

# SECURE WITH STEEL

## FDS – SAFIR Interface

*Nicola Tondini*  
*Jean-Marc Franssen*

Esch-sur-Alzette (L)  
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**3 problems** have to be solved. Each of them is governed by different equations.

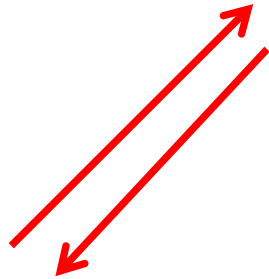
1. **Fire development** => Temperatures and flows in the compartment. It requires a 3D model.
2. **Thermal response** => Temperatures in the structural elements. A 2D model is generally sufficient.
  - Elements across the compartment.
  - Elements on the boundaries of the compartment.
3. **Mechanical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

# LEVEL OF COUPLING

IN REALITY EVERYTHING IS COUPLED



2. Temperatures in elements



1. Compartment



3. Structural behaviour

### 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).

### 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

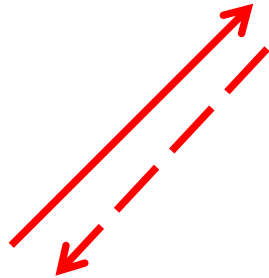
1. A CFD software A must communicate with an FE software X.
  - Modifications have to be made in both codes.
  - Issues about different time steps must be addressed.
  - Will not work with a CFD software B or an FE software Y.

### ISSUES

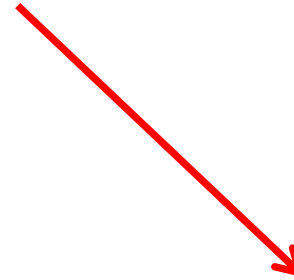
2. Each run requires a specialist in CFD and a specialist in FE (or someone who is specialist in both).
3. Capacity demand of the hardware and CPU time increases, especially during the debugging of the model.
4. If the structure must be changed (either because it does not satisfy the fire resistance requirement, or because the architect changes the project), everything has to be recalculated.

## Option 2: WEAK COUPLING STRATEGY

2. Temperatures in elements



1. Compartment



3. Structural behaviour

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<sup>(\*)</sup> 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

## 2. Temperatures in the elements

Non load  
bearing wall,  
floors, ceilings

Load bearing  
wall, floors,  
ceilings

Load bearing  
beams and  
columns

**CFD**

**FE**

1. Compartment

3. Structural behaviour

## ESSENTIAL FEATURES

- 1) The **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



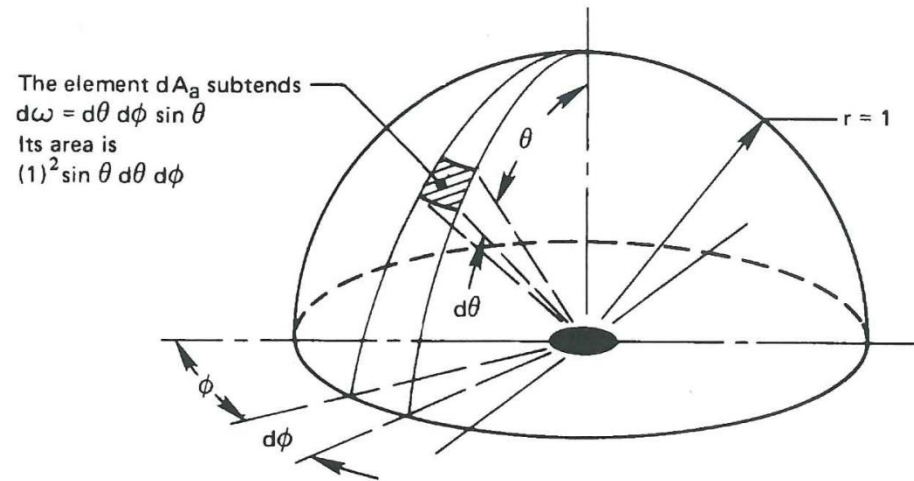
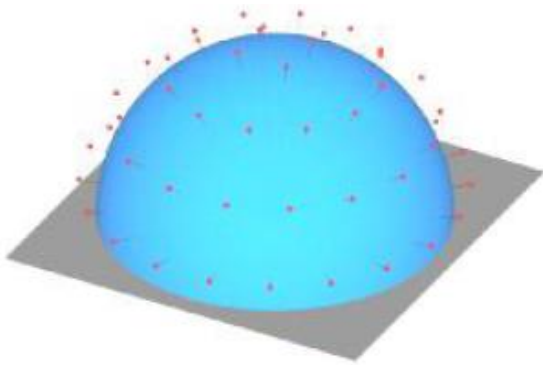
## INFORMATION:

- Temperatures
- Convection factors
- Radiant intensities

## SAFIR

- Thermal response
- Mechanical response

## TRANSFERRED INFORMATION: Radiant intensities $I$



Flux received by a surface

$$dq = Id\omega \cos \vartheta \text{ where } d\omega = \sin \vartheta d\vartheta d\phi$$

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

### TRANSFERED INFORMATION: Radiant intensities

Radiant intensities from different directions are preferred to impinging radiant fluxes on predefined surfaces 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.

The fluxes at the surface of the structural elements will be computed within the FE software by integrating the radiant intensities which allows taking into account possible shadow effects in concave sections.

## 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  $p \cdot q$  coupled analyses in a two-way coupling approach.
- By transferring radiant intensities rather than fluxes, shadow effects in concave sections can be considered,

### 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.

### Consequences:

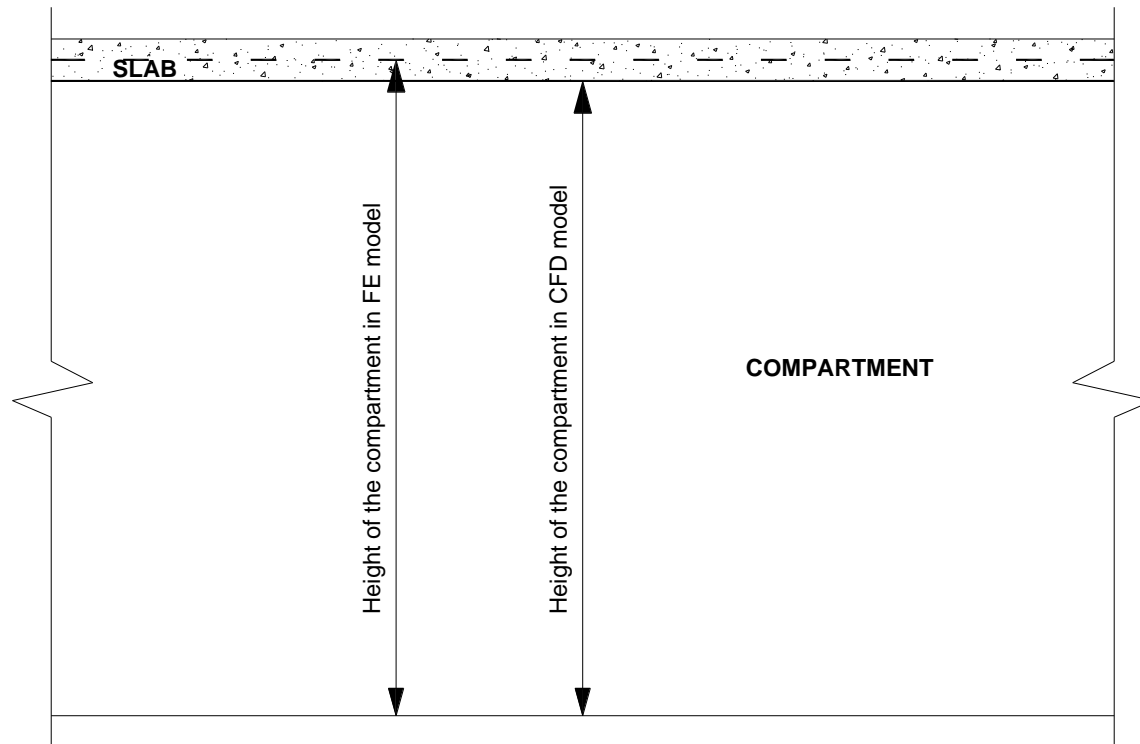
- i) a series of 2D thermal analyses for different sections along the structural elements rather than a unique 3D thermal analysis can be made.
- ii) a 1x1 m<sup>2</sup> concrete columns in a 100 m<sup>2</sup> compartment must clearly be considered in the CFD model because it influences the mass and 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.



- 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.

