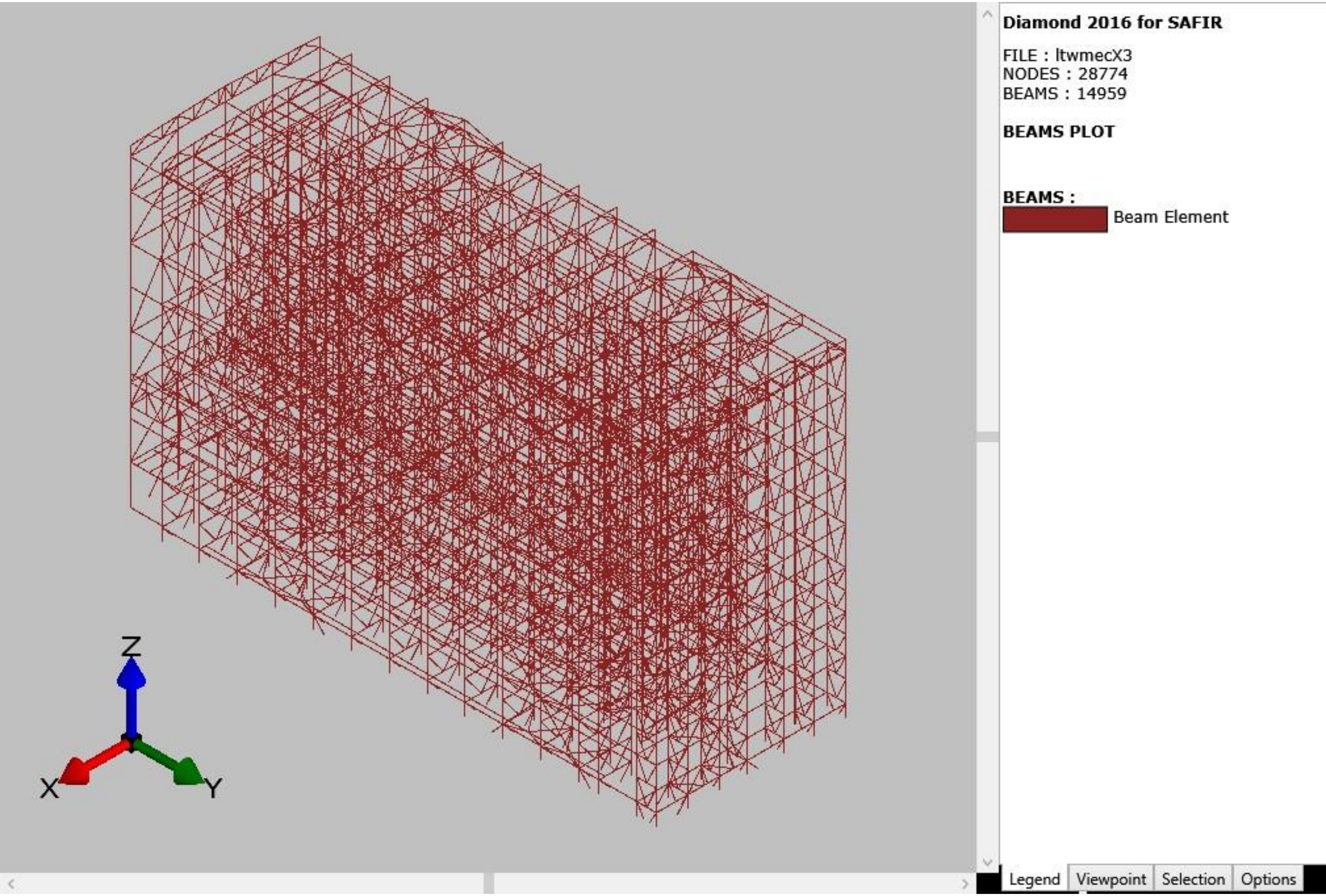
Results of mechanical analysis

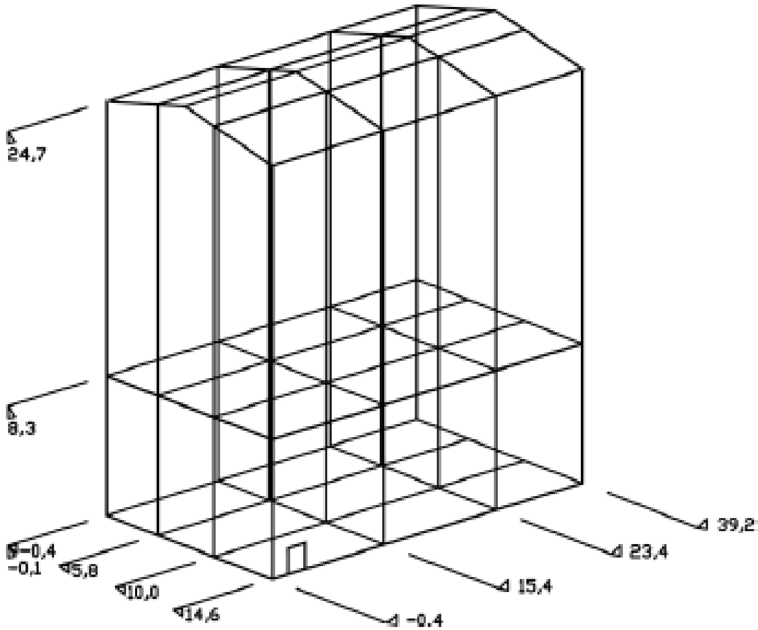




Displacements amplified