Buro Happold **the engineering of excellence**

Fire Engineering in Practice – State of the Art in Performance-based Design

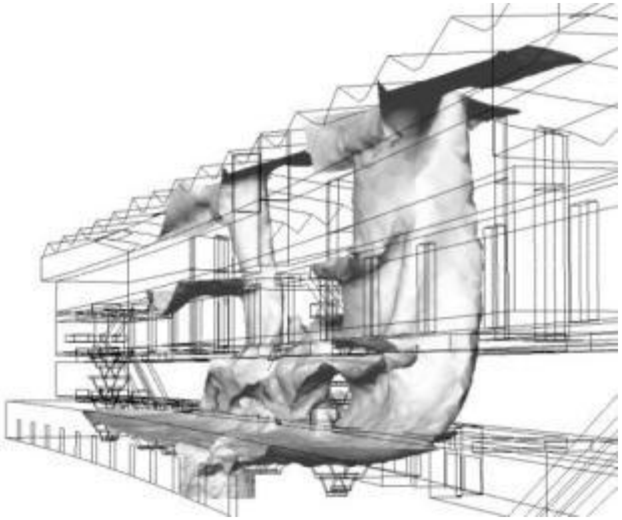
Dr Florian Block

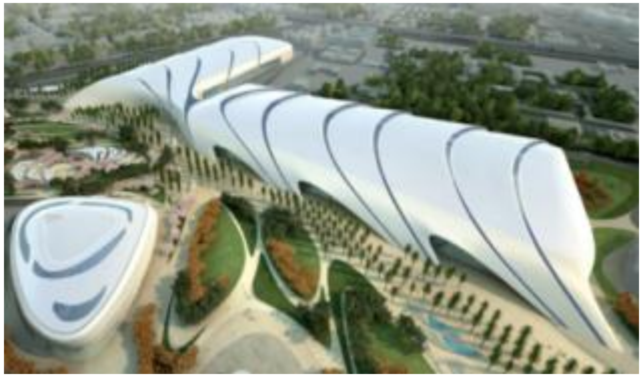
COST TU904 – 2013 Training School - Naples

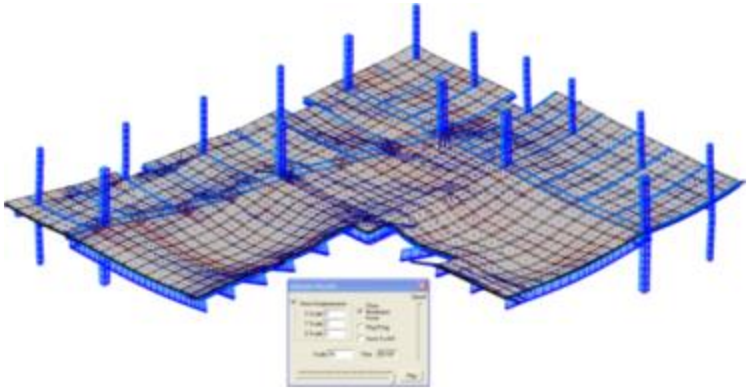
7th of June 2013

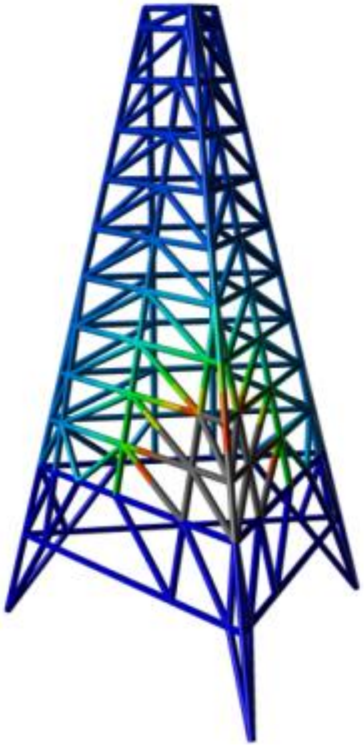
Agenda

- What does a Fire Engineer do?
- What is Performance Based Design?
- How is Performance Based Design done in reality?
- Project examples
- Conclusions