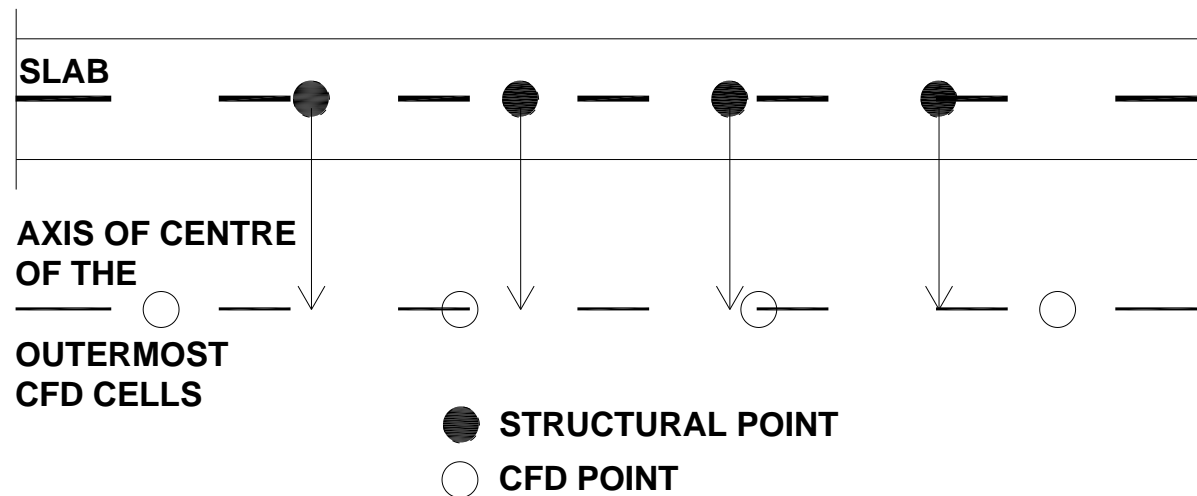
## LIMITATIONS

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



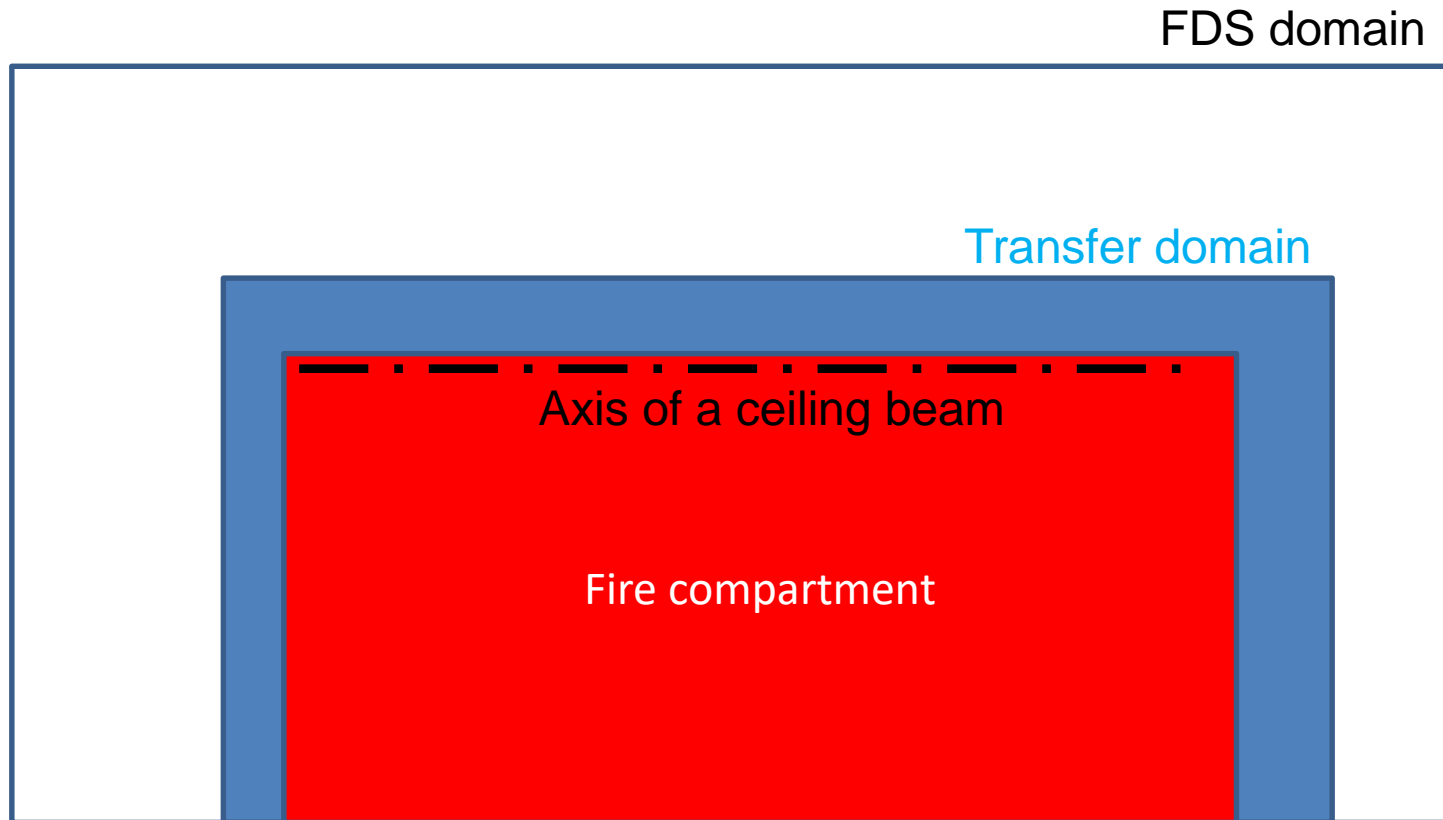
# WEAK COUPLING STRATEGY

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.