by a factor of 20

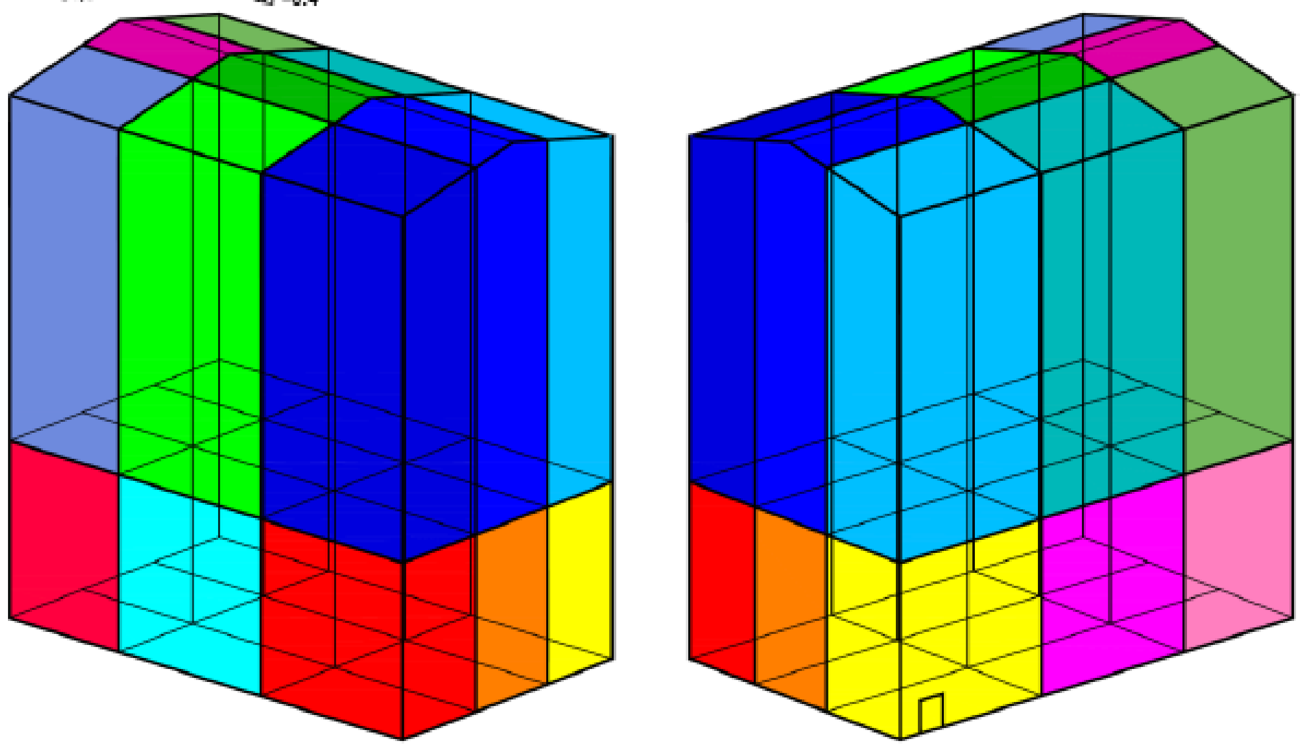
Steel rack structure (courtesy Dr Angel Guerrero Castells, IGNIA, Spain)