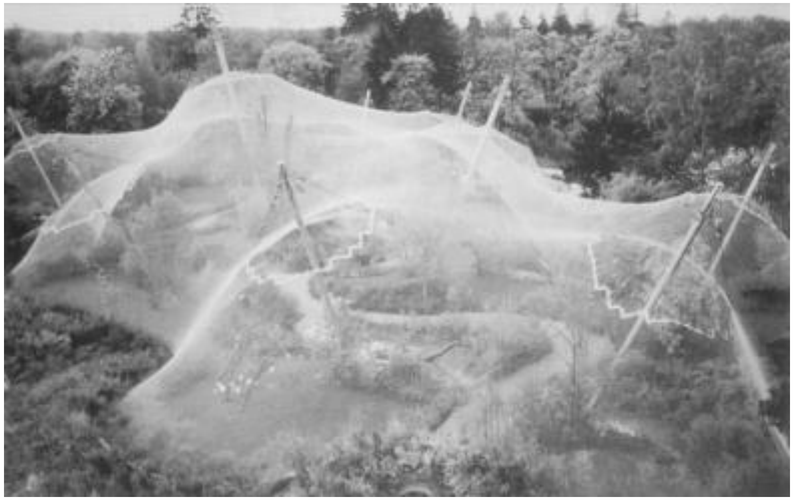
Buro Happold

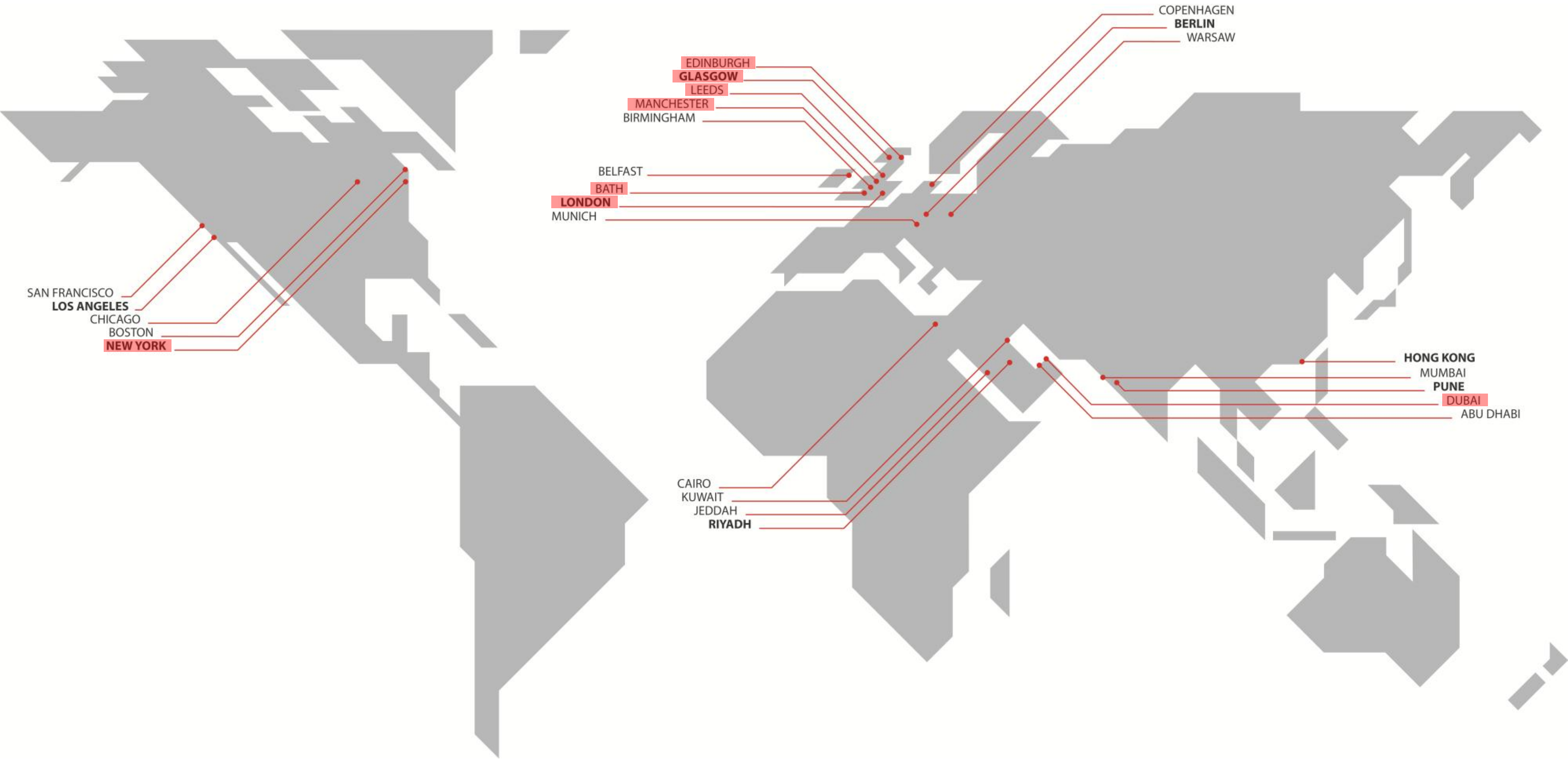
Founded 1976 in Bath by Sir Ted Happold and 6 partners