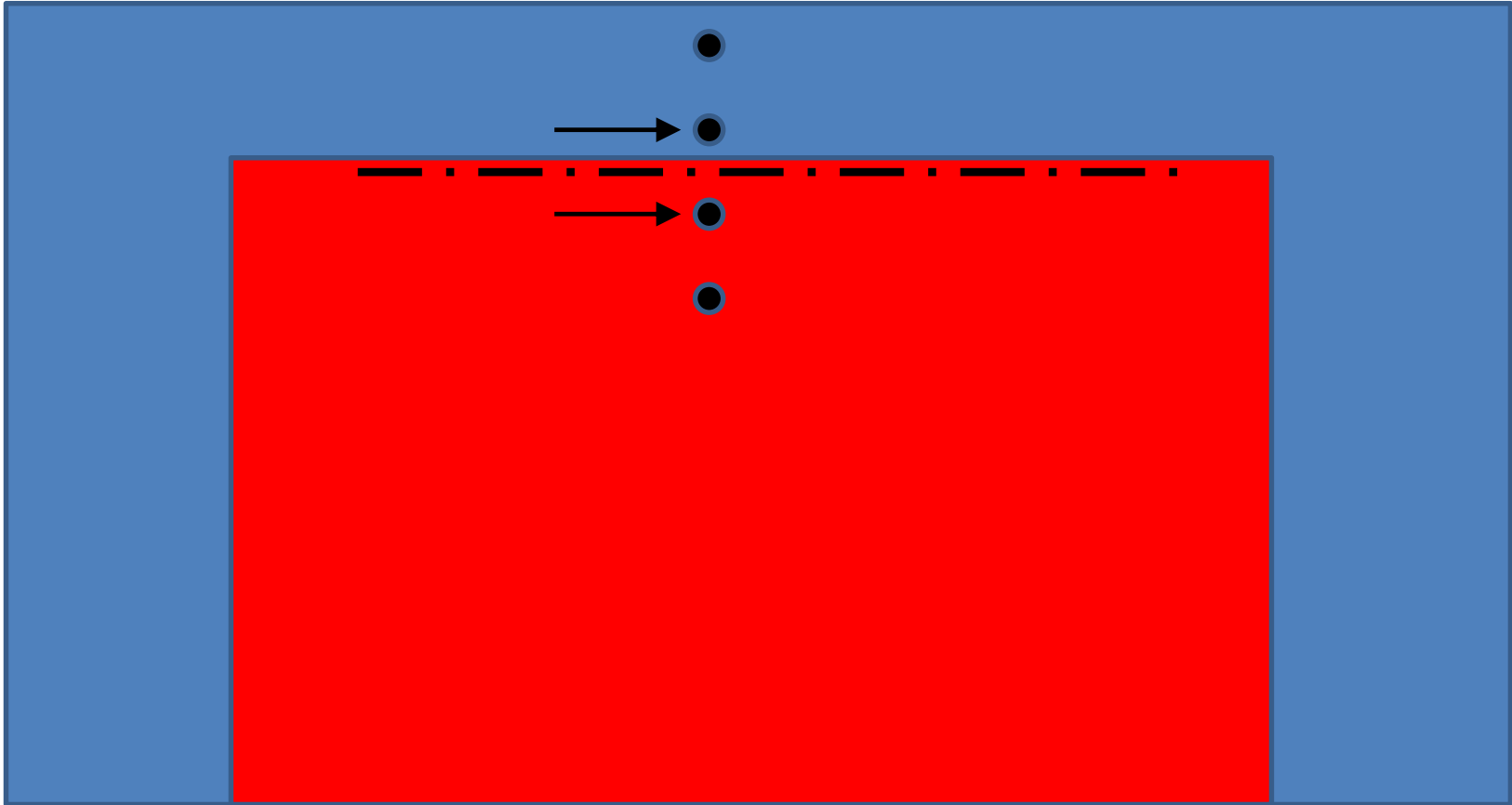
# WEAK COUPLING STRATEGY

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



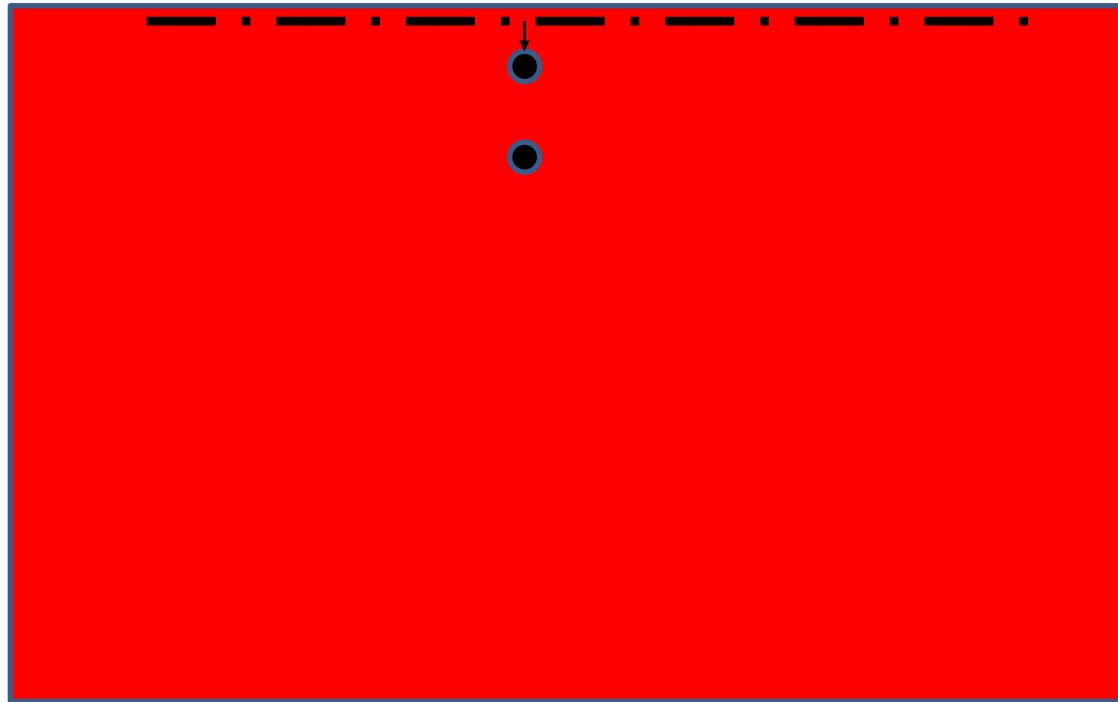
## WEAK COUPLING STRATEGY

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 Pol of the beam to the nearest points in the transfer domain..



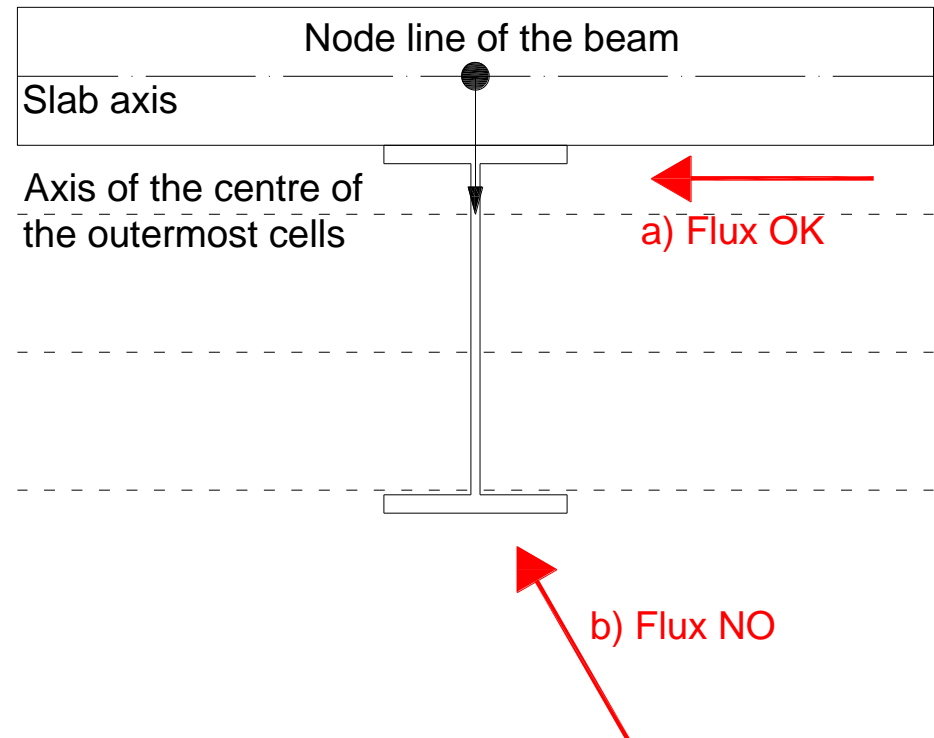
### LIMITATIONS

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 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

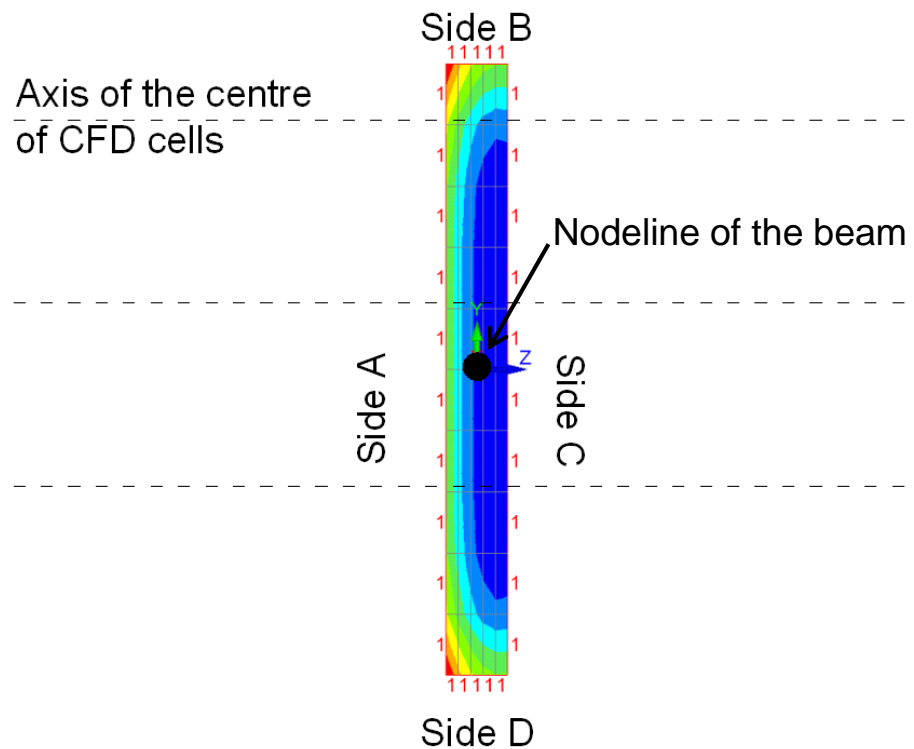


If the flux is a jet stream parallel to the ceiling, this assumption is on the safe side. Conversely, if the flux has predominant direction from bottom to top this assumption may not be safe anymore.



## WEAK COUPLING STRATEGY

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 grid where required by the fire.
3. He runs FDStoSAFIR that will write information in a transfer file according to a well defined and standardised format. These results describe the thermal environment in the compartment.

## 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 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 a subdomain of the fds domain chosen by the CFD specialist (we call it the transfer domain). The distance between points in the transfer domain is chosen by the CFD specialist; it may not coincide with the grid of the CFD domain (eg. 10 cm for the cells in the CFD analysis and 33 cm used in the 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.

- 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.