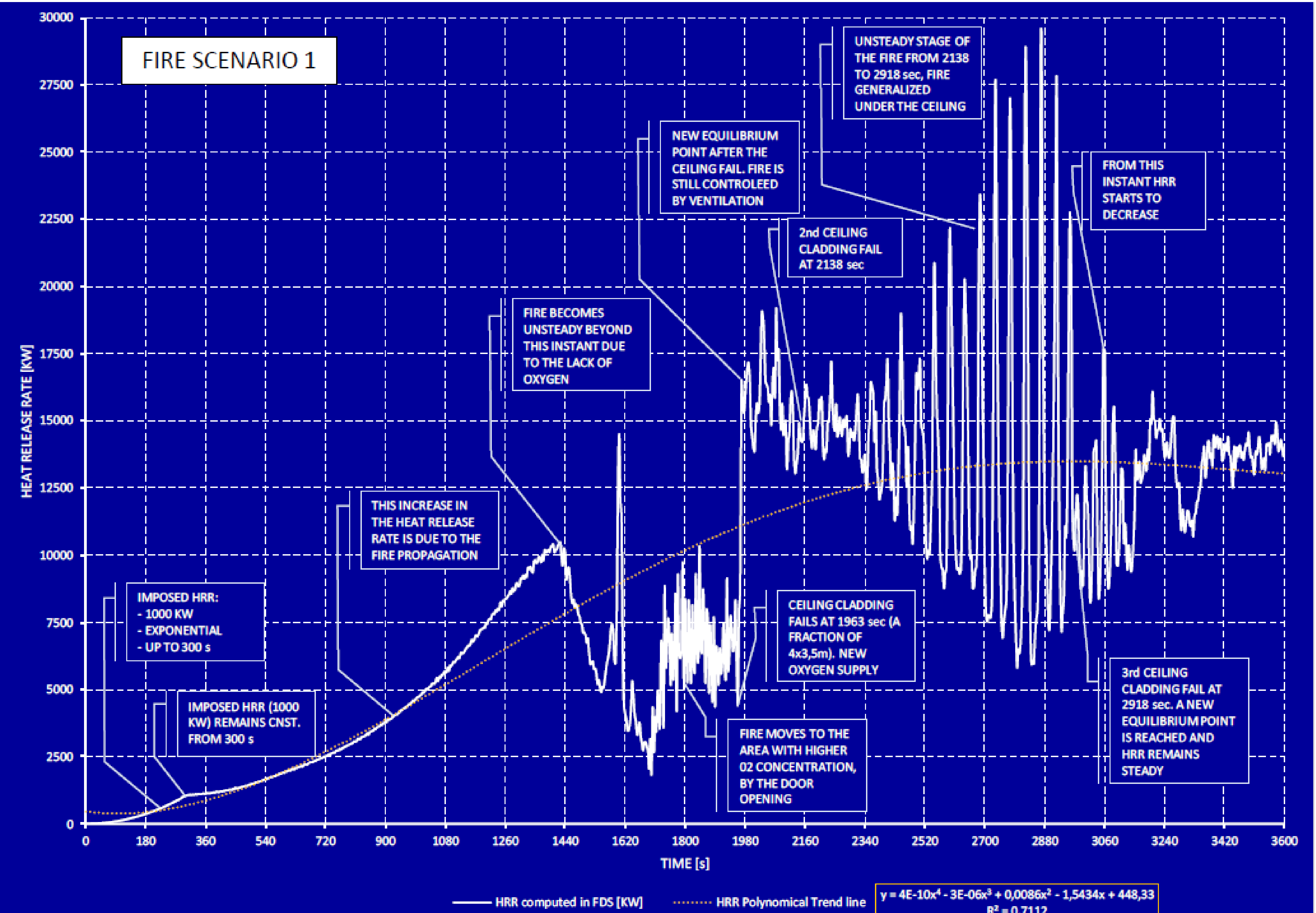


Summary of the mesh features:

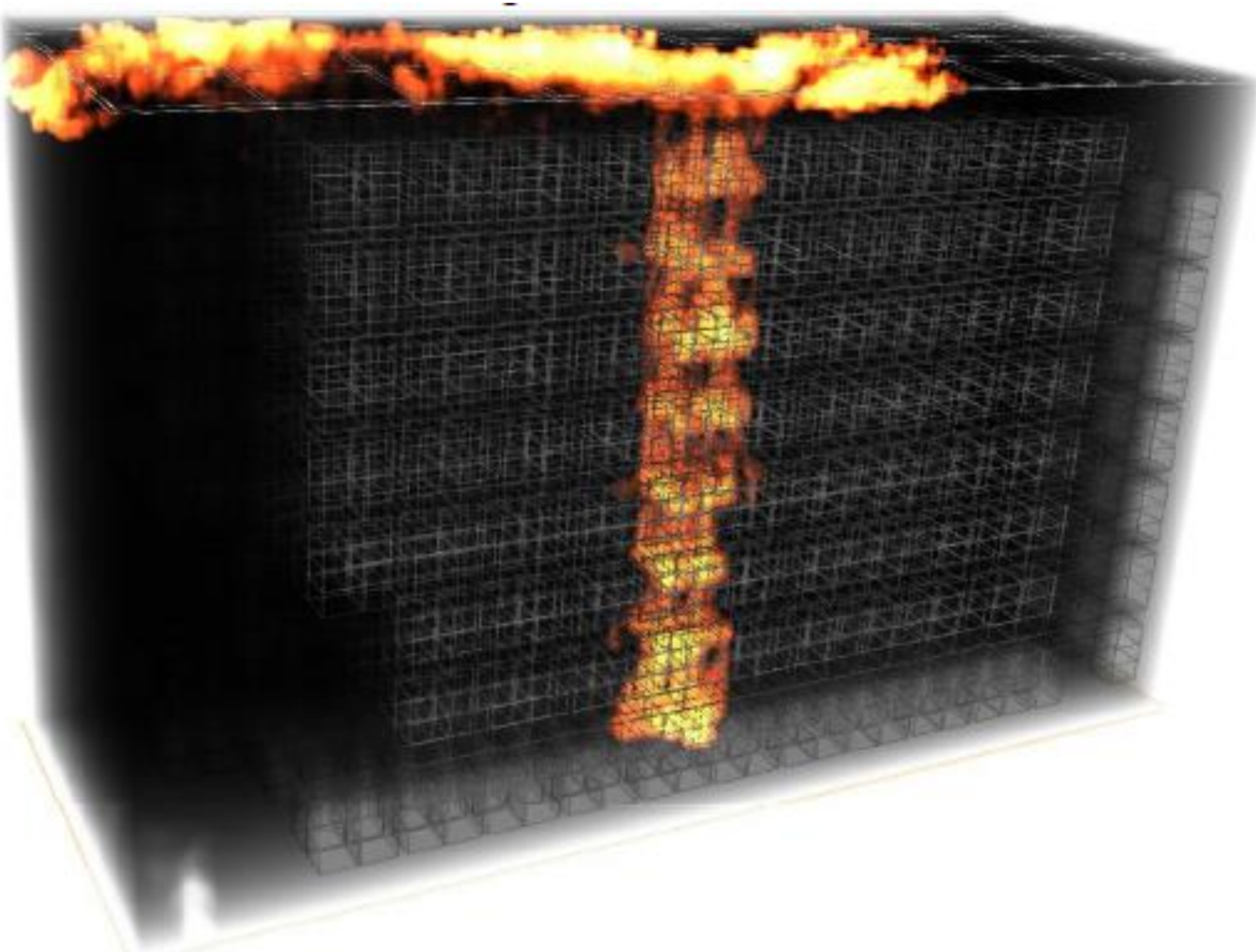
- 18 CFD meshes,
- 7.365.000 cells,
- 10 cm x 10 cm x 20 cm cells
- D* / δx equals 37,51 for the generally assumed 10 centimetres thick cell in both X and Y directions, and 18,755 for the 20 centimetres cells size in the Z vertical direction
- Characteristic fire diameter D* 3.751 meters



