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Structural fire design approaches of sprinklered steel buildings using computational modelling

Teräsrakentamisen T&K-päivät 2023
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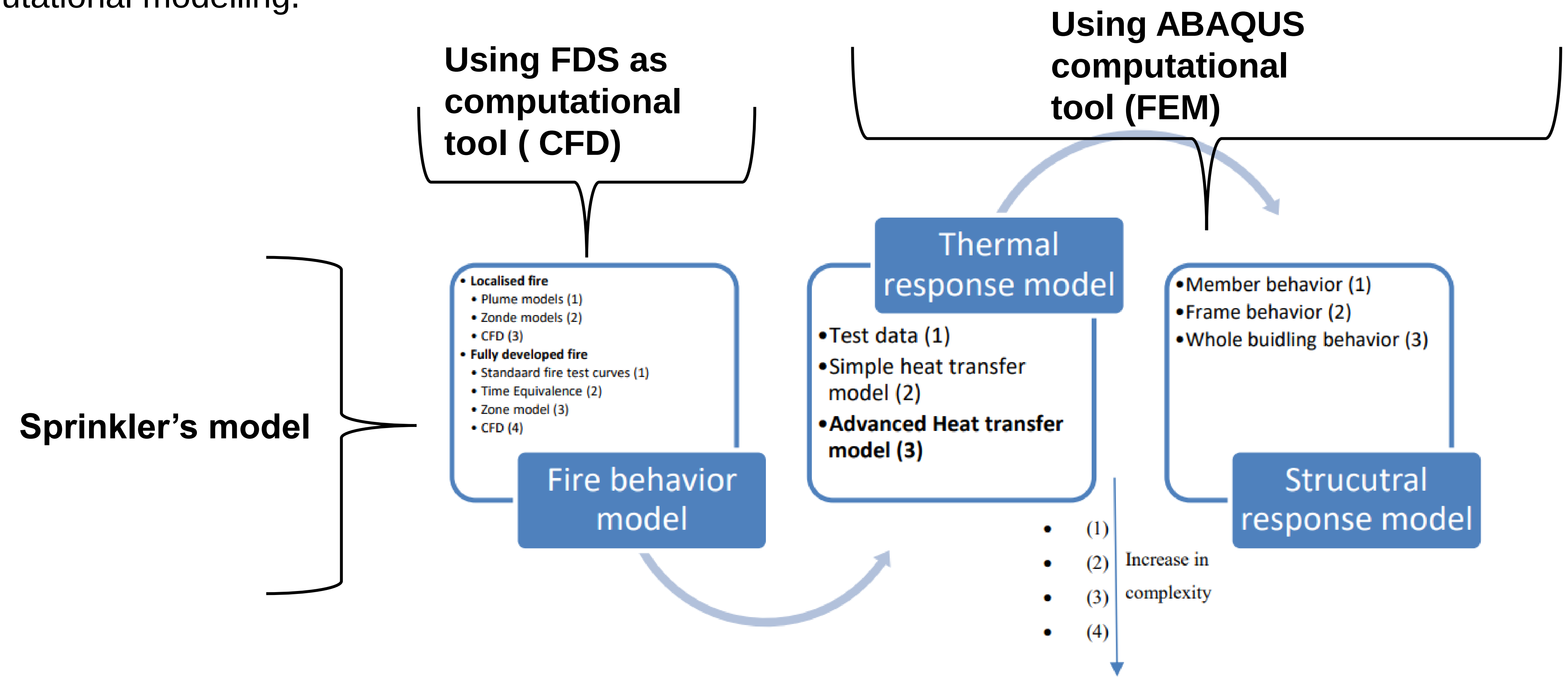
Häme University of Applied Sciences

Agenda

- Overview of structural fire design approaches using computational modelling
- Fire dynamics modelling technique
- Thermal response modelling technique
- Structural response modeling technique
- Simulation examples of fire dynamics, thermal response and structural response model from RIFS project

Structural fire design approaches

- Design process to determine the performance of the structure exposed to fire using computational modelling.



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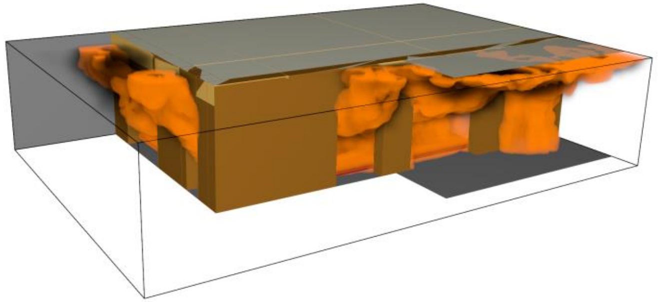
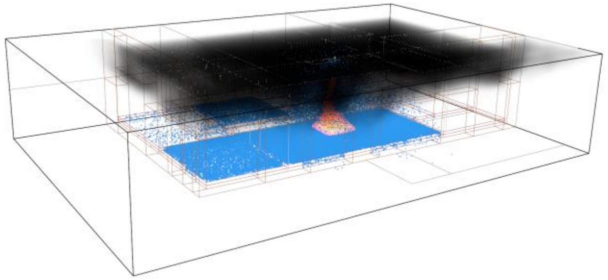


Fire dynamcis model



- Sprinkler’s model
  - Estimation of sprinkler’s model parameters for FDS input
- Modelling of fire
  - Defining ignition source and heat release rate
  - Defining ignition temperature, heat release rate (HRRPUA) for combustible obstructions (objects)
- Modelling of other structure in fire dynamics model
  - Defining thermal material properties of obstruction
  - Defining relevant output request (thermocouple devices, 2D slice for temperature and similar)

↓

Output: time-temperature curve

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Thermal and structural analysis

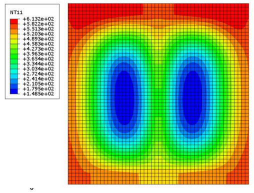
Heat transfer procedure

Input: time-temperature curve from fire behavior model

Preprocessing
- **Input time-temperature curve from fire behavior model.**
- **Abaqus/CAE or input file for modelling the 2D cross-section**
- **Convectiona and radiation boudnary condition with reference fire temperture curve**
- Third-party preprocessor (eg hypermesh)

Analysis
- **Abaqus /Standard**
- Abaqus/Explicit can be used somtime
- **Transient heat transfer analysis using Abaqus/Standard for 2D temperature analysis**

Postprocessing
- Visualization an post procesing of results using Abaqus/CAE
- Third-party postprocessor(eg hypermesh)
- **Obtained nodal temperature for structural analysis**



(a) frame column cross section

Output: temperature histories in member

Temperature mapping

Structural analysis procedure

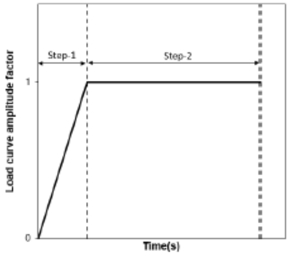
Input: temperature histories in member

Preprocessing
- **Abaqus/CAE or input file for modelling the geometry**
- **Mapping fire tempeature histories in beam temperature points and nodes of shell elements**
- Third-party preprocessor (eg hypermesh)

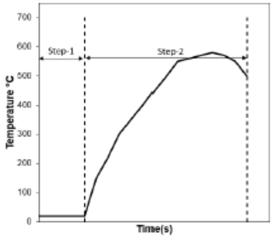
Analysis Step 1
- **Abaqus/Explicit**
- **Apply mechanical loading to the structure**

Analysis step 2
- **Apply heating due to fire**
- **Abaqus/Explicit**

Postprocessing
- Visualization an post procesing of results using Abaqus/CAE
- Third-party postprocessor(eg hypermesh)