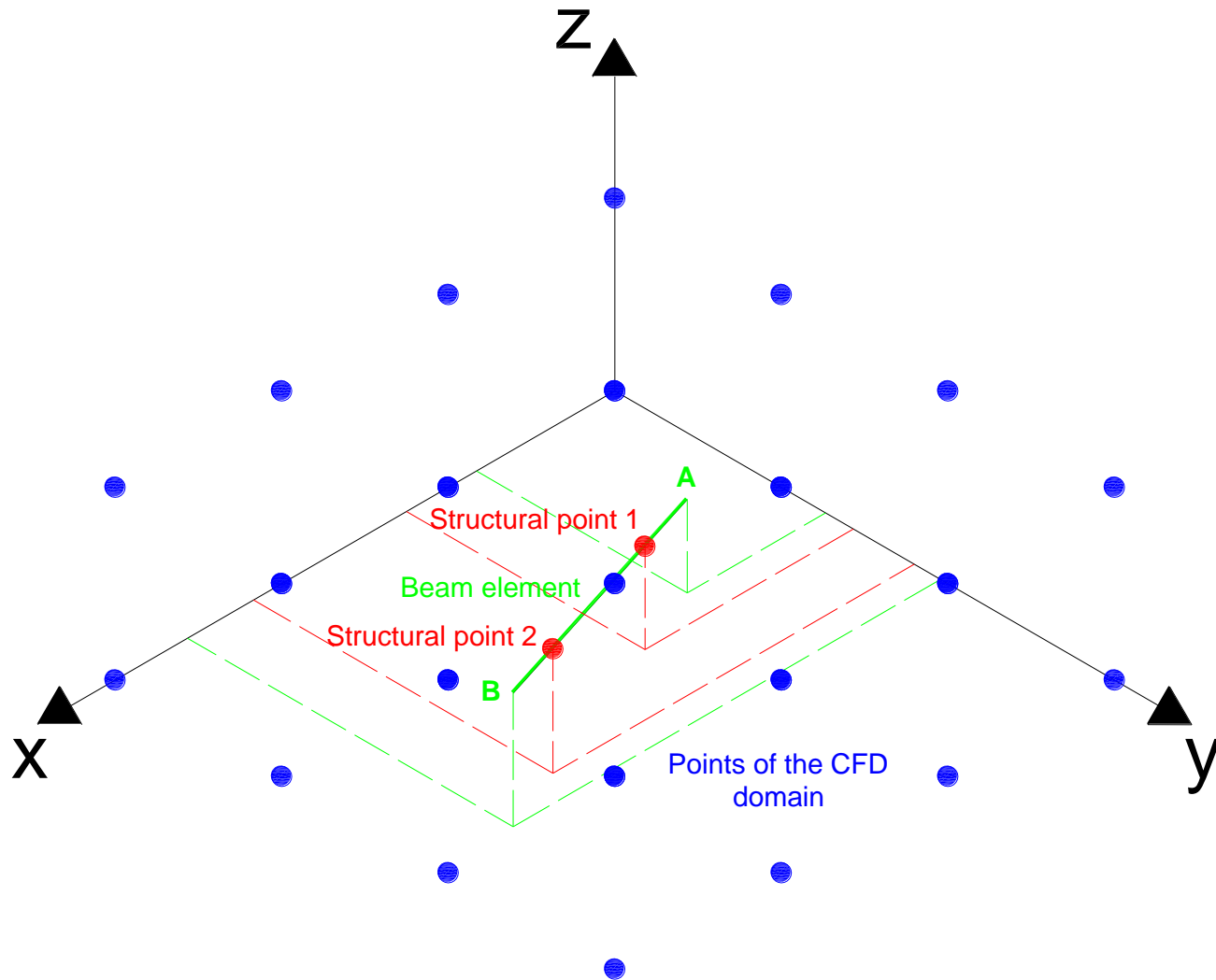
## INTERPOLATION

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.
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.