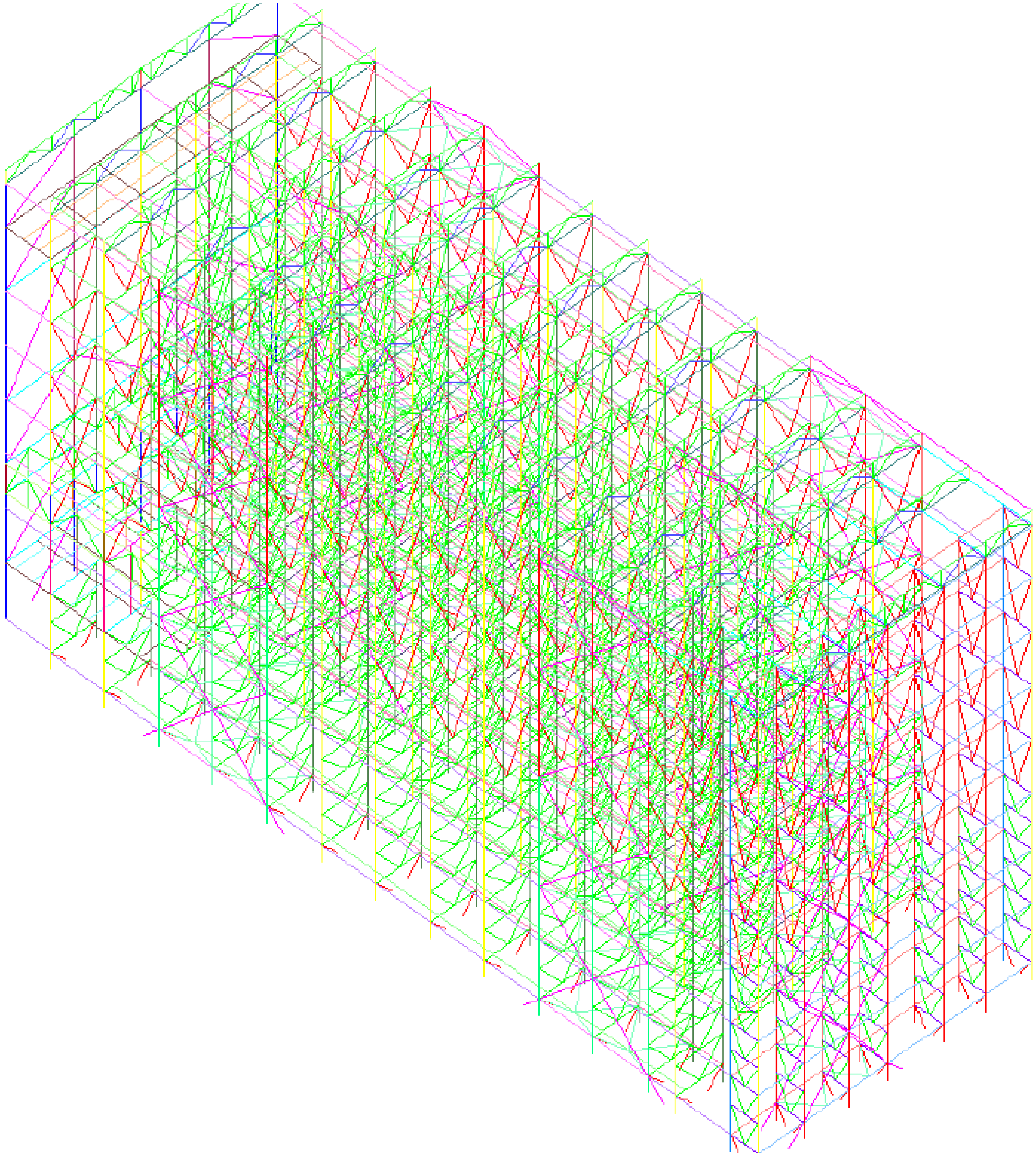
18 CFD Meshes



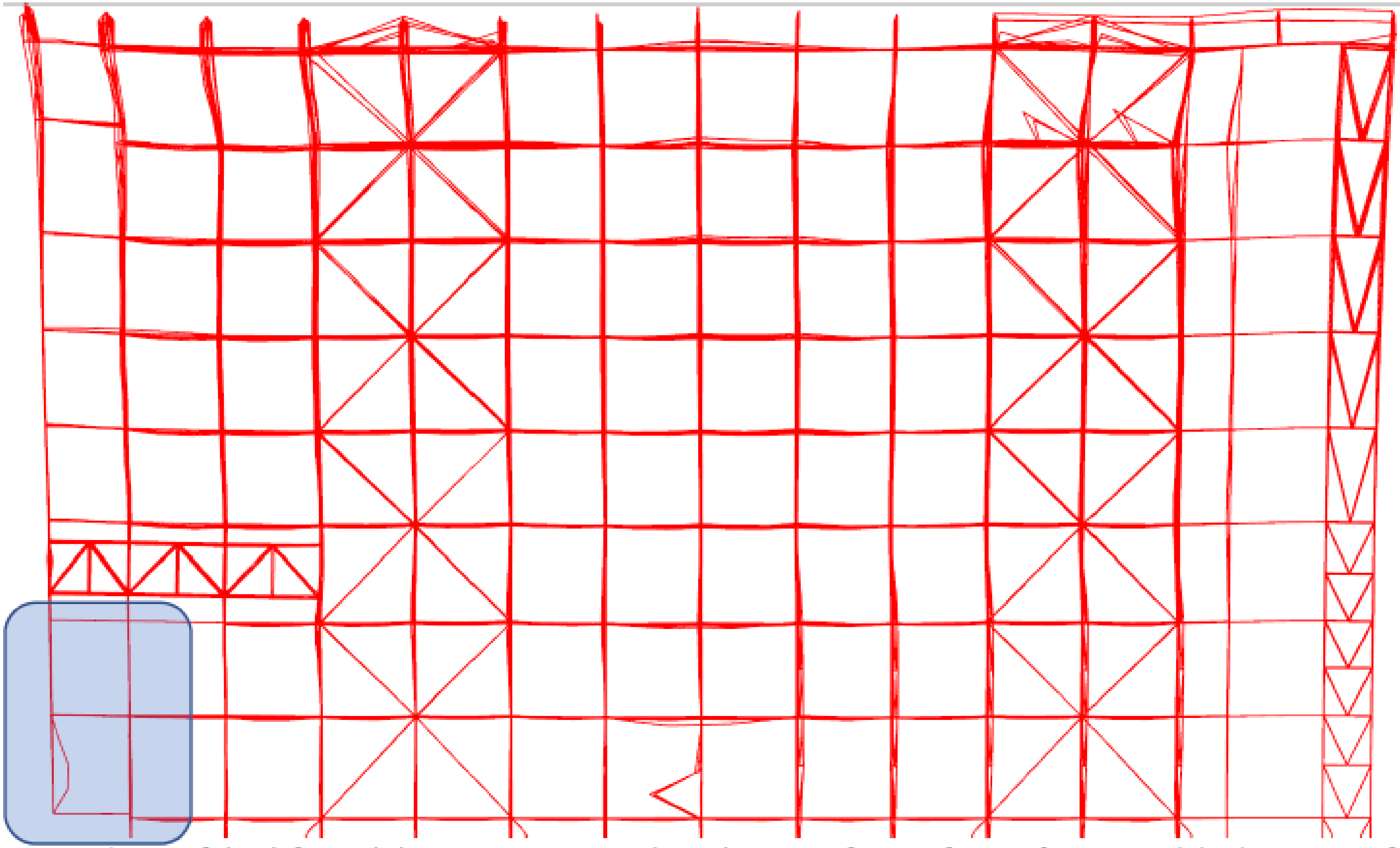
FIRE SCENARIO 1
HEAT RELEASE RATE [KW]
TIME [s]
UNSTEADY STAGE OF THE FIRE FROM 2138 TO 2918 sec, FIRE GENERALIZED UNDER THE CEILING
NEW EQUILIBRIUM POINT AFTER THE CEILING FAIL. FIRE IS STILL CONTROLEED BY VENTILATION
FROM THIS INSTANT HRR STARTS TO DECREASE
2nd CEILING CLADDING FAIL AT 2138 sec
FIRE BECOMES UNSTEADY BEYOND THIS INSTANT DUE TO THE LACK OF OXYGEN
THIS INCREASE IN THE HEAT RELEASE RATE IS DUE TO THE FIRE PROPAGATION
IMPOSED HRR: - 1000 KW - EXPONENTIAL - UP TO 300 s
CEILING CLADDING FAILS AT 1963 sec (A FRACTION OF 4x3,5m). NEW OXYGEN SUPPLY
IMPOSED HRR (1000 KW) REMAINS CNST. FROM 300 s
FIRE MOVES TO THE AREA WITH HIGHER 02 CONCENTRATION, BY THE DOOR OPENING
3rd CEILING CLADDING FAIL AT 2918 sec. A NEW EQUILIBRIUM POINT IS REACHED AND HRR REMAINS STEADY
HRR computed in FDS [KW]
HRR Polynomical Trend line
y = 4E-10x⁴ - 3E-06x³ + 0,0086x² - 1,5434x + 448,33
R² = 0,7112