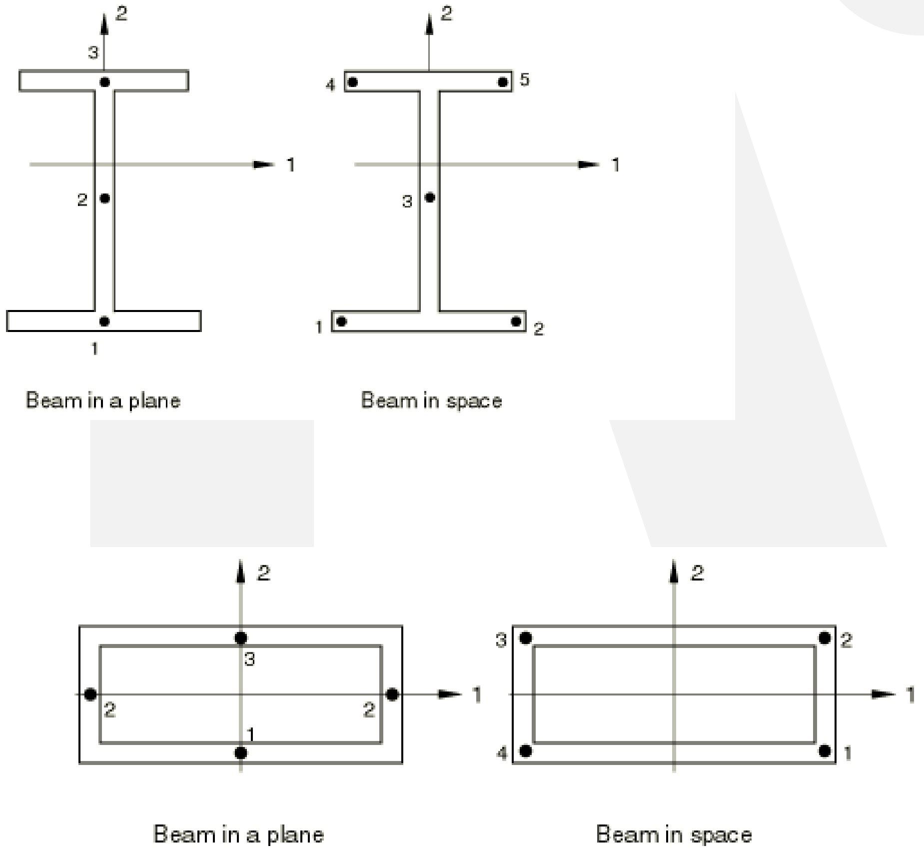


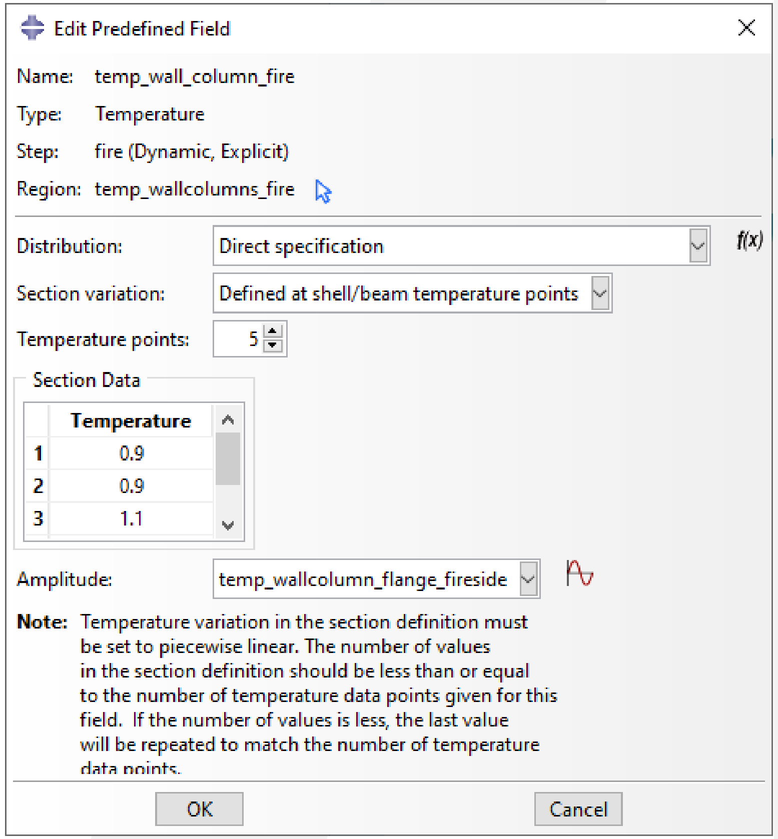
(a) load curve for mechanical loading



(b) curve for temperature loading due to fire

Temperature points for beam section: ABAQUS

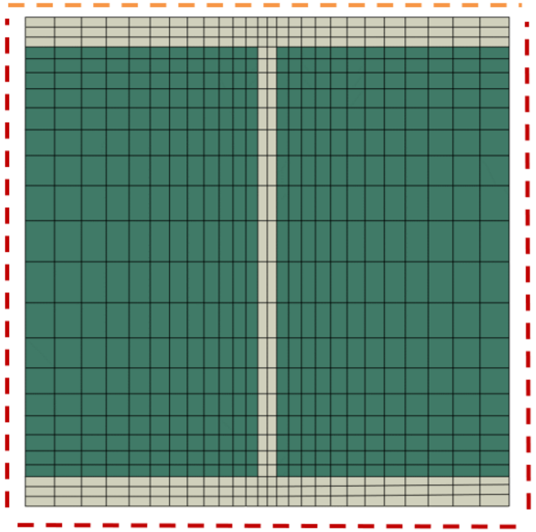




Thermal response analysis modelling technique

- Fire test: Concrete infilled steel column and topped steel beam
- Thermal analysis tecnique validation

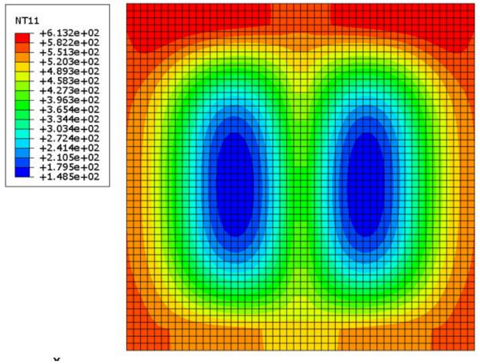
Cooke, G.M.E, Latham, D.J. (1987). The inherent fire resistance of a loaded steel framework. *Steel Construction Today*, 1, 49-58.



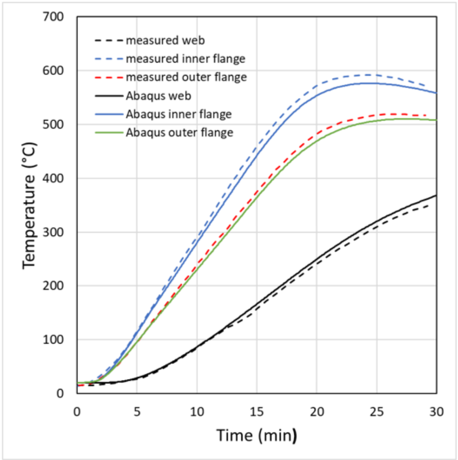
(a) simple frame column cross-section mesh

Unexposed surface side
Surface exposed to fire
$\varepsilon = 0.8, \ \alpha = 25$ W/mK

(a) FE model



(a) frame column cross section



(a) temperature histories in frame column cross-section

(b) Comparison of FE results and fire test

Structural response analysis modelling technique

- Fire test: Concrete infilled steel column and topped steel beam
- Structural analysis technique validation

Cooke, G.M.E, Latham, D.J. (1987). The inherent fire resistance of a loaded steel framework. *Steel Construction Today*, 1, 49-58.

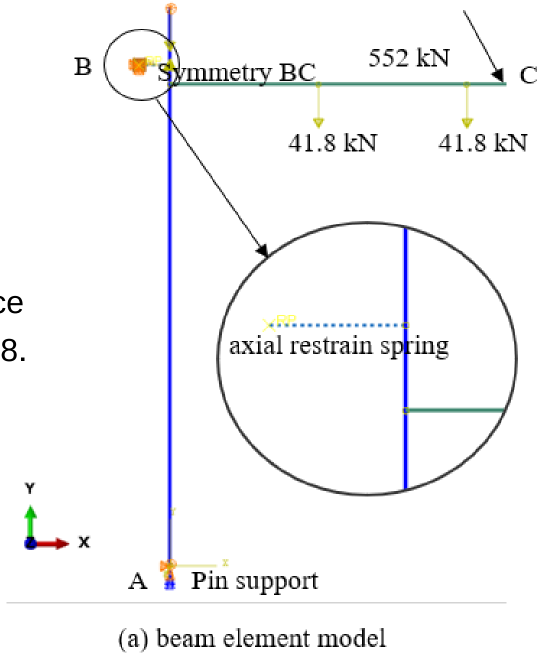


Figure 31 FE models for simple frame

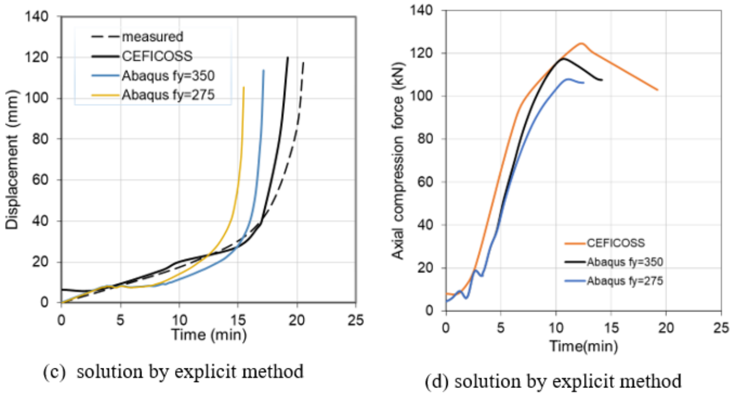


Figure 32 Mid-span vertical displacement and axial compression response of beam using the implicit and explicit solution of beam element model.

(a) FE model

(b) Comparison of FE results and fire test

Simulation examples of fire dynamics, thermal response and structural response model

- Examples from Risk-informed Fire Safety of sustainable sprinklered buildings using computational modeling (RIFS) project.
- Example structure 1: Lightweight Steel Framed (LSF-frame) residential building with sprinklers
- Example structure 2: Warehouse
- Fire scenarios: without sprinkler (case 1) and with sprinklers (case2)

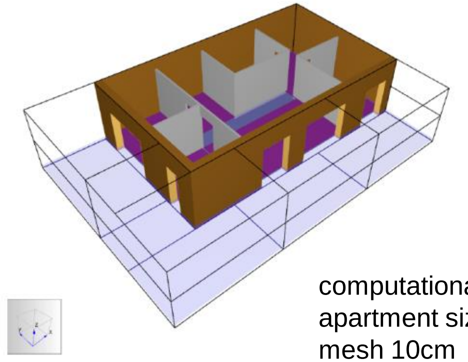
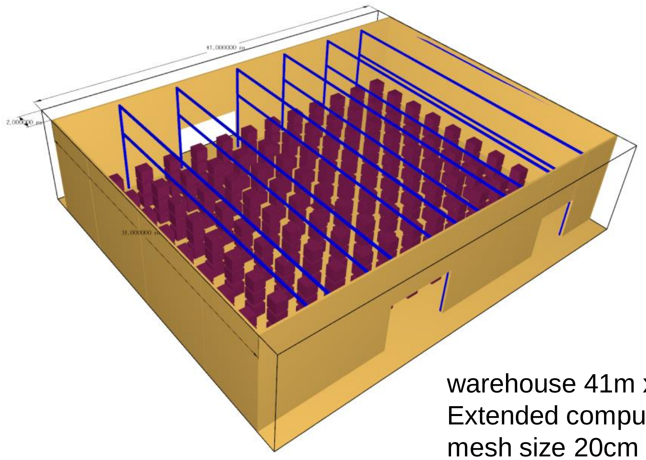


Figure 1 Overview of the 3-bedroom apartment.

computational domain 15m x 10m
apartment size 12m x 7m
mesh 10cm



warehouse 41m x 31m
Extended computational 41m x 35m
mesh size 20cm

Example strcuture 1: Lightweight Steel Framed (LSF-frame) residential building with sprinklers

- Sprinkler’s parameters estimation for FDS input
- Modeling of fire using heat release rate (HRR)
  - Defining ignition of fire starts in the middle of living room with heat release rate per unit area.
  - Modelling the combustible fuel on the struture using FDS default simple chemistry reaction model
- Fire dyanmics
- Thermal analysis of LSF wall panels
  - No sprinkler’s case
- Structural analysis of critical LSF wall panels
  - No sprinkler’s case

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Example strcuture 1: Location of sprinklers, thermocouples and devices placed in FDS model

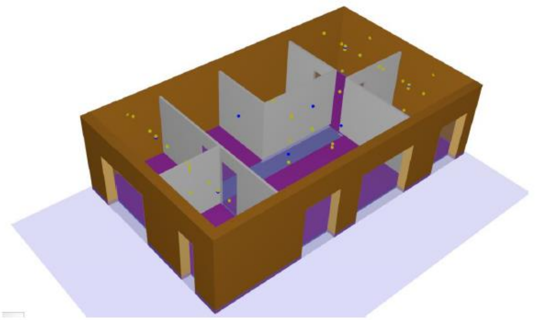


Figure 10 Location of sprinklers, thermocouples and devices placed in FDS model (bule dots represent the sprinklers, yellow dots represent the thermocouples).