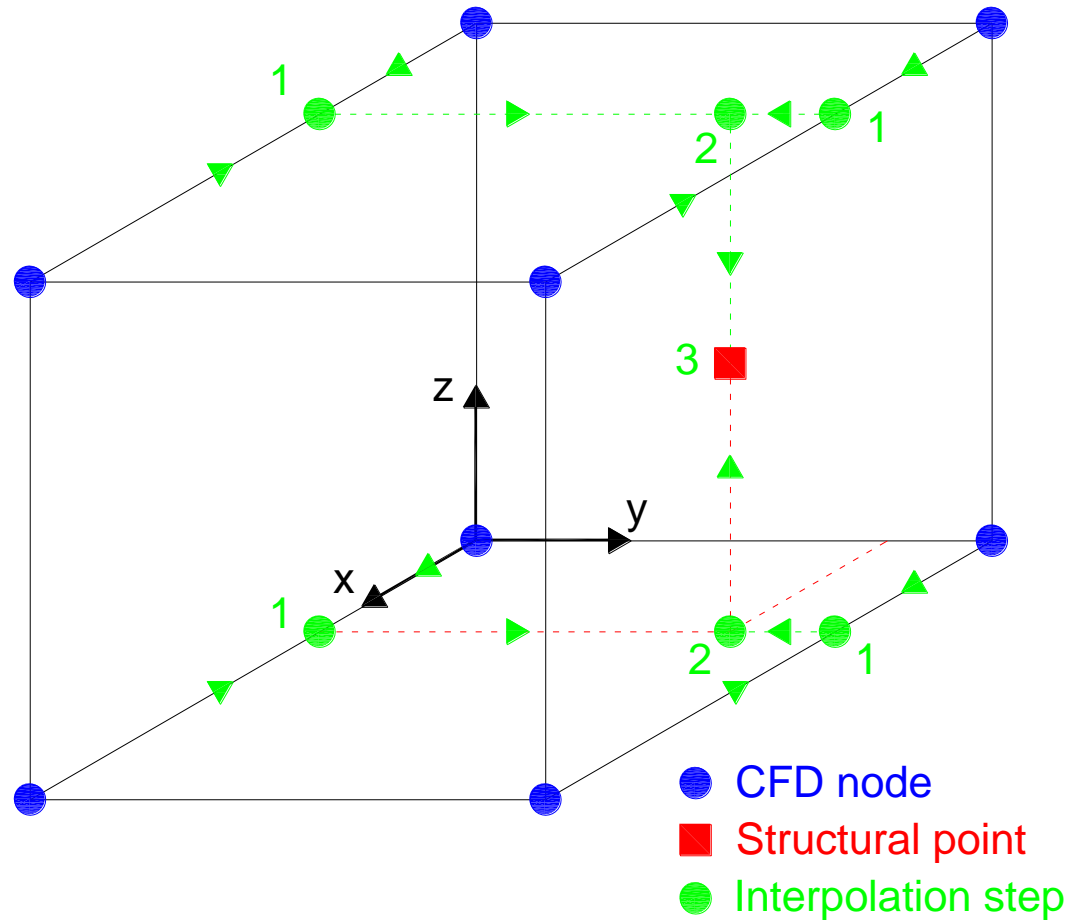
# INTERPOLATION

General representation of the scenario being analysed



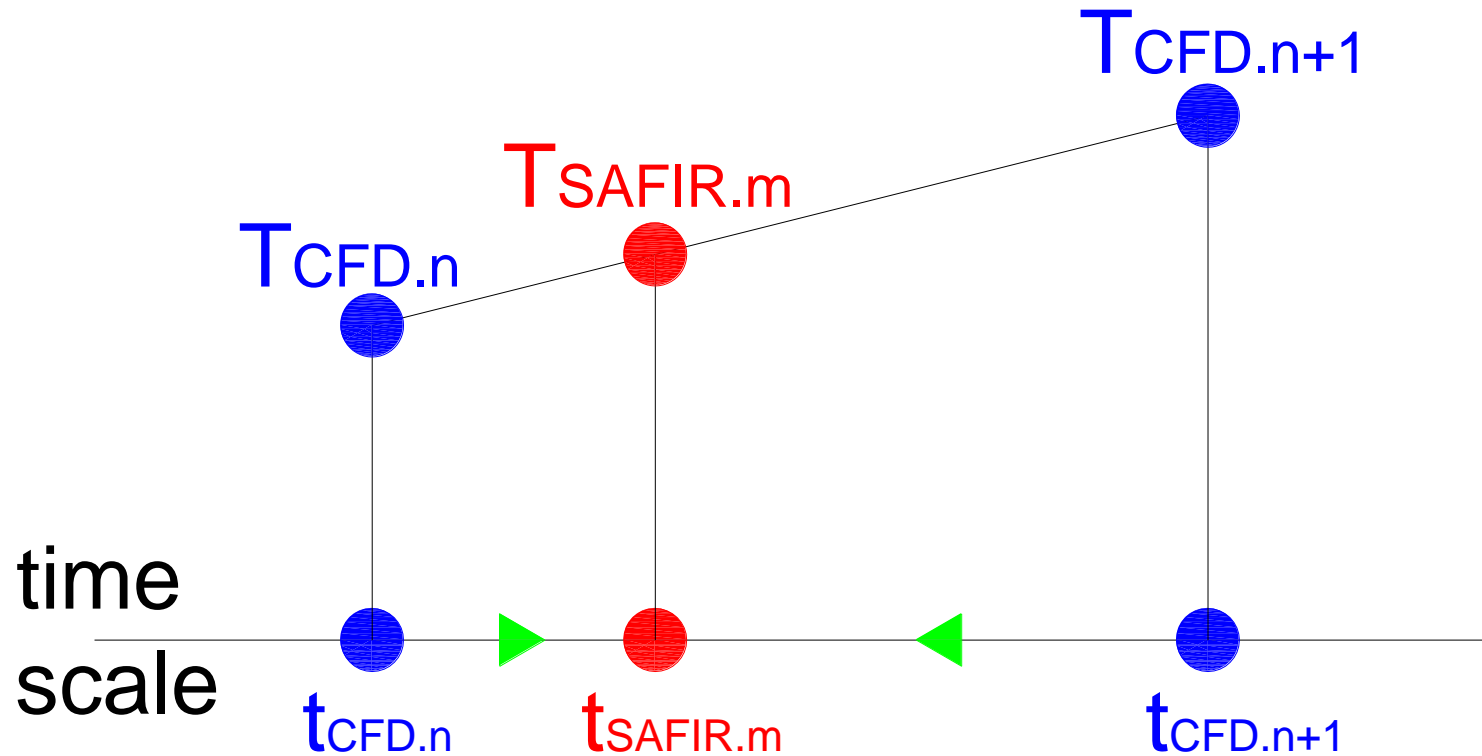
# CARTESIAN INTERPOLATION

A trilinear interpolation has been implemented



# TIME INTERPOLATION

A linear interpolation has been implemented



## 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).

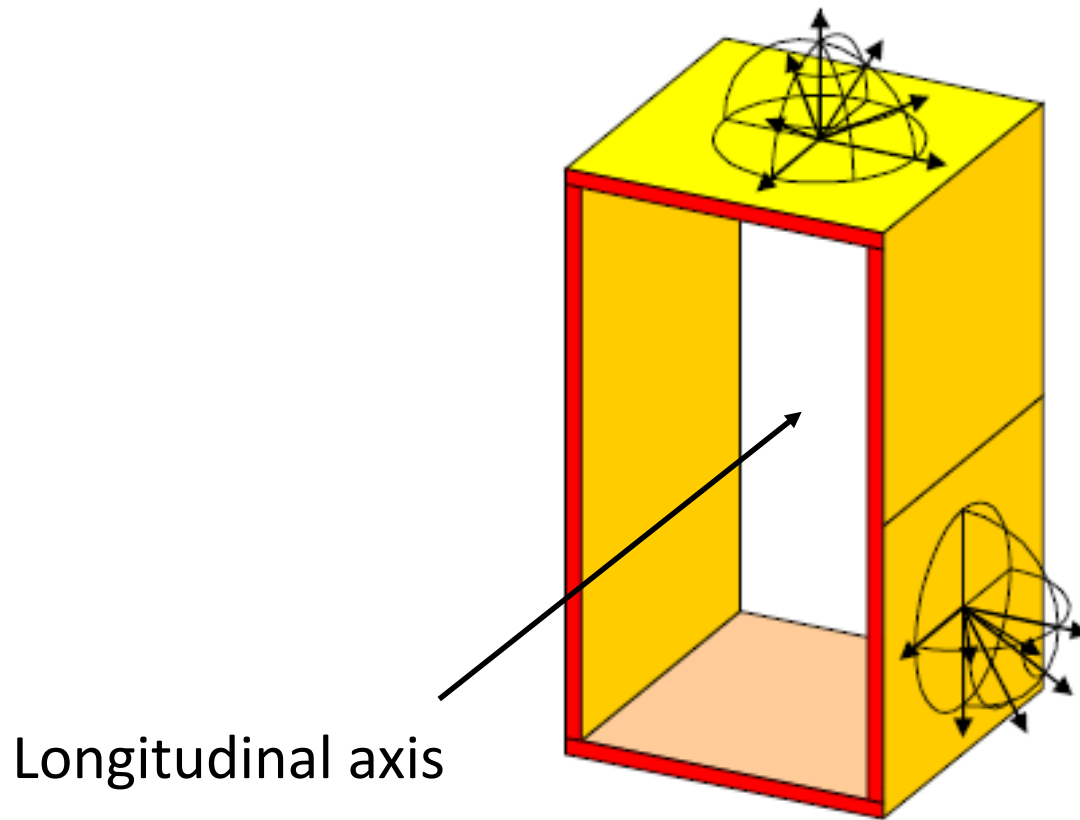
As a consequence, **rotations** of axes may be required to find the **surface system of coordinates** taking into account:

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

# SPHERICAL INTEGRATION

## CONVEX ELEMENT

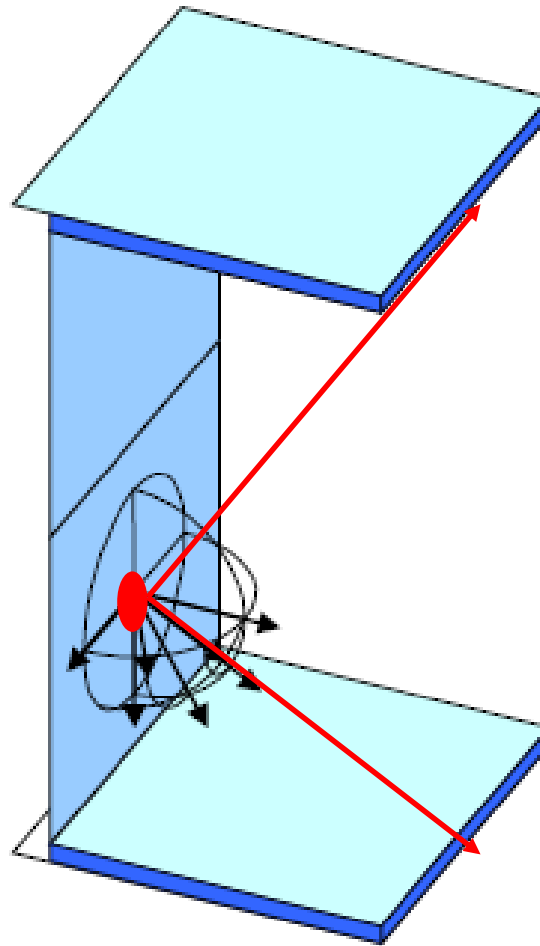
Integration on a complete hemisphere



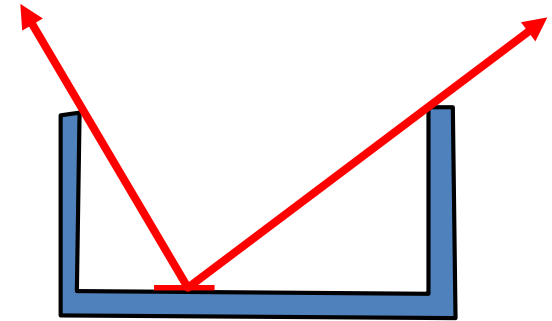
# SPHERICAL INTEGRATION

## CONCAVE ELEMENT

Integration on “clear sky”



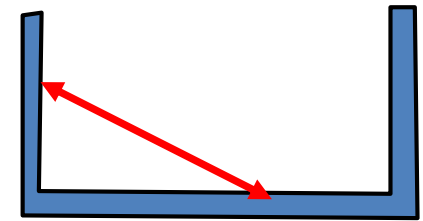
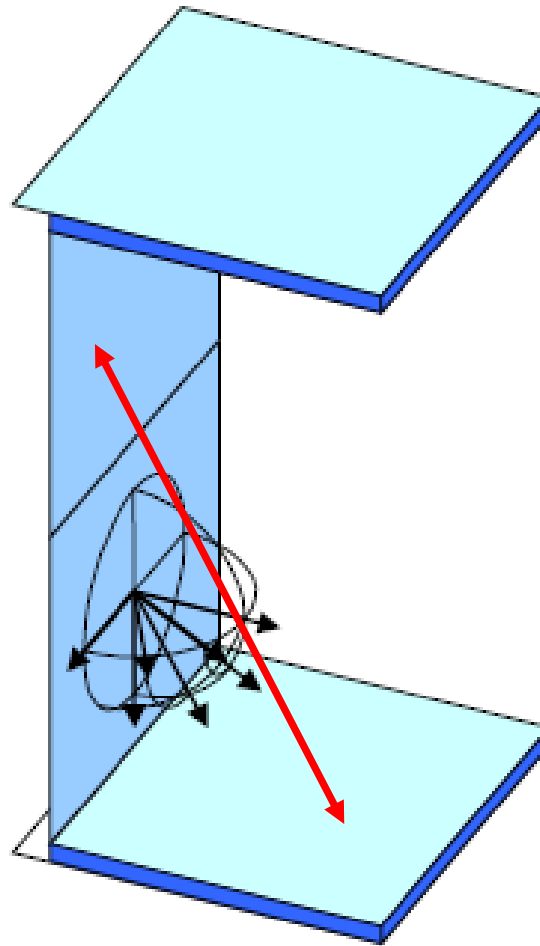
View angle