26 Offices around the world

~1500 members of staff

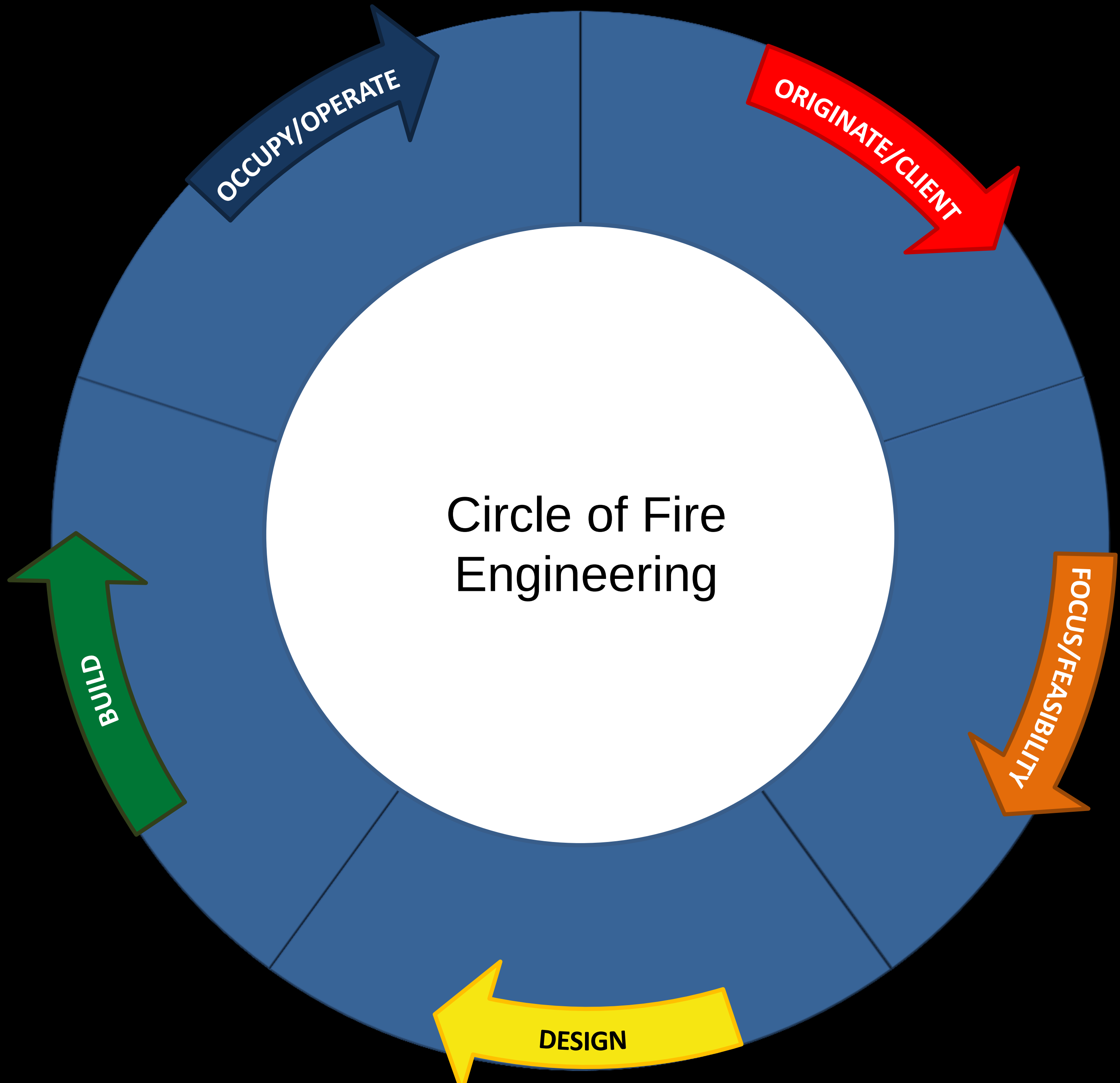
- Structural Engineering
- Building Services
- Facades
- Infrastructure
- Sustainability
- Geotechnics
- Lighting
- Etc…..
- And Fire Engineering