Figure 12 Location of thermocouples below the ceiling

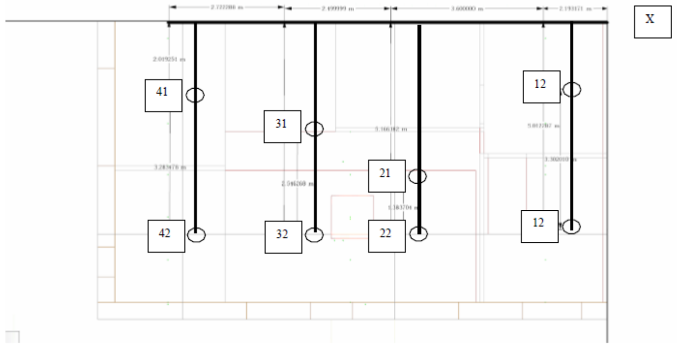


Figure 2 Configuration of the pipe array and the position of sprinklers within the apartment.

(a) Tyco resident sprinkler LF11 series

Picture: https://www.tyco-fire.com/products-and-solutions/sprinklers-nozzles-and-accessories/residential

Example strcuture 1 : Estimation of sprinkler model parameter for FDS

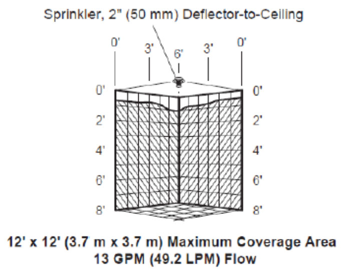


Figure 3 Wall wetting pattern for selected sprinkler LF11 K83.5 sprinkler (Serries LF11 johnsoncontrol.com, 2022)

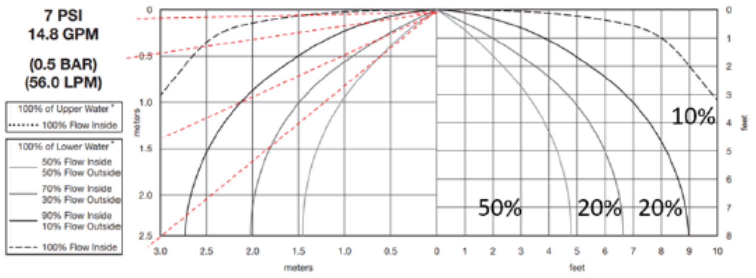
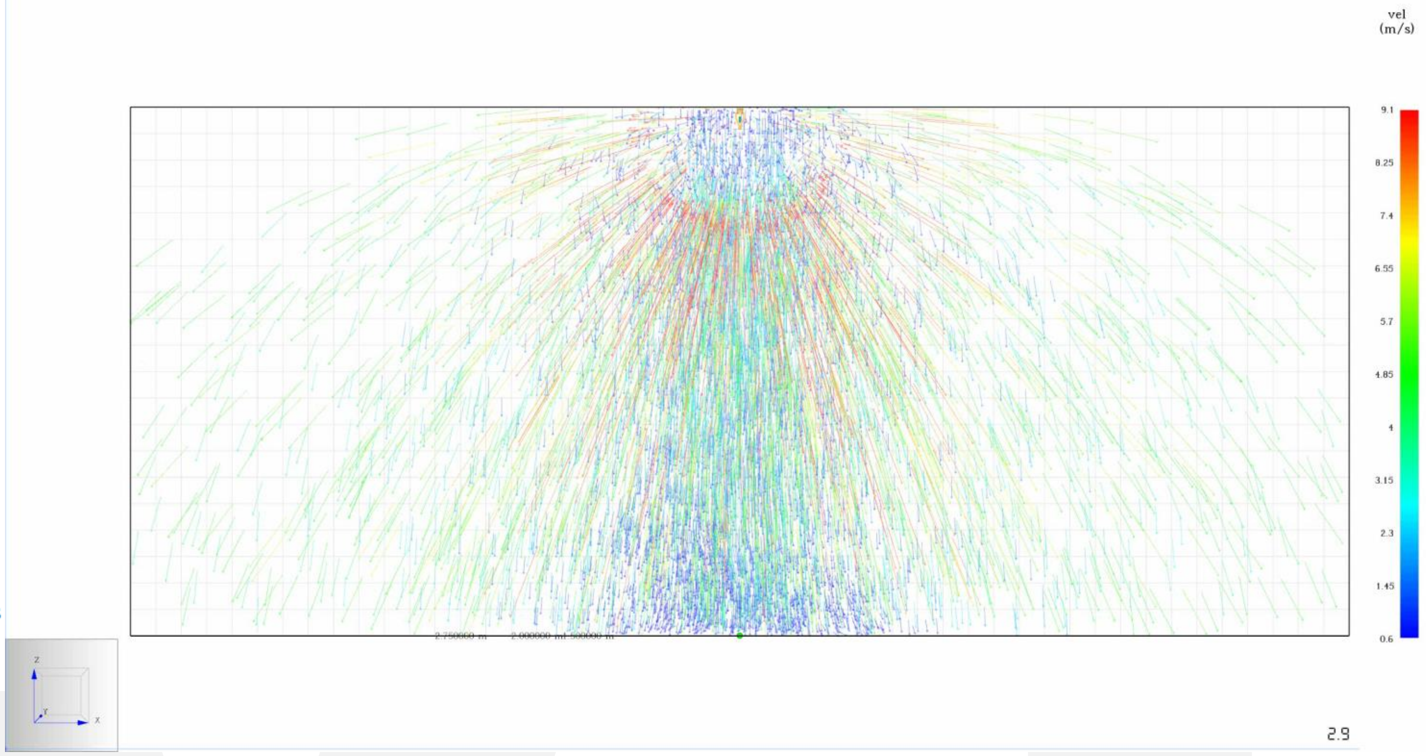


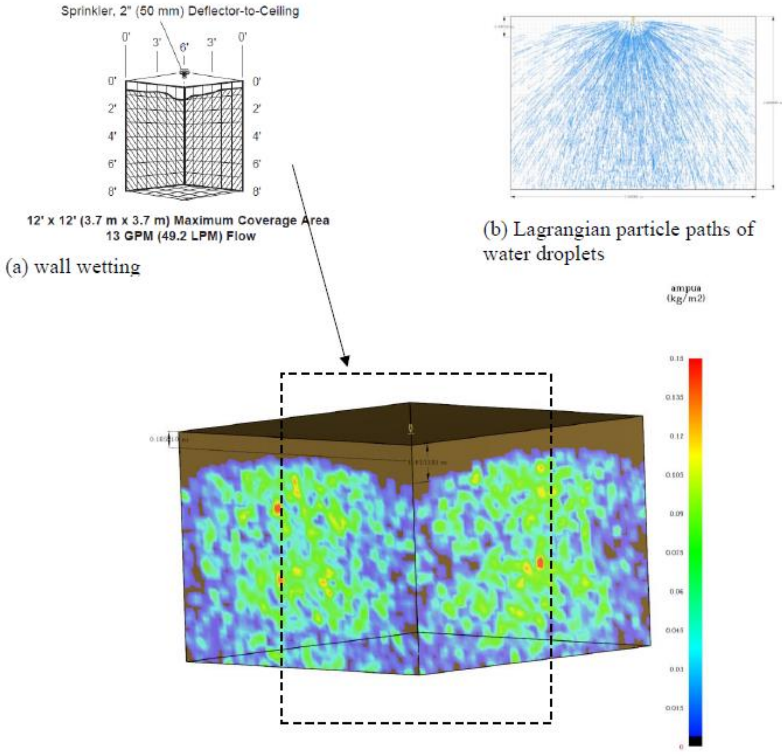
Figure 4 Assumed spray profile pattern for selected sprinkler LF11 K83.5 Serries johnsoncontrol.com, 2022)

Table 2 Input parameter for spray table based on Figure 4.

Flow fraction	Velocity (m/s)	Elevation angle 1 (°)	Elevation angle 2 (°)	Azimuth angle 1 (°)	Azimuth angle 2 (°)
0.5	10.5	0	51	0	360
0.2	10.5	51	63	0	360
0.2	10.5	62	81	0	360
0.1	10.5	81	89	0	360



Example strcuture 1: Estimation of sprinkler model parameter for FDS



(a) wall wetting

(b) Lagrangian particle paths of water droplets

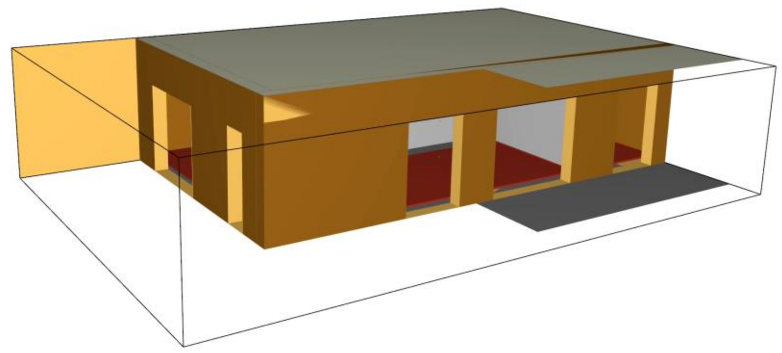
(c) AMPUA (Accumulated mass per unit area) in the wall wetting. The dotted box is the area shown equivalent figure (a).