# SPHERICAL INTEGRATION

## CONCAVE ELEMENT

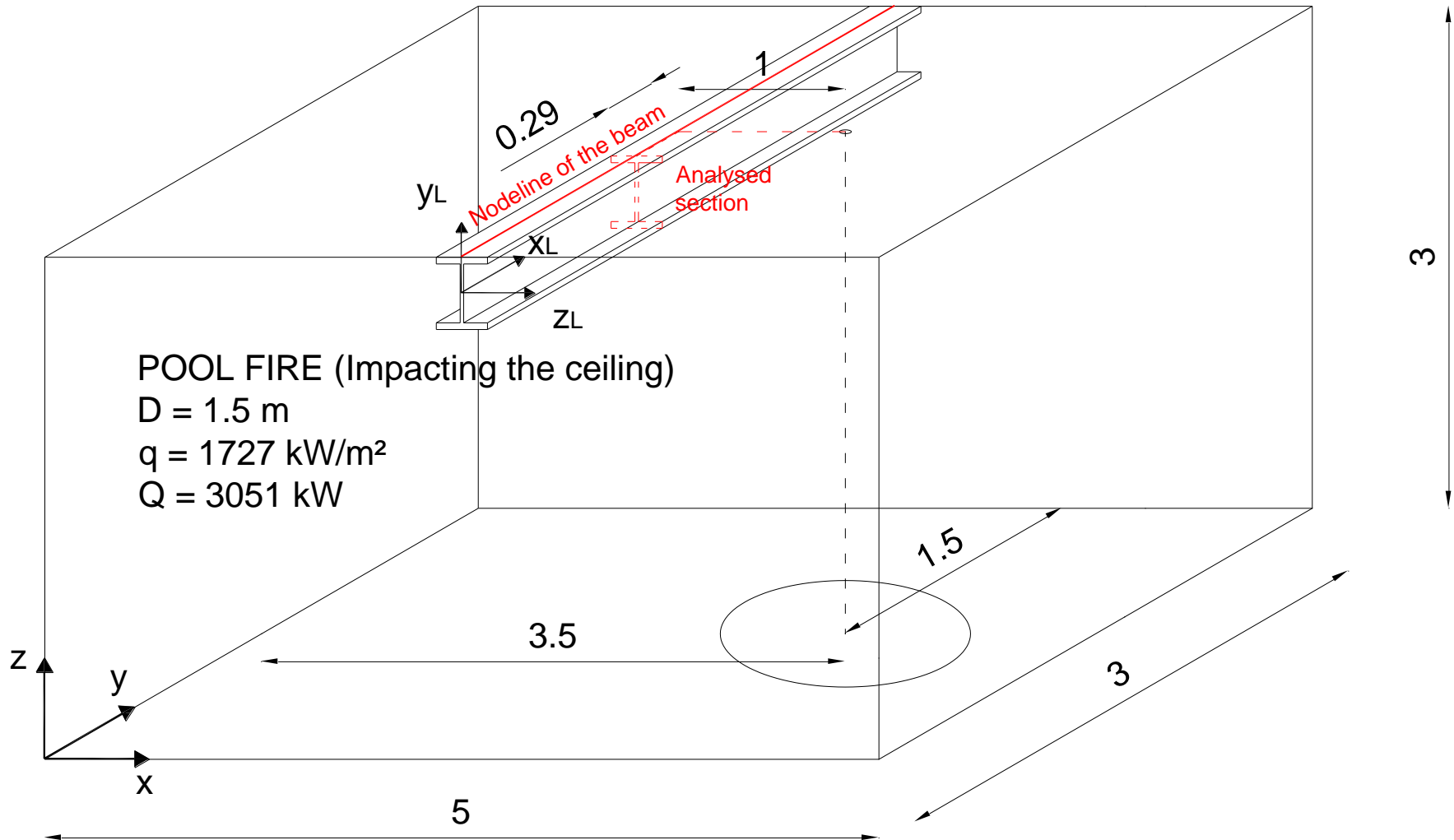
Note: radiation between boundaries of the section is not considered.





# EXAMPLES: Compartment pool fire (FDS vs. HASEMI)

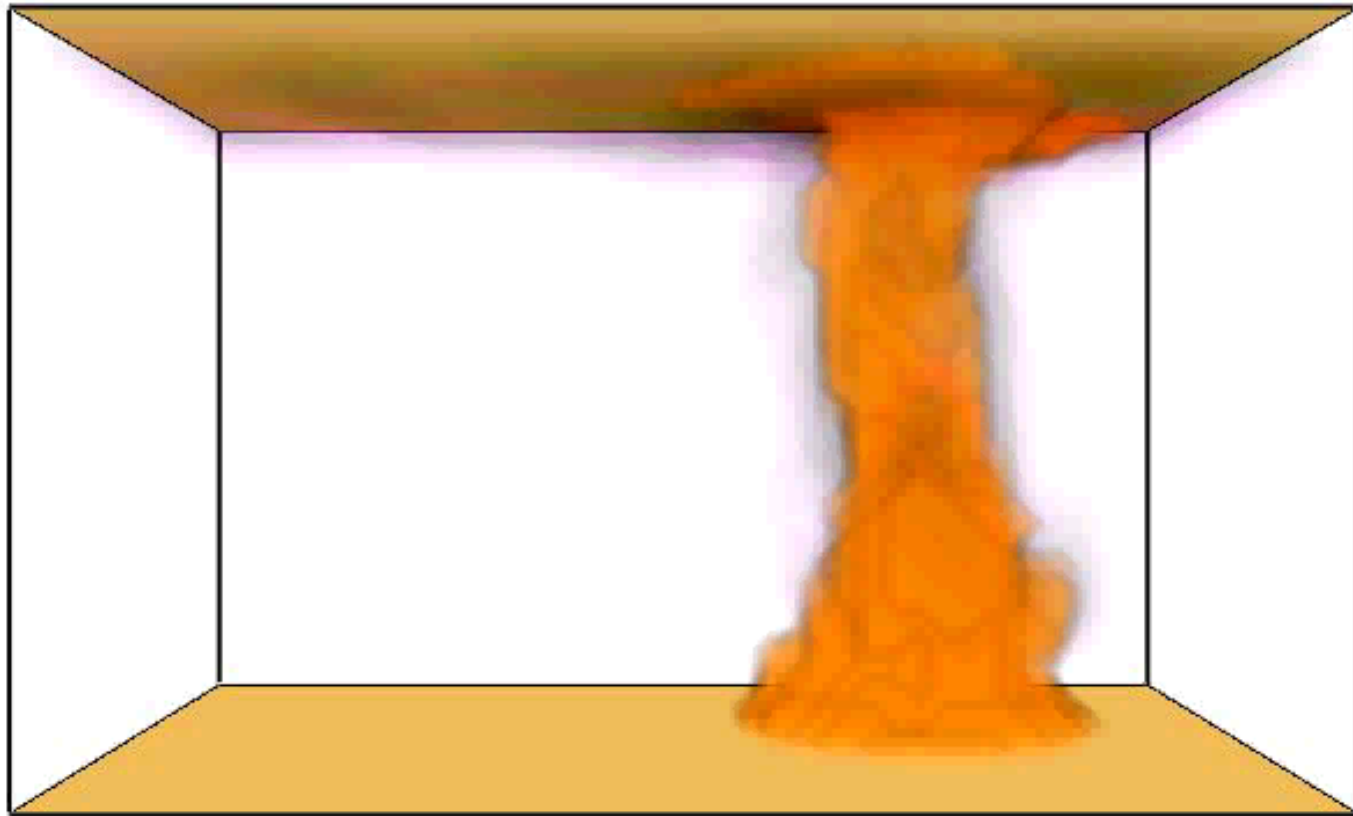
## GEOMETRY



# EXAMPLES: Compartment pool fire (FDS vs. HASEMI)

## SIMULATION IN FDS

Smokeview 5.6 – Oct 29 2010



Frame: 500

Time: 31.90

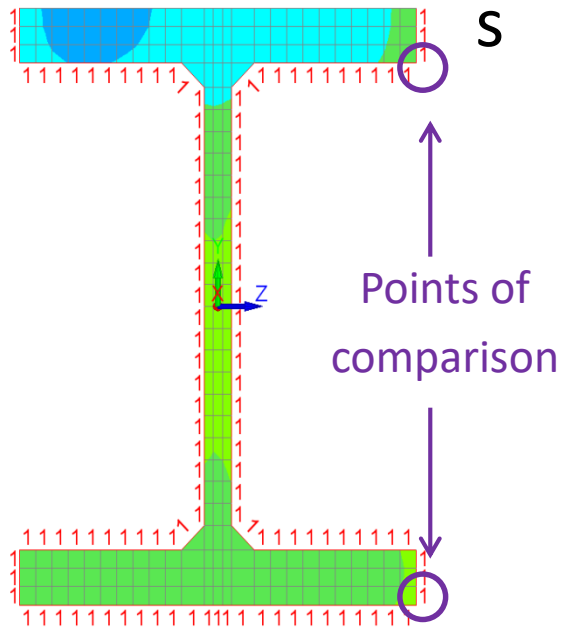


■ >200 (kW/m<sup>3</sup>)