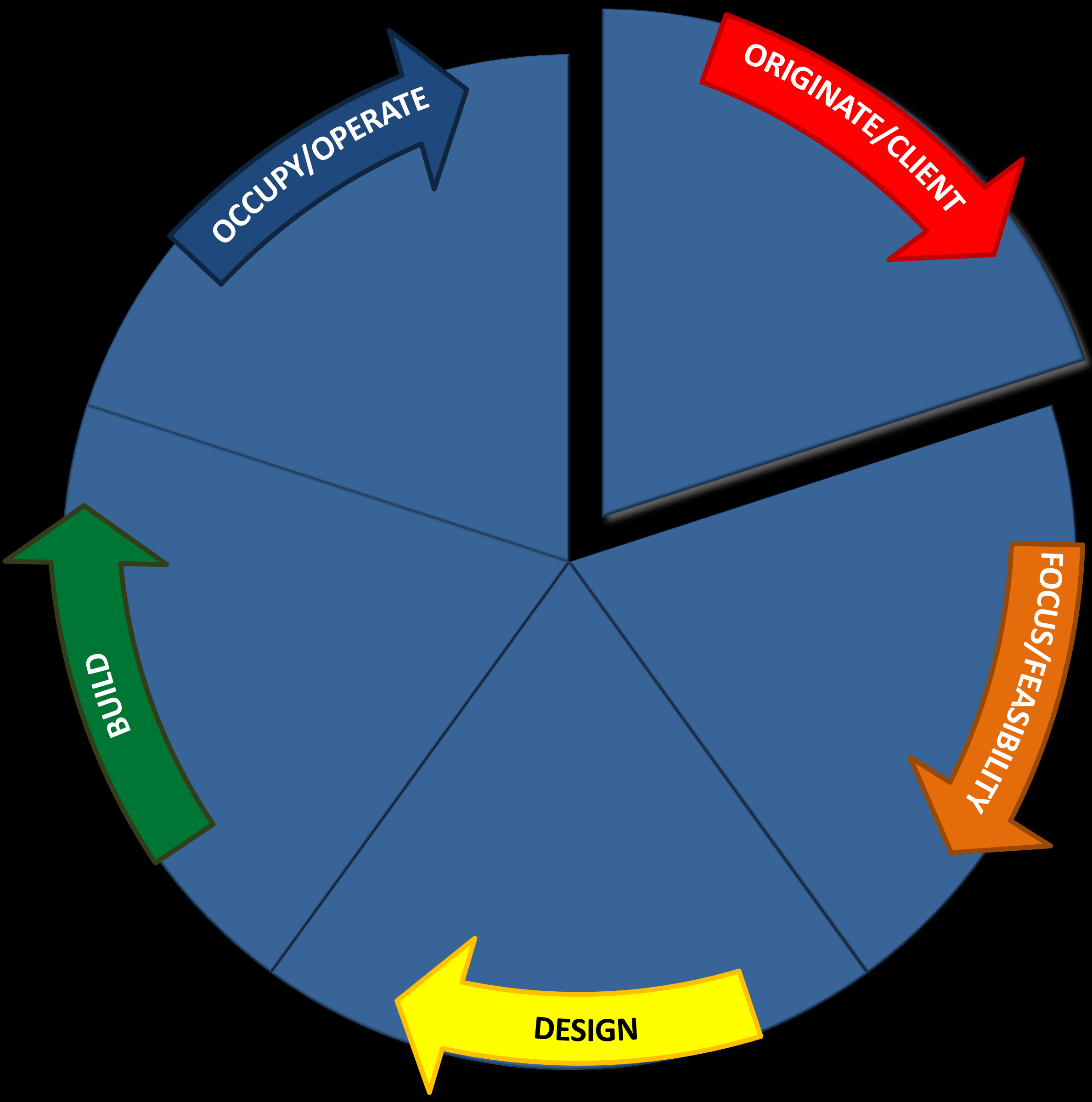




Buro Happold Office Locations

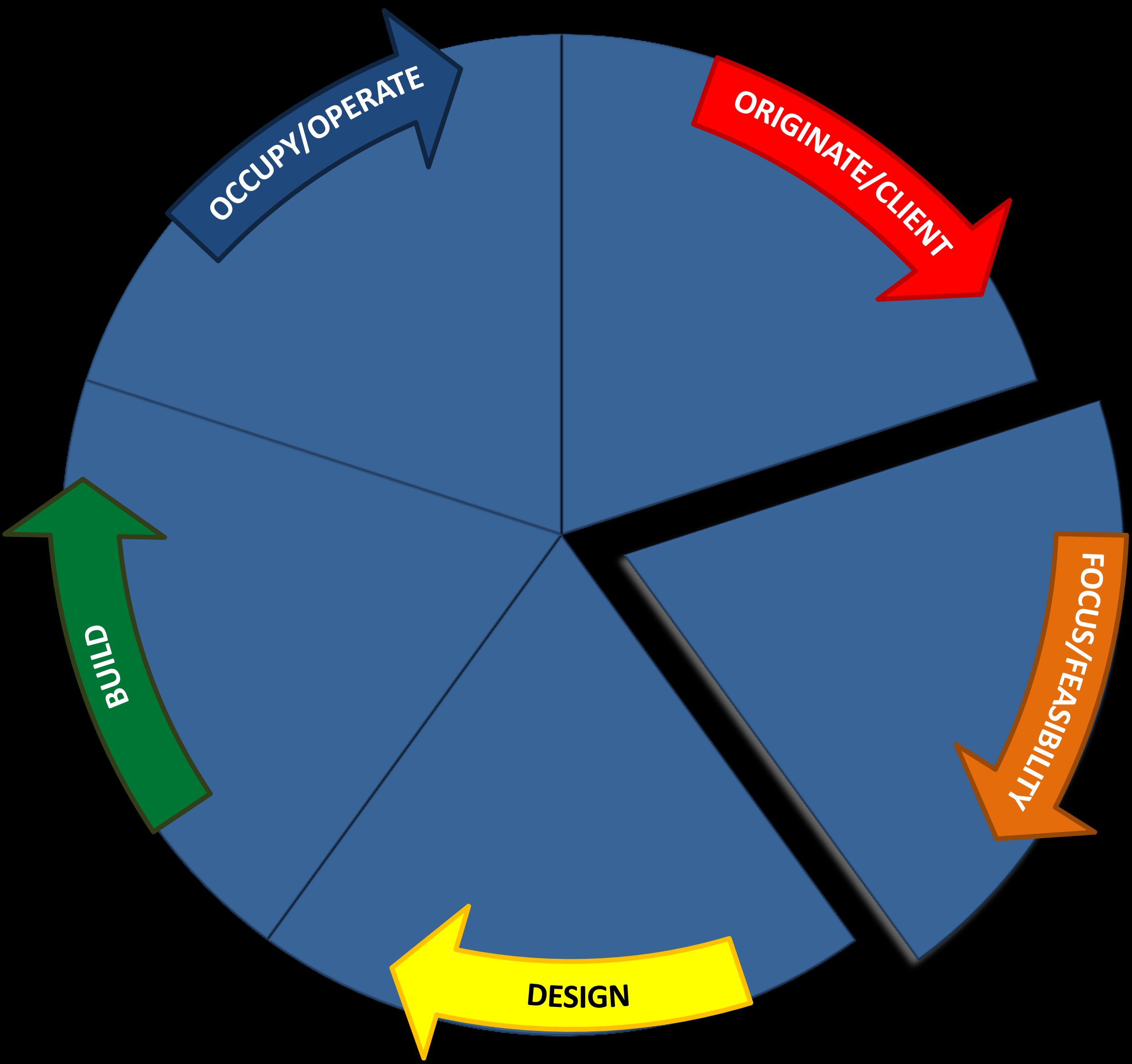
Buro Happold FEDRA Office


Circle of Fire Engineering
ORIGINATE/CLIENT
FOCUS/FEASIBILITY
DESIGN
BUILD
OCCUPY/OPERATE