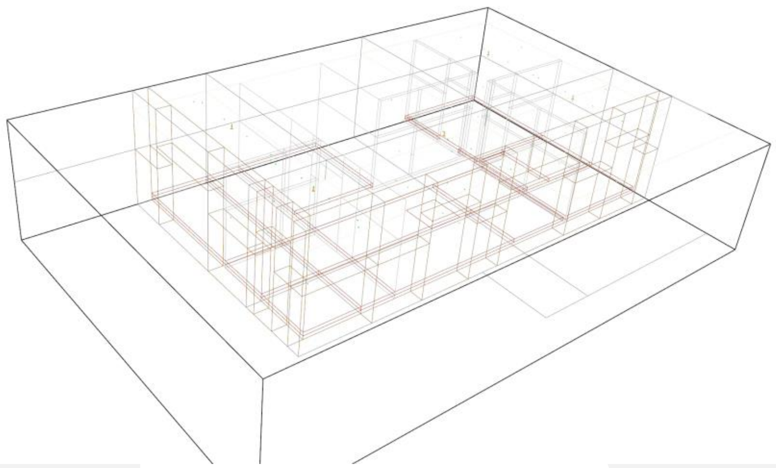
Figure 5 Wall wetting pattern from TYCO documents and FDS simulation when initial velocity v=10.5 m/s

Table 4 Summary of input parameters used in FDS to model sprinklers.

			Description/Comments
Activation	Temperature link	Residential link	
	Activation temperature	68°C	From manufacture document
	Response Time Index (RTI)	50 $(m/s)^{1/2}$	Fast response from Viking [1]
	C factor	0 $(m/s)^{1/2}$ (default)	
Spray model	Ejected particles	**Water particles**	
	Flow rate		
	Operating pressure	K-factor	
	0.52 bar	83.5 L/min.atm^1/2	From manufacture document
	Calculated flow rate	60 L/min	Calculated using equation $K\sqrt{p}$
	Jet Stream		
	Initial velocity	**4.33 m/s**	Calculated from equation 1 based on the minimum required operating pressure 0.52 bar
		10.5 m/s	calculated by dividing the volume flow by the orifice area
	Offset	Stream type	
	0.1 m	**Spray Table**	**Offset:** assumed based on cell size **Spray table:** According to Table 2
	Droplet per second	10000	Assumed, default in FDS is 5000
Water particles	Size distribution		
	Median diameter	1161 µm	Calculated from equation 2 and round up
	Distribution	Rosin-Rammler-lognormal	default
	Minimum diameter	20um	default
	Max diameter	Infinity	default
	Gamma D	2.4	default

Example strcuture 1: Case 1 and Case





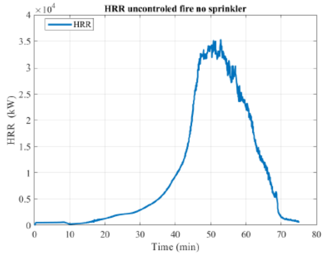
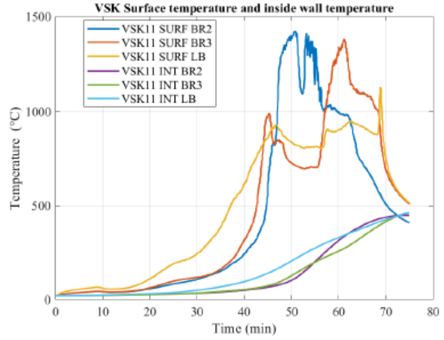
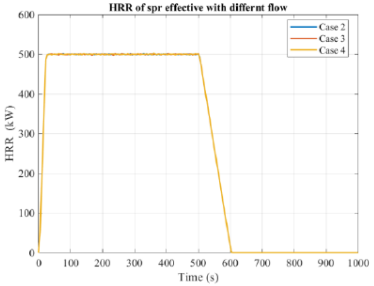


Figure 13 HRR of case 1 fire scenario.



(b) HRR and temperature without sprinkler



(a)

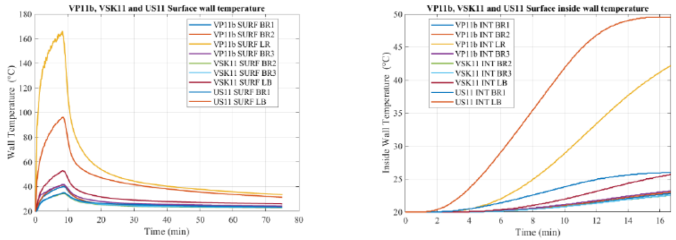


Figure 21 Comparison of surface and inner temperatures of ceiling VP11b, internal wall VSK and external wall US11 from Case 2 fire scenario.

(a) HRR and temperature with sprinkler

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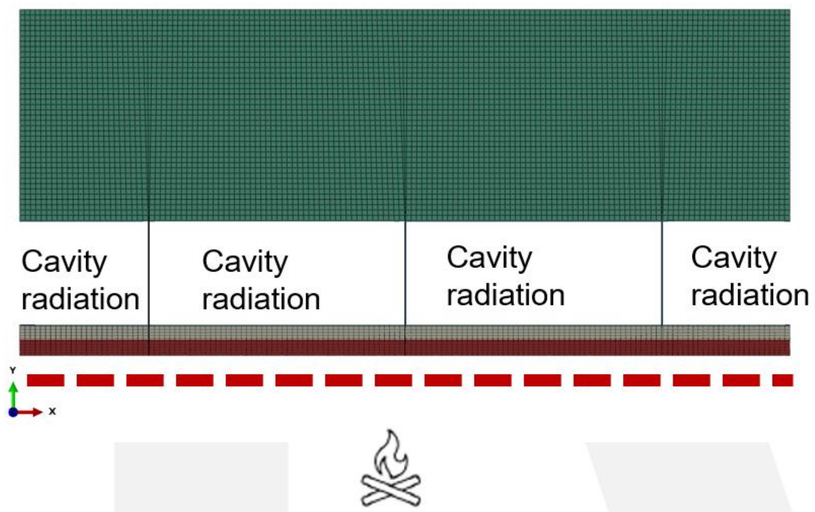
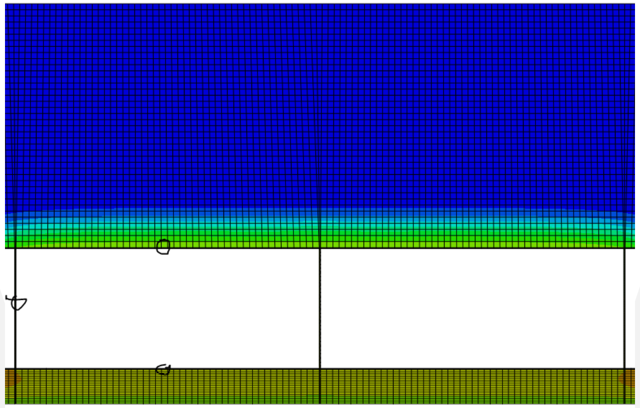
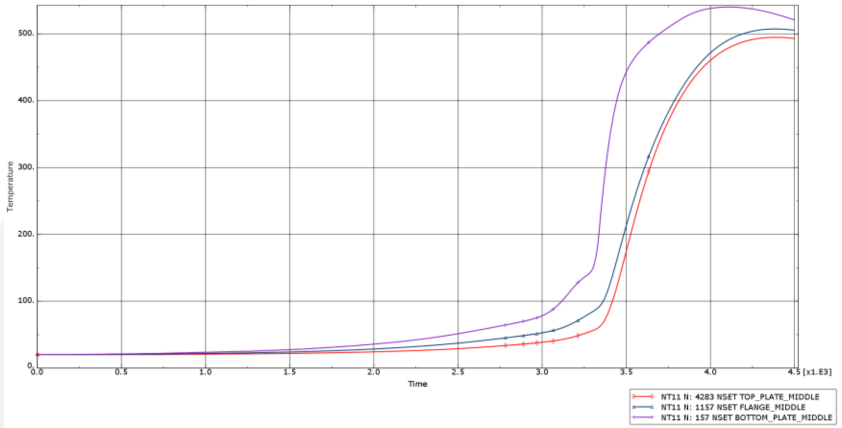
Example strcuture 1: Thermal response model