# EXAMPLES: Compartment pool fire (FDS vs. HASEMI)

## RESULTS

FDS – SAFIR @  $t = 3600$

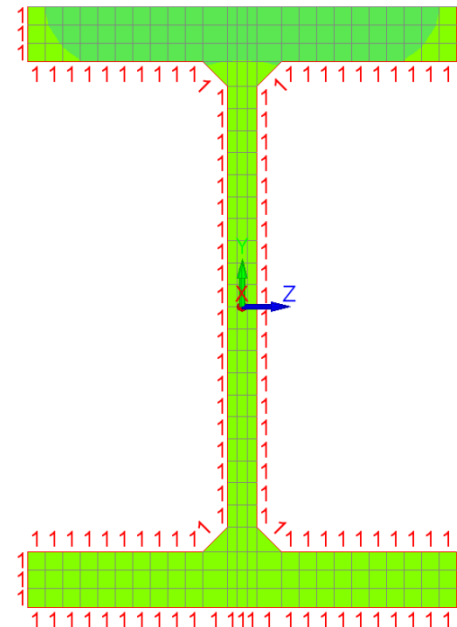


FILE: HE400MS\_CFD\_AdbSym  
NODES: 292  
ELEMENTS: 220

SOLIDS PLOT  
FRONTIERS PLOT  
TEMPERATURE PLOT

TIME: 3600 sec  
>Tmax  
800.00  
737.50  
675.00  
612.50  
550.00  
487.50  
425.00  
362.50  
300.00  
<Tmin

HASEMI @  $t = 3600$  s



FILE: HE400MS\_HSM  
NODES: 292  
ELEMENTS: 220

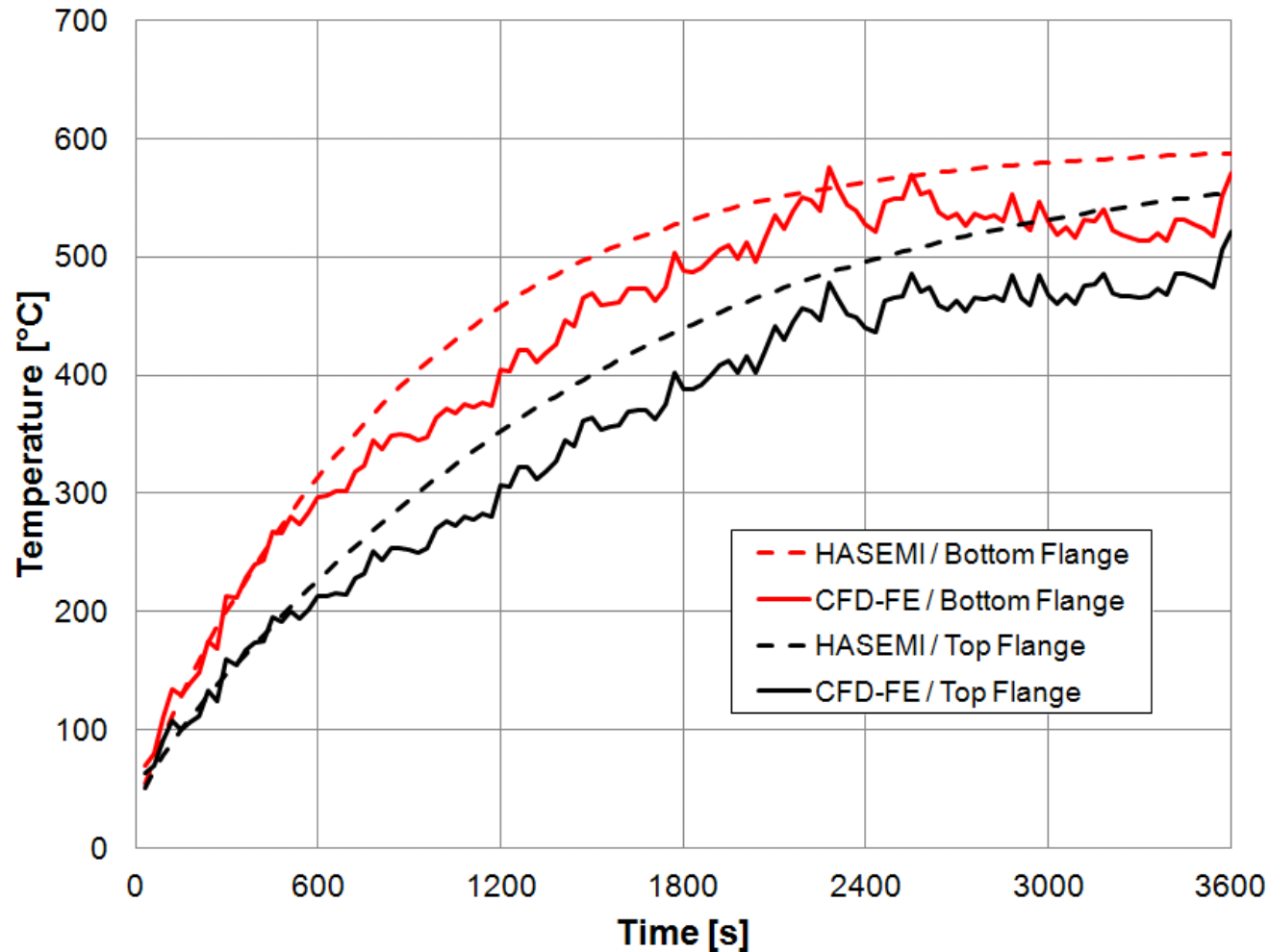
SOLIDS PLOT  
FRONTIERS PLOT  
TEMPERATURE PLOT

TIME: 3600 sec  
>Tmax  
800.00  
737.50  
675.00  
612.50  
550.00  
487.50  
425.00  
362.50  
300.00  
<Tmin

Adiabatic conditions at the top upper flange

## RESULTS

### Comparison in terms of temperature



### 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.

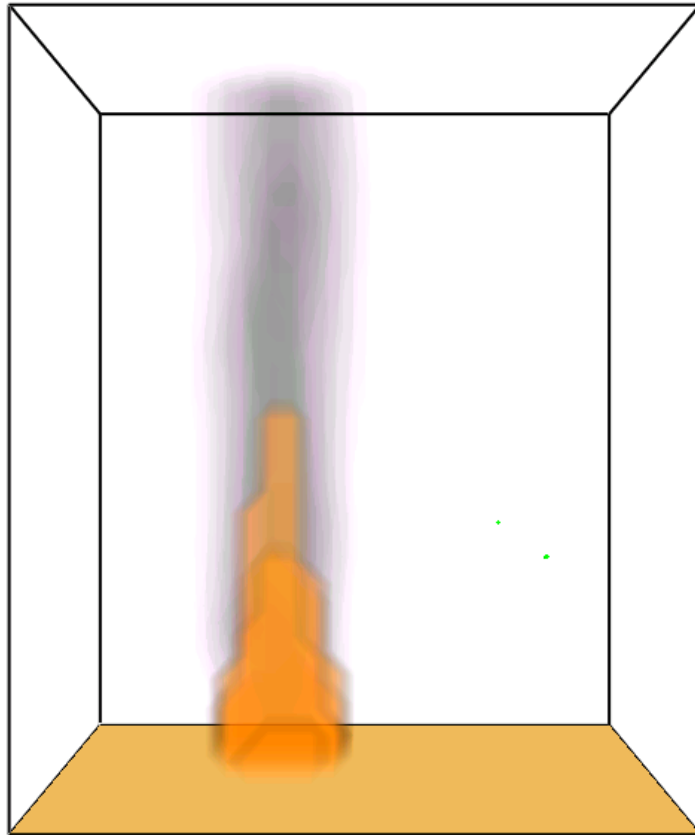
For this purpose, pool fire tests were performed and in order to measure temperatures at different heights, an instrumentation set-up was designed.