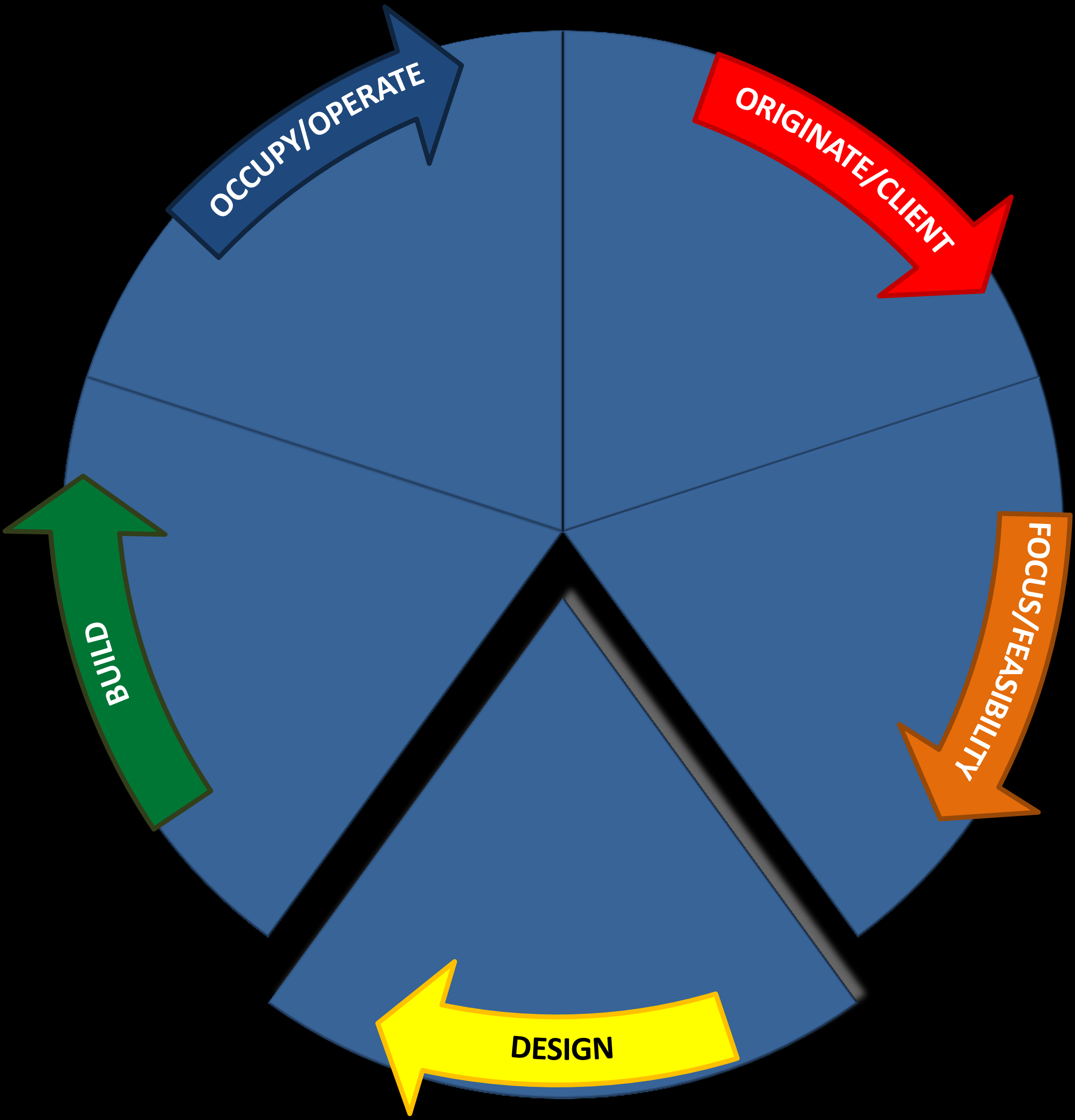
Fire Safety Objectives

- Life-safety
- Property protection – *Museums, galleries*
- Business continuity – *Finance institutes, data centres, manufacturing facilities*
- Security Requirements - *Prisons*
- Educational continuity - *Schools*
- Operational requirements – *Hospitals (surgical theatres)*
- Specific local requirements – *Local AHJ*