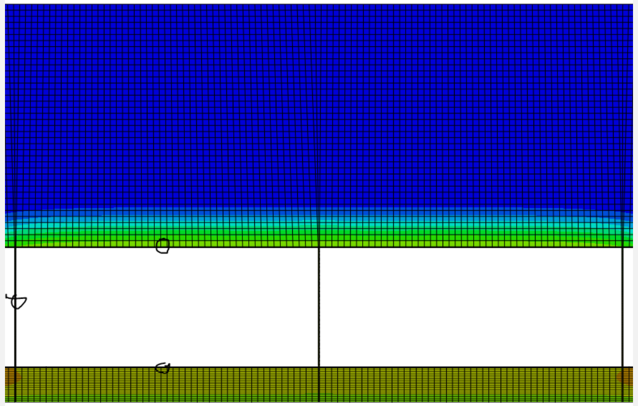


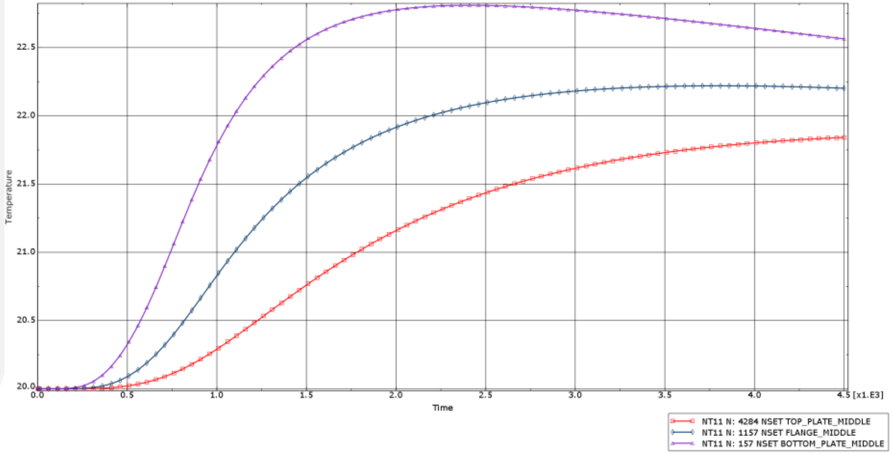
Case 1: No sprinkler’s



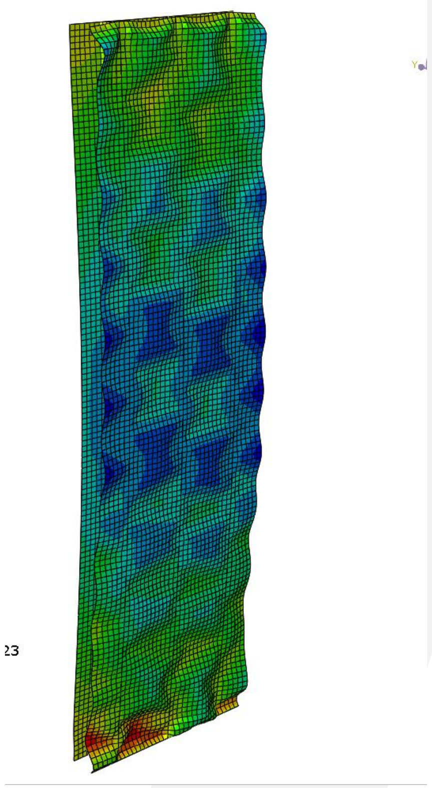


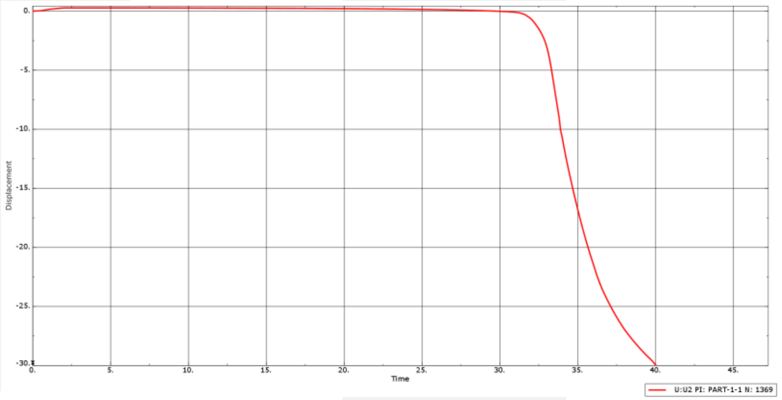
Case 1: Sprinkler present





Structural response of critcal LSF wall panels





Collapse time =
55 min

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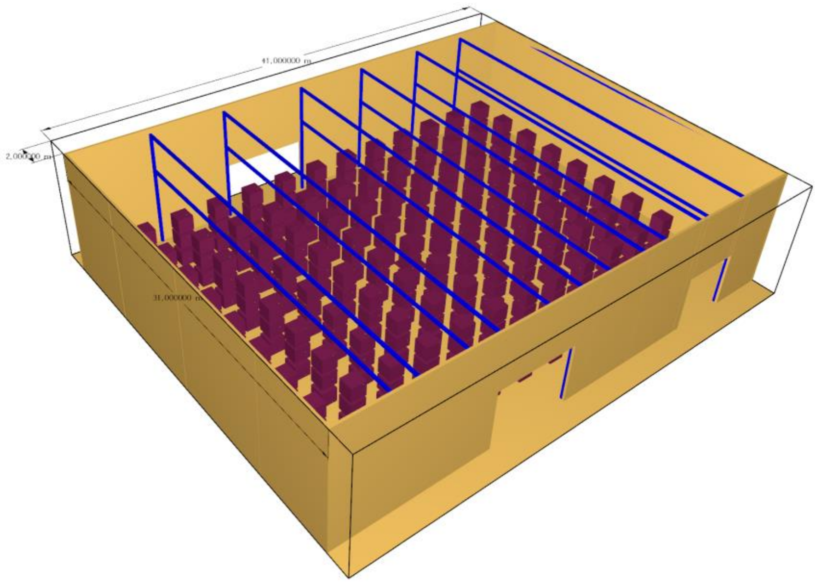
Example strcuture 2 : Warehouse



- Sprinkler’s parameters
- Modeling of fire
    - Defining ignition of fire starts in the middle of living room with heat release rate per unit area
    - Modelling the combustible fuel on the struture using FDS default simple chemistry reaction model. HRR of a typical wood pallet (SFPE Handbook 2016).
- Fire dyanmics
- Thermal analysis member (2D thermal analysis)
- Structural analysis of wareouse as tubular frame solutions

Fig. 26.72 The geometric arrangement of a stack of wood pallets

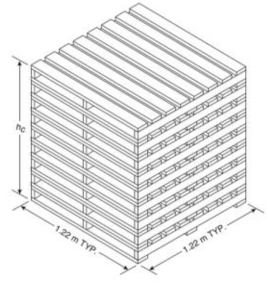
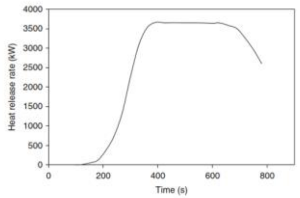


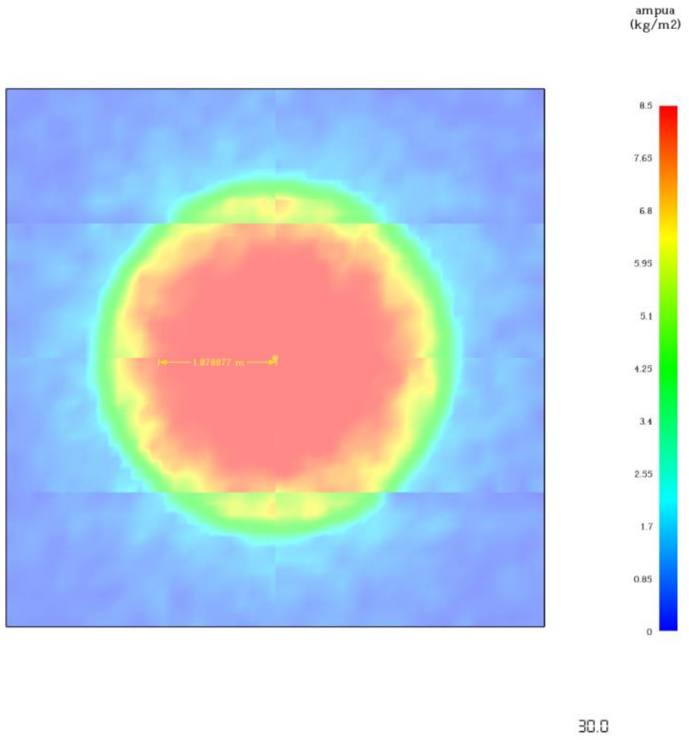
Fig. 26.73 HRR of a typical wood pallet stack (1.22 × 1.22 × 1.22 m high)

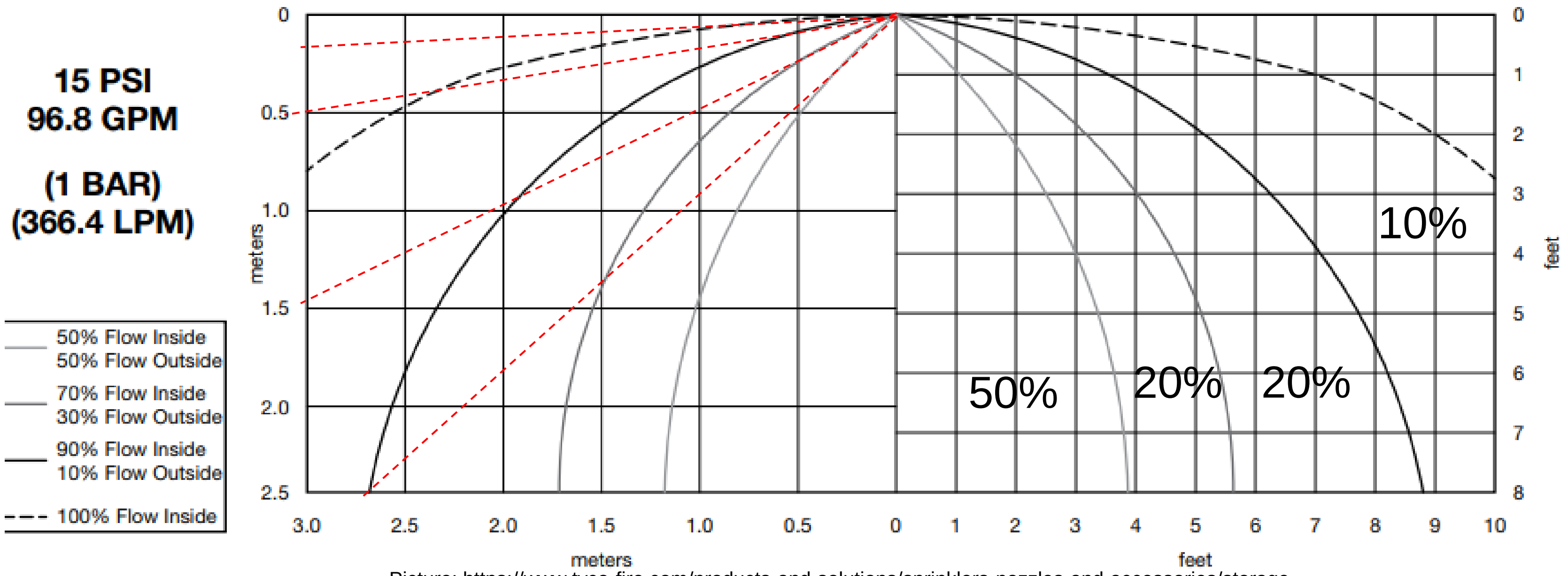


Picture: SFPE Handbook 2016

Example strcuture 2: Estimation of sprinkler model parameter for FDS

Spray Profile Patterns





Picture: https://www.tyco-fire.com/products-and-solutions/sprinklers-nozzles-and-accessories/storage

Table 2. Input parameter for spray table based on figure 3.