Fire state at the end of the simulation (3.600 seconds)



General Perspective (rear) of the 3D structural model developed



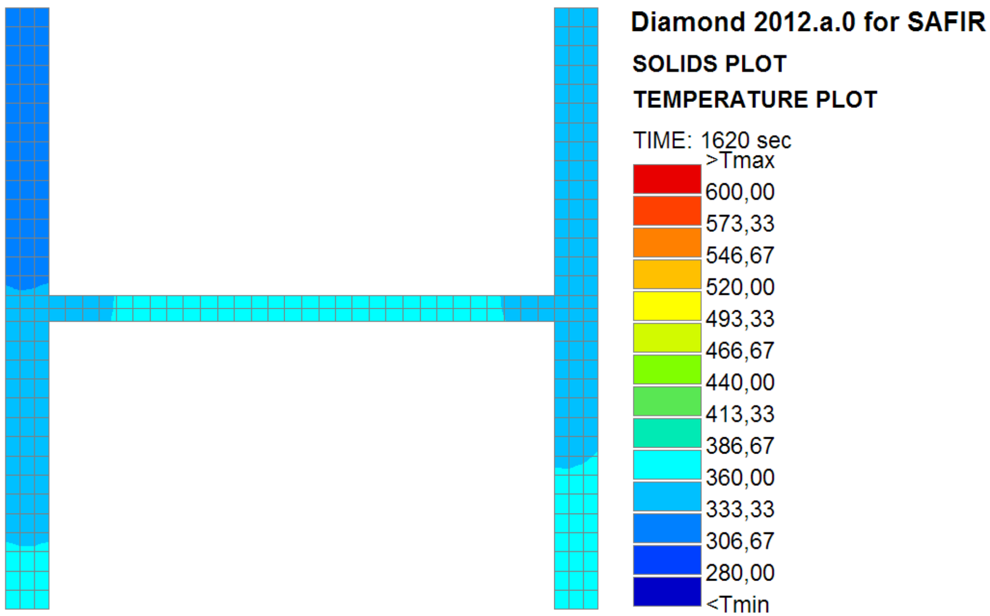
Lateral view of the deformed shape at 3.600 seconds, with a magnification factor of 20. Lateral displacements of the façade vertical bracing have decreased significantly according to the previous chart.