# LOCAFI Project



## LOCAFI Project

110



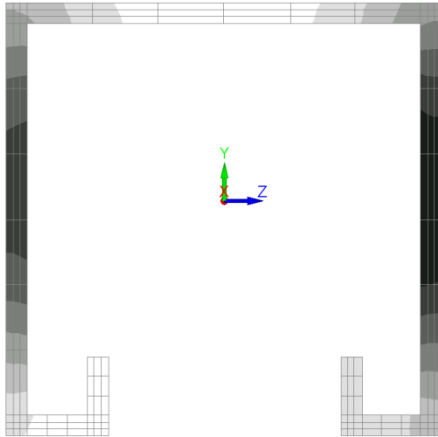
>103 (kW/m<sup>3</sup>)



# EXAMPLES: Rack analysis

## LOCAFI Project

## Results of thermal analysis



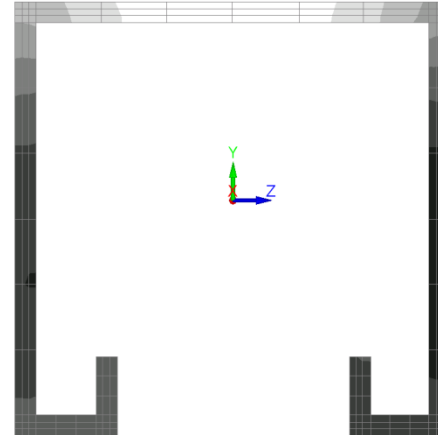
Section A

Diamond 2011.a.2 for SAFIR

FILE: Beam  
NODES: 196  
ELEMENTS: 144

**SOLIDS PLOT**  
**TEMPERATURE PLOT**

TIME: 1200 sec  
255.80  
253.94  
252.08  
250.21  
248.35  
246.49  
244.63  
242.76  
240.90



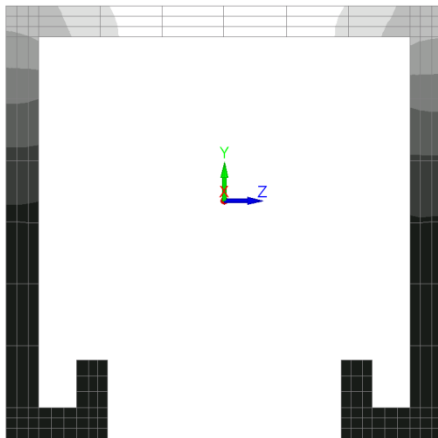
Section B

Diamond 2011.a.2 for SAFIR

FILE: Beam  
NODES: 196  
ELEMENTS: 144

**SOLIDS PLOT**  
**TEMPERATURE PLOT**

TIME: 1200 sec  
185.20  
182.54  
179.88  
177.21  
174.55  
171.89  
169.23  
166.56  
163.90



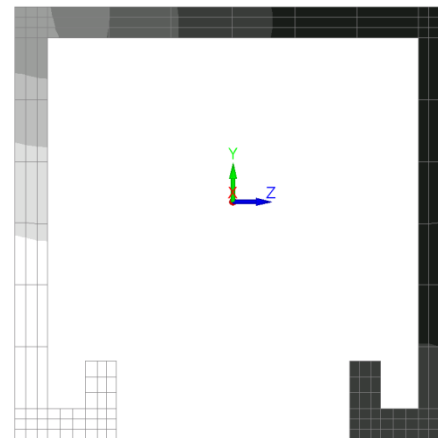
Section C

Diamond 2011.a.2 for SAFIR

FILE: Column  
NODES: 196  
ELEMENTS: 144

**SOLIDS PLOT**  
**TEMPERATURE PLOT**

TIME: 1200 sec  
159.20  
156.46  
153.73  
150.99  
148.25  
145.51  
142.78  
140.04  
137.30



Section D

Diamond 2011.a.2 for SAFIR

FILE: Obi2  
NODES: 196  
ELEMENTS: 144

**SOLIDS PLOT**  
**TEMPERATURE PLOT**

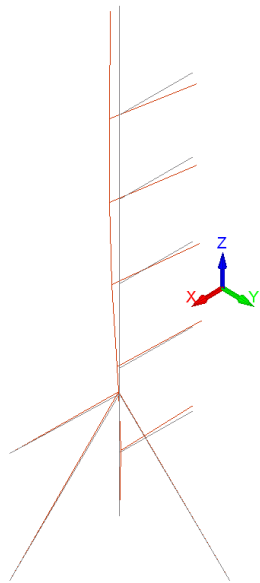
TIME: 1200 sec  
129.30  
123.79  
118.28  
112.76  
107.25  
101.74  
96.23  
90.71  
85.20



# EXAMPLES: Rack analysis

## LOCAFI Project

### Results of mechanical analysis



5.0 E-02 m

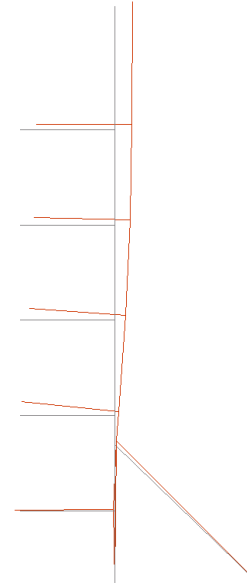
Diamond 2011.a.2 for SAFIR

FILE: StructObl\_OK  
NODES: 36  
BEAMS: 15  
TRUSSES: 0  
SHELLS: 0  
SOILS: 0

**BEAMS PLOT**  
**DISPLACEMENT PLOT ( x 20)**

TIME: 1200 sec

■ Beam Element



5.0 E-02 m

Diamond 2011.a.2 for SAFIR

FILE: StructObl\_OK  
NODES: 36  
BEAMS: 15  
TRUSSES: 0  
SHELLS: 0  
SOILS: 0

**BEAMS PLOT**  
**DISPLACEMENT PLOT ( x 20)**

TIME: 1200 sec

■ Beam Element

Displacements amplified by a factor of 20

## Recent developments

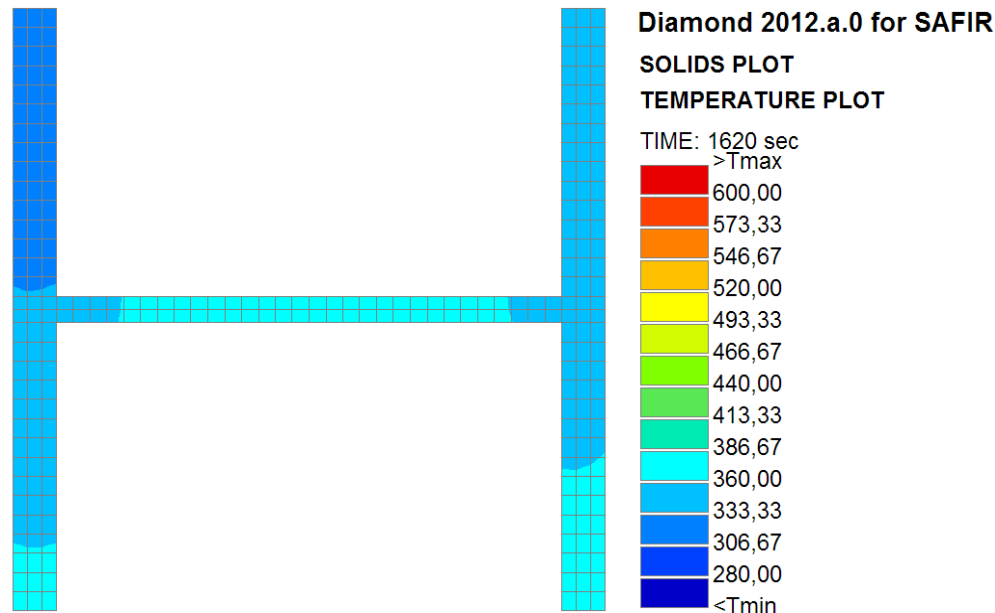
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- 1) Compilation of FDS 6 with modified sources including interface lines has been done (original development was made with FDS 5),
- 2) All available threads of the computer are used by OpenMP. Not yet possible to run FDS6-SAFIR on a cluster of computers (MPI).
- 3) If the transfer file is larger than 4 Gb SAFIR cannot read the data. This is less crucial as the information can now be written in the transfer file at only some points of the CFD grid (dxSAFIR command in the fds input file)

# OPEN ISSUES

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- 1) 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 in OpenMP is under way and should improve the situation



# OPEN ISSUES

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EXAMPLE: Open car park, run in 2017,

- Intel Xeon E5440 2.83 GHz 2 processors and 4 cores each, 16 Gb RAM
- Analysis duration = 74 min
- SAFIR thermal analysis (77 h) & mechanical analysis (1h)

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		TEMPERAT	
TETA	0.9	TETA	0.9
TINITIAL	20.0	TINITIAL	20.0
MAKE.TEMCD		MAKE.TSHCD	
Compartment.in		Compartment.in	
BEAM_TYPE 1		SHELL_TYPE 2	
NMAT 2		NMAT 1	
ELEMENTS		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 a special version of the executable of FDS: FDS6-SAFIR.EXE

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 file with the following line

&FDStoSAFIR STATUS=.TRUE.,T\_BEGIN=0., T\_END=300. ,DT=30.,

XB = 10, 15, 0., 2., 0., 5. dxSAFIR = 1., 0.5, 0.5 /