Flow fraction	Velocity (m/s)	Elevation angle 1 (°)	Elevation angle 2 (°)	Azimuth angle 1 (°)	Azimuth angle 2 (°)
0.5	14.7	0	42	0	360
0.2	14.7	42	64	0	360
0.2	14.7	64	81	0	360
0.1	14.7	81	86	0	360

$$\operatorname{atan}\left(\frac{2.7}{3}\right)=41.987\ deg$$

$$90\ deg-\operatorname{atan}\left(\frac{1.45}{3}\right)=64.204\ deg$$

$$90\ deg-\operatorname{atan}\left(\frac{0.5}{3}\right)=80.538\ deg$$

$$90\ deg-\operatorname{atan}\left(\frac{0.2}{3}\right)=86.186\ deg$$

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Example strcuture 2: Estimation of sprinkler model parameter for FDS input

- Tyco Storage sprinklers Model ESFR-25
- 25.5 K-factor Pendent Sprinkler
- Early Suppression, Fast Response

Picture: tyco-fire.com

Table 4. Summary of input parameters used in FDS to model sprinklers.

			Description/Comments
Activation	Temperature link	Storage	
	Activation temperature	100°C	From manufacture document
	Response Time index (RTI)	50 $(m/s)^{1/2}$	Fast response from Viking [1]
	C factor	0 $(m/s)^{1/2}$ (default)	
Spray model	Ejected particles	**Water particles**	
	Flow rate		
	Operating pressure	K-factor	
	1 bar	362.9 L/min.atm^1/2	From manufacture document
	Calculated flow rate	366.4 L/min	Calculated using equation $K\sqrt{p}$
	Jet Stream		
	Initial velocity	**6 m/s**	Calculated from equation 1 based on the minimum required operating pressure 0.52 bar
		14.7 m/s	calculated by dividing the volume flow by the orifice area
	Offset	Stream type	
	0.17 m	**Spray Table**	**Offset:** assumed based on cell size **Spray table:** According to Table 2
	Droplet per second	8000	Assumed, default in FDS is 5000
Water particles	Size distribution		
	Median diameter	1520 µm	Calculated from equation 2 and round up
	Distribution	Rosin-Rammler-lognormal	default
	Minimum diameter	20um	default
	Max diameter	Infinity	default
	Gamma D	2.4	default

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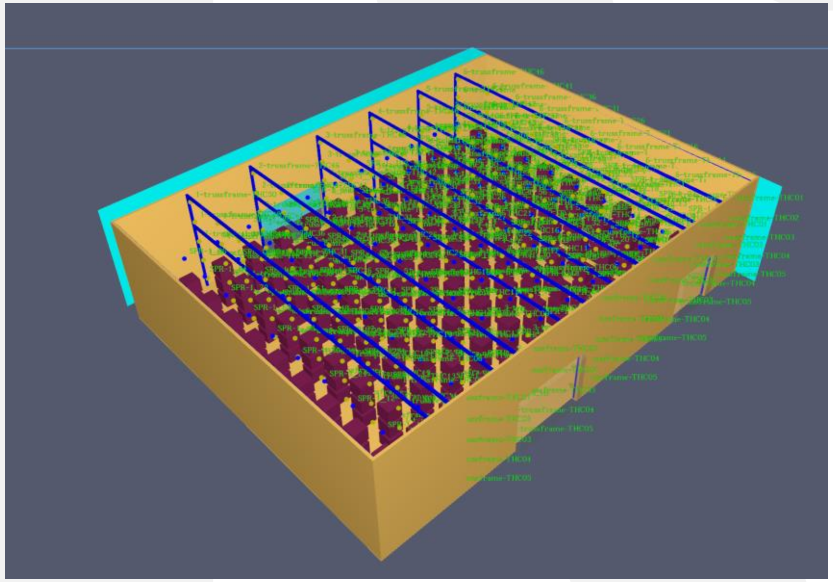
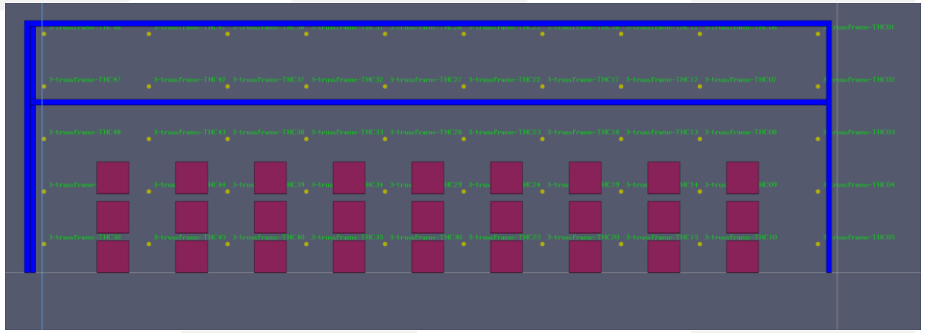
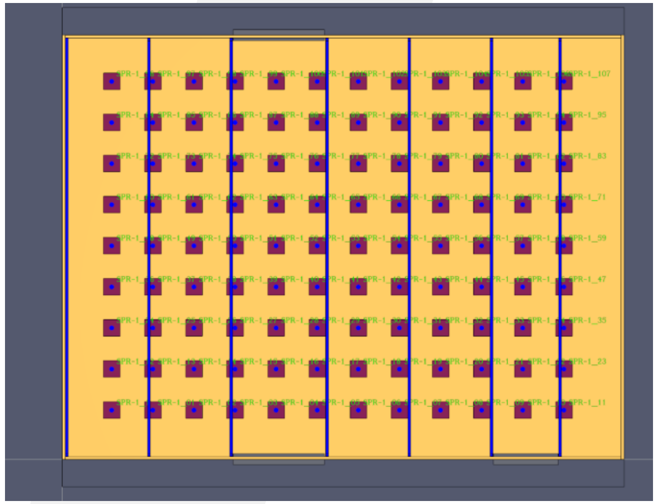
Example strcuture 2: Location of sprinklers, thermocouples and devices placed in FDS model







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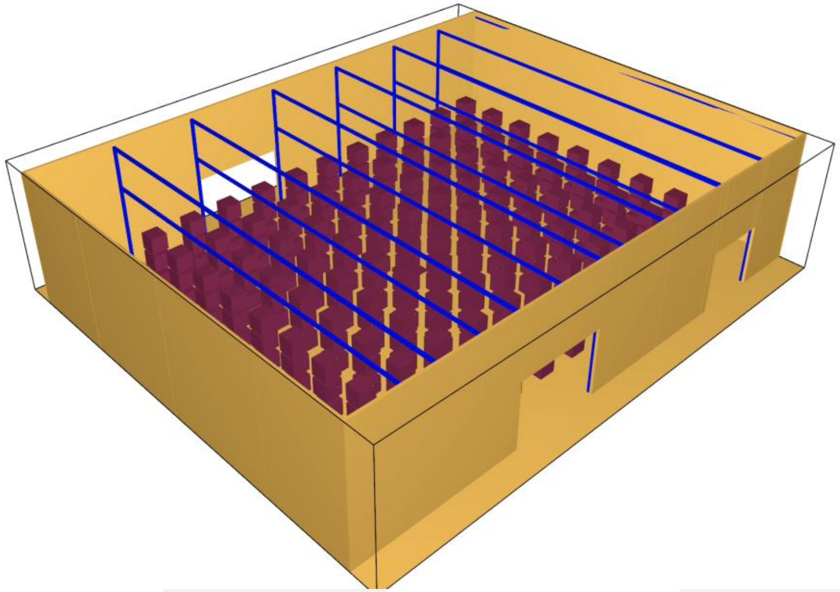
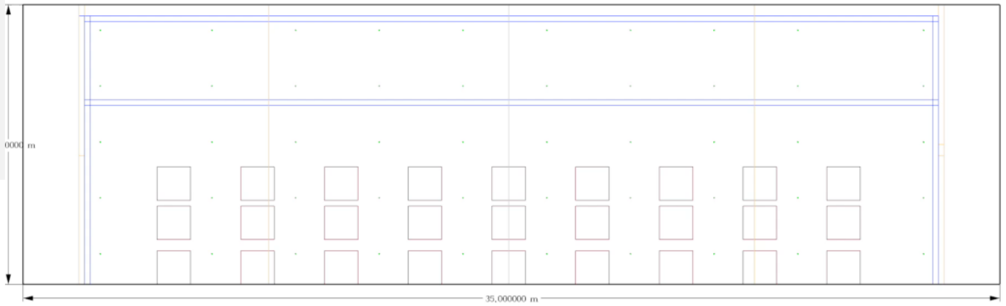
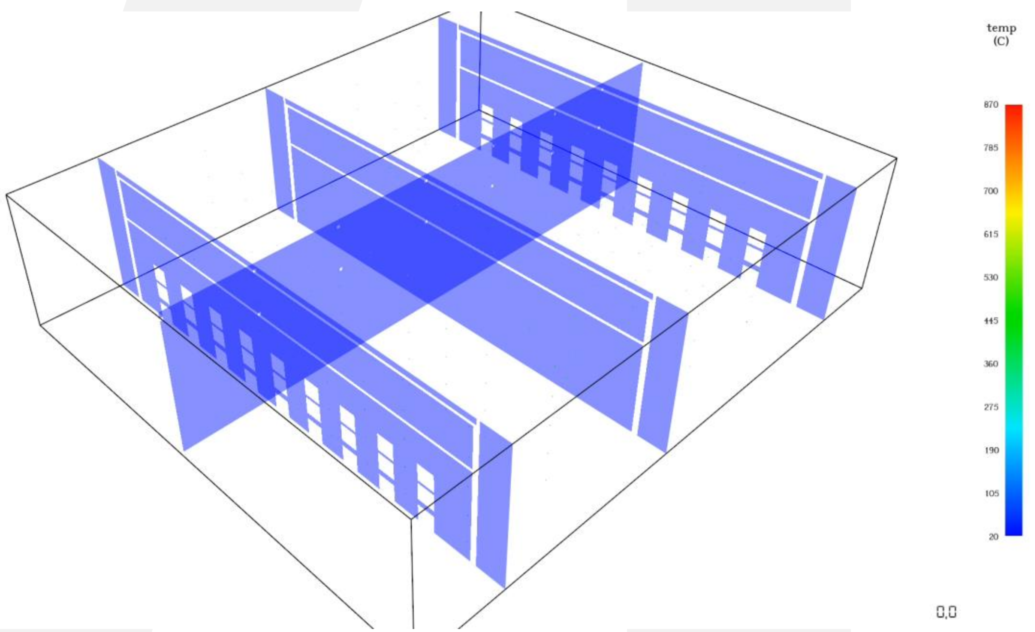
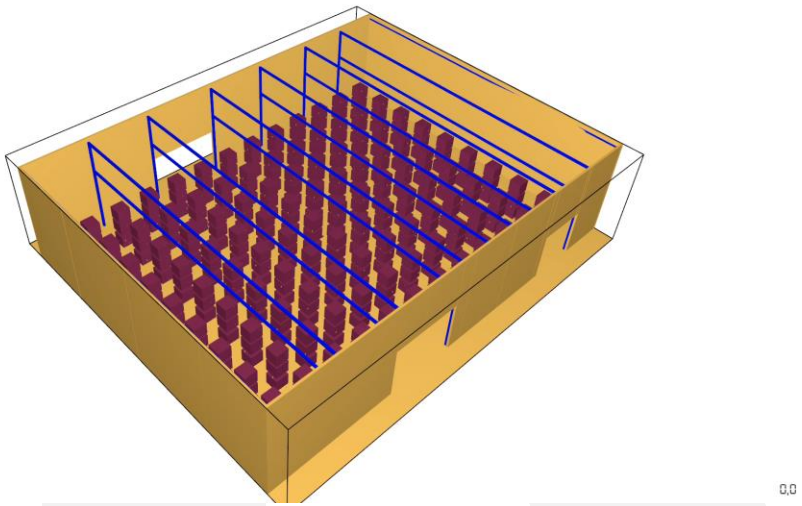
Results: Case 1 simulation vidoes