Recent developments

1) The possibility for FDS to write the transfer file according to the format required by SAFIR has been integrated by NIST in FDS 7.
2) SAFIR cannot read the data if the transfer file is larger than 4 Gb. This is less crucial as the information can now be written in the transfer file at only some points of the CFD grid.

OPEN ISSUES

4) The thermal analysis for beam elements finely meshed may take a large amount of time for a structure with a significant number of beams. This is due to the procedure that integrates radiant intensities in order to get the heat flux impinging a surface. Parallelisation of SAFIR 2019 in OpenMP has improved the situation.



Q: Practically speaking, in SAFIR, how does it work?

A: Procedure very similar to the one used for HASEMI fire.

1) In the input file for thermal analysis, replace MAKE.TEM by MAKE.TEMCD or MAKE.TSH by MAKE.TSHCD;
2) Next line, give the name of the input file for the structural analysis (this file must be present in the same folder);
3) Next line, give the number of the type of section considered.

Examples:

```
   TEMPERAT
       TETA          0.9
   TINITIAL         20.0
MAKE.TEMCD
Compartment.in
 BEAM_TYPE 1
       NMAT 2
   ELEMENTS
```

```
 TEMPERAT
      TETA          0.9
  TINITIAL         20.0
MAKE.TSHCD
Compartment.in
SHELL_TYPE   2
      NMAT   1
  ELEMENTS
```

4) In the FIXATION commands, introduce a FLUX command where is needed.

FLUX 105 NO NO CFD NO

5) Introduce the information for torsion properties only in the first .TEM file of the list, for example in b0001_1.tem or in s0019_1.tsh

6) Repeat the procedure for all section types.

How does it work in FDS?

1) You need FDS version 7

2) Control the number of radiation intensities with the following line

&RADI NUMBER_RADIATION_ANGLES=30/
30 will give the radiation intensities in 32 directions
64 will give the radiation intensities in 72 directions
100 will give the radiation intensities in 104 directions

3) Generate the transfer files with lines such as these:

&RADF XB=2.3, 6.6,   1.3, 5.3,   0, 3.5, I_STEP=3, J_STEP=3, K_STEP=3/
&DUMP T_RADF_BEGIN=0., T_RADF_END=30., DT_RADF=10.

A specific command line is introduced for the creation of the transfer file. This is the command "RADF". This command has several arguments:

- "XB" gives the limits of the transfer domain as X_{min}, X_{max}, Y_{min}, Y_{max}, Z_{min}, $Z_{max.}$. The transfer domain may not extend outside the FDS domain described by "XB" in the "MESH" command. It is good practice to have the boundaries of the transfer domain aligned with the cells of the CFD domain.
- "T_RADF_BEGIN" (optional) gives the first time for which information will be written in the transfer file. It is good practice to write T_RADF_BEGIN = 0 in order to have initial conditions written in the transfer file. By default, T_RADF_BEGIN is set to the start time of the simulation, T_BEGIN.
- "T_RADF_END" (optional) gives the last time for which information will be written in the transfer file. The value given for "T_RADF_END" in the command "FDStoSAFIR" may not be greater than the value given for "T_END" in the command "TIME". By default, T_RADF_END is set to T_END.
- "DT_RADF" (optional) gives the time step after which information will be written in the transfer file. It is good practice that the result of (T_RADF_END – T_RADF_BEGIN) / DT_RADF be an integer. By default, DT_RADF, the time interval, is the end time minus the start time divided by 5.

I_STEP, J_STEP and K_STEP (optional) allow skipping cells in the transfer file in order to reduce the size of this file.
For example, if there are 20 cells in the transfer domain in the direction X, utilisation of "I_STEP=3" will make FDS to write the information for cells 1, 4, 7, 10, 13, 16 and 19. The information will not be written for cell 20.

The time limits and intervals for writing the information in the transfer file are described in the DUMP line.

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