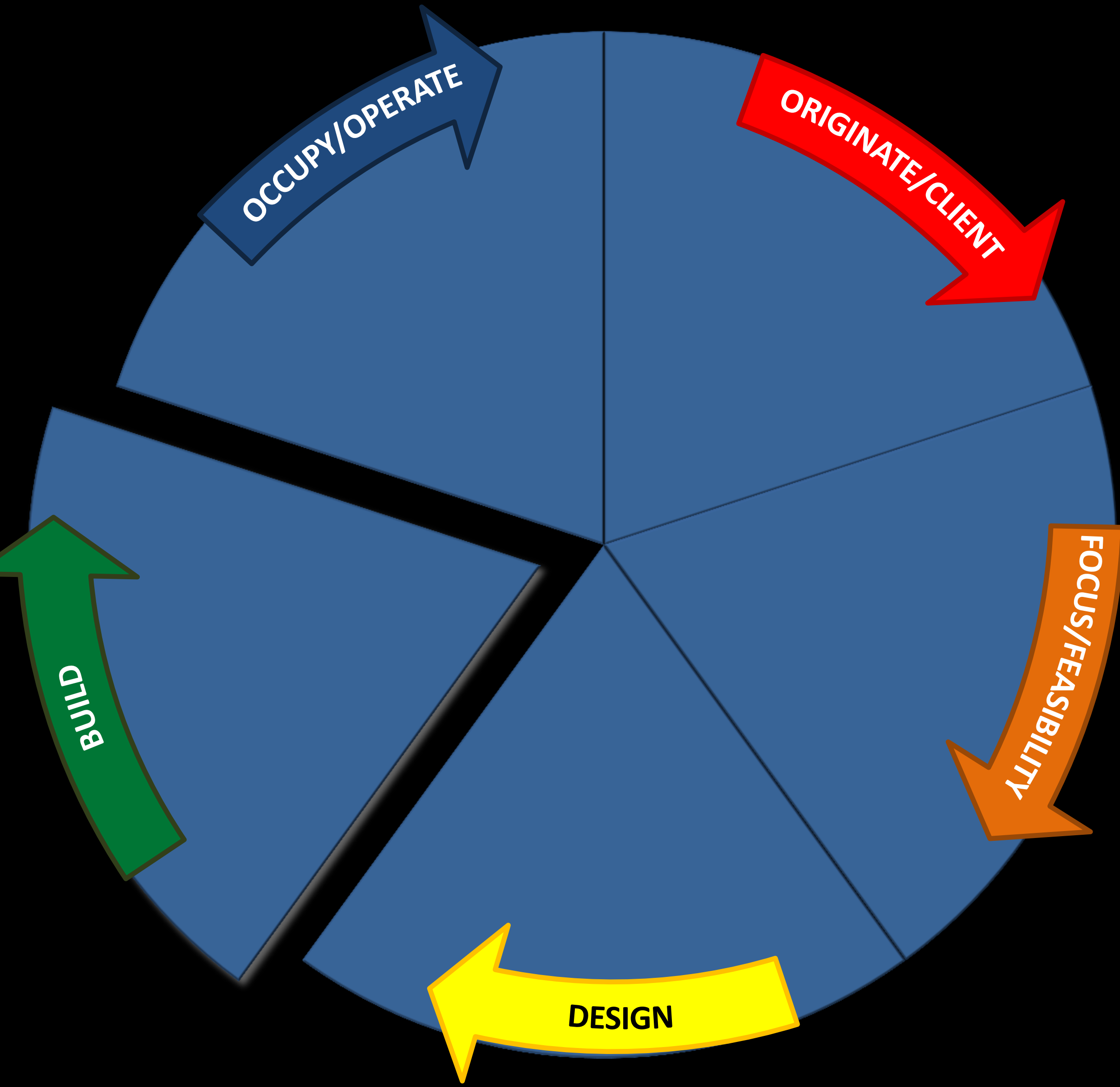
Focus/Feasibility

- Emergency vehicle access around site & to buildings
- Fire protection infrastructure
- Building separation distances
- Required protection of facades
- Building access requirements