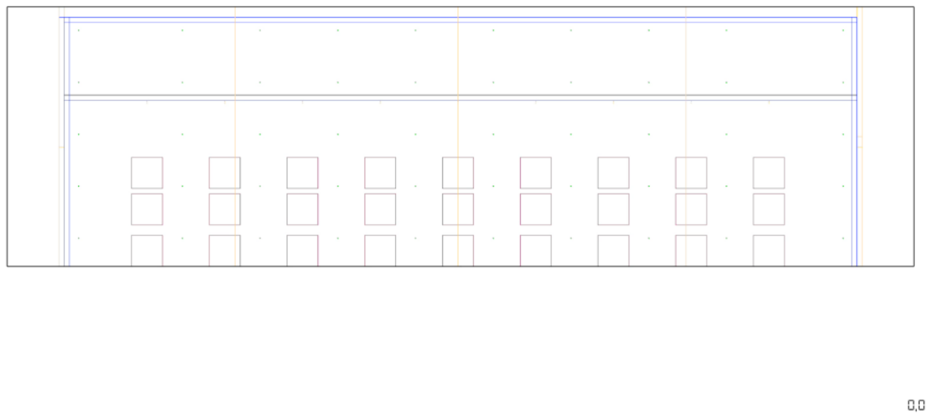


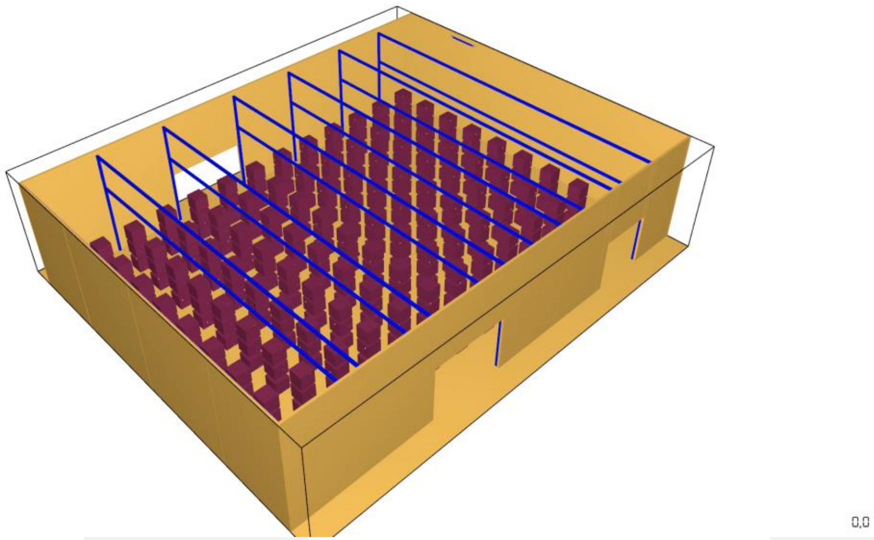


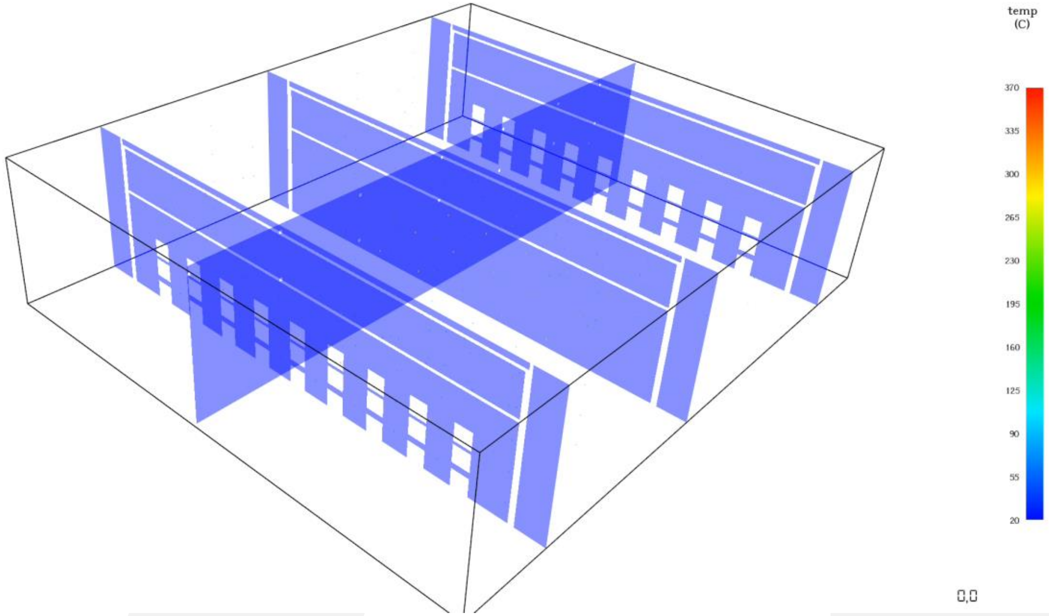


Results: Case 2 simulation vidoes









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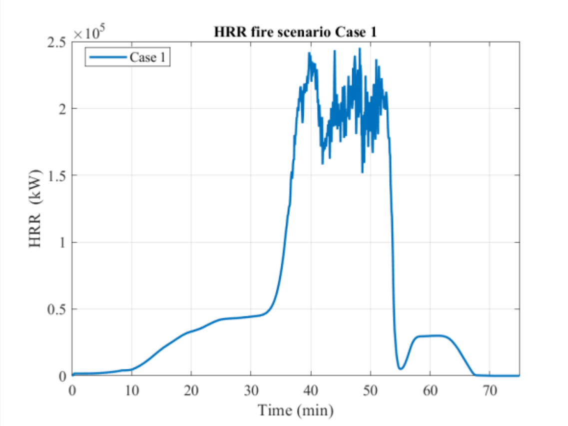
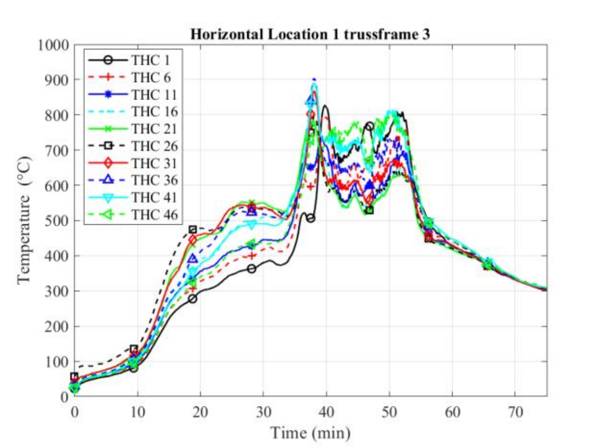
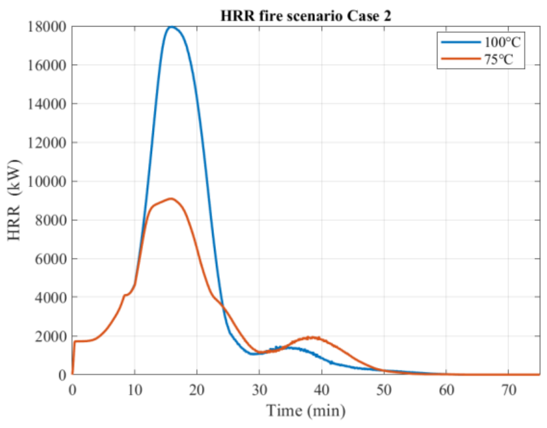
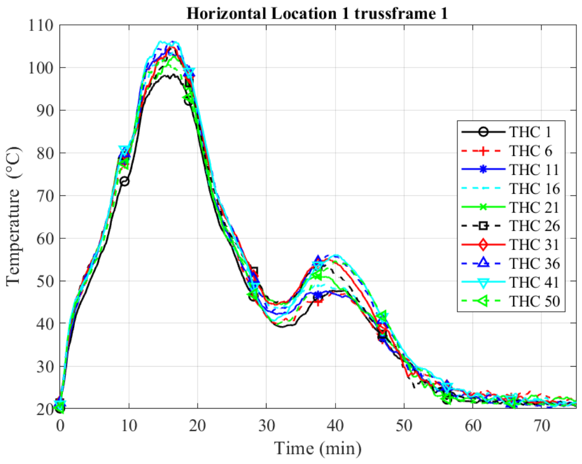
Results: Case 1 and Case 2



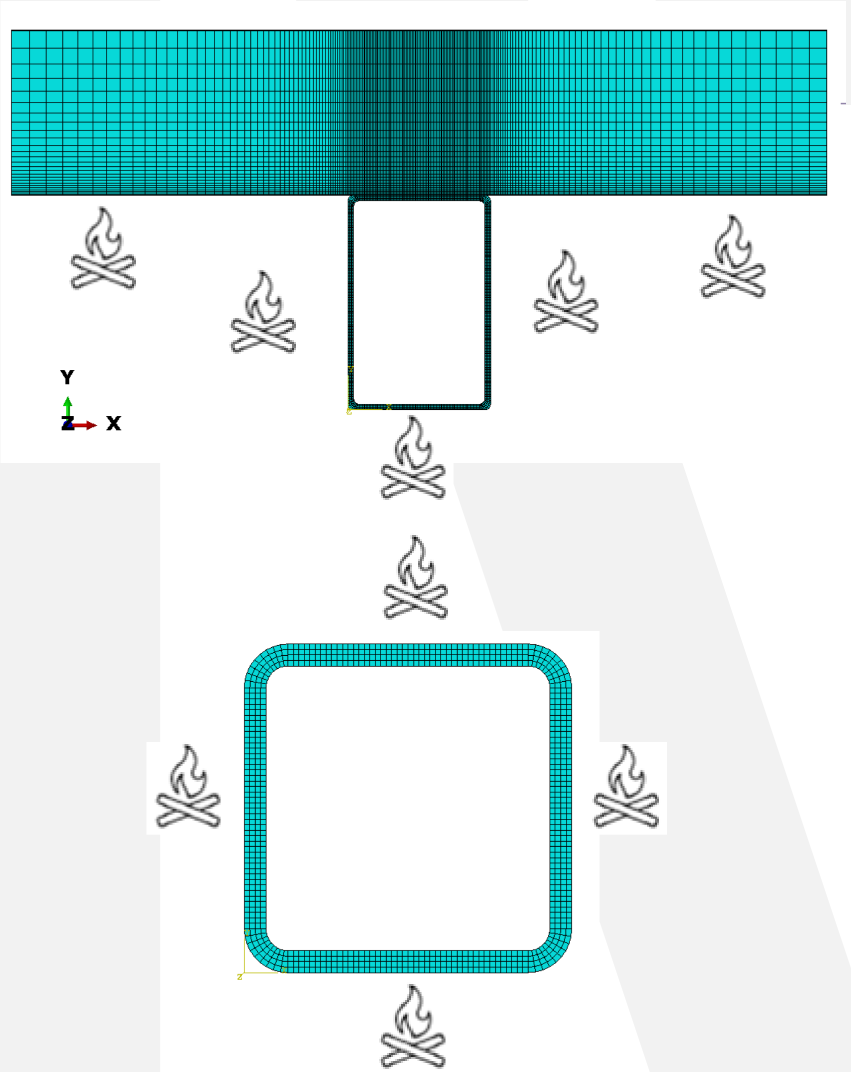


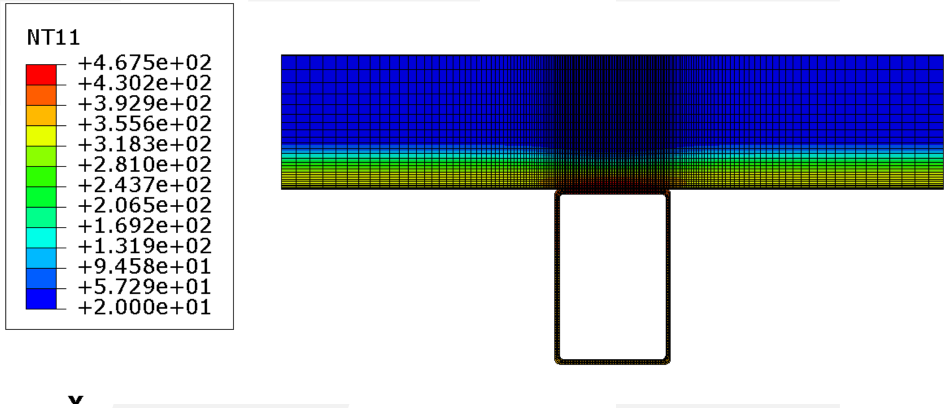


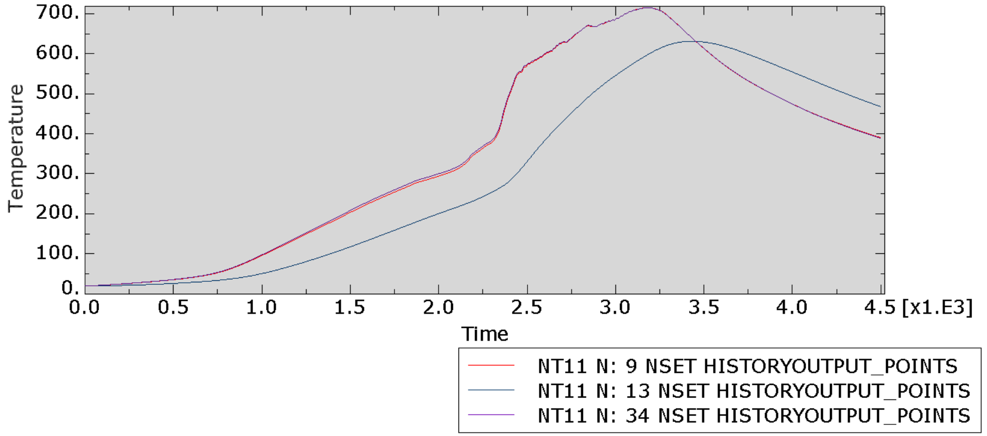


Example strcuture 2: Thermal response model

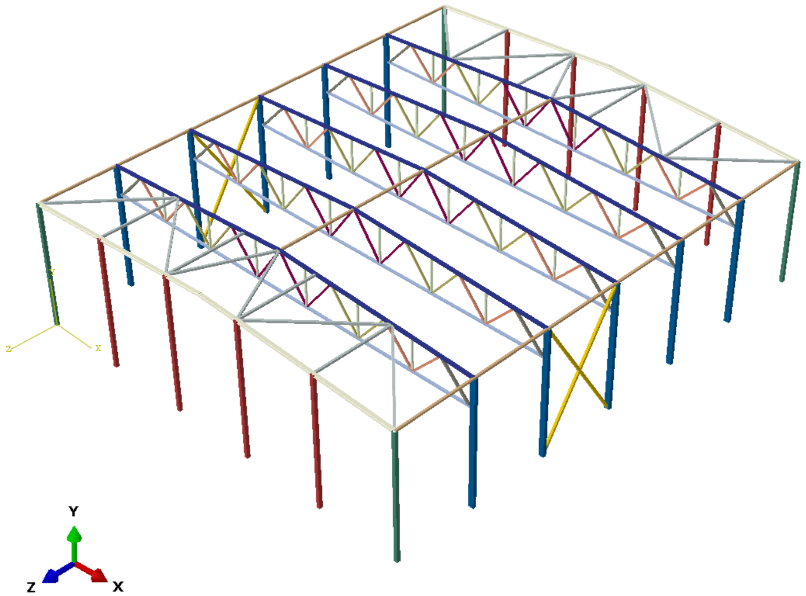
Thermal analysis of member





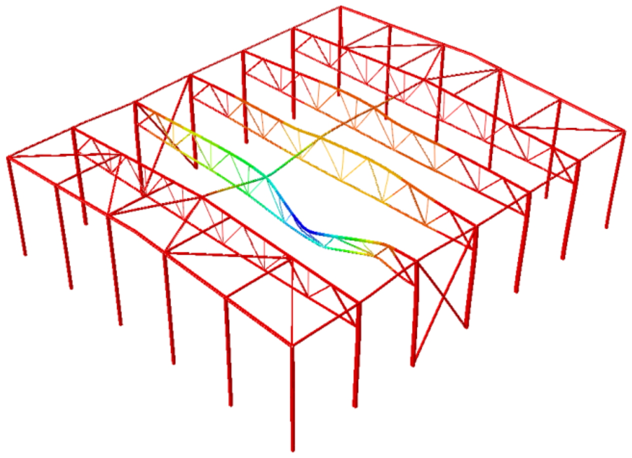


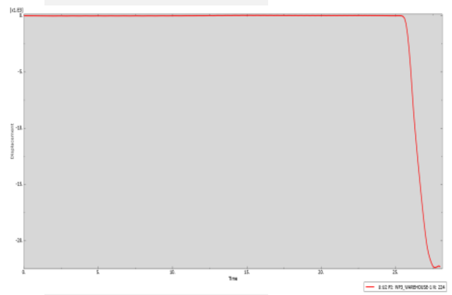
Example strcuture 2: Structural response



Structural model

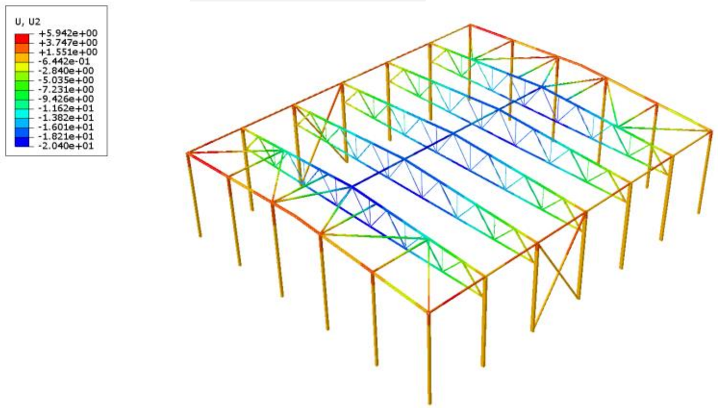
Structural response model case 1





Collapse time = 38 min

Structural response model case 2



No Collapse time

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Thank you for you attenion !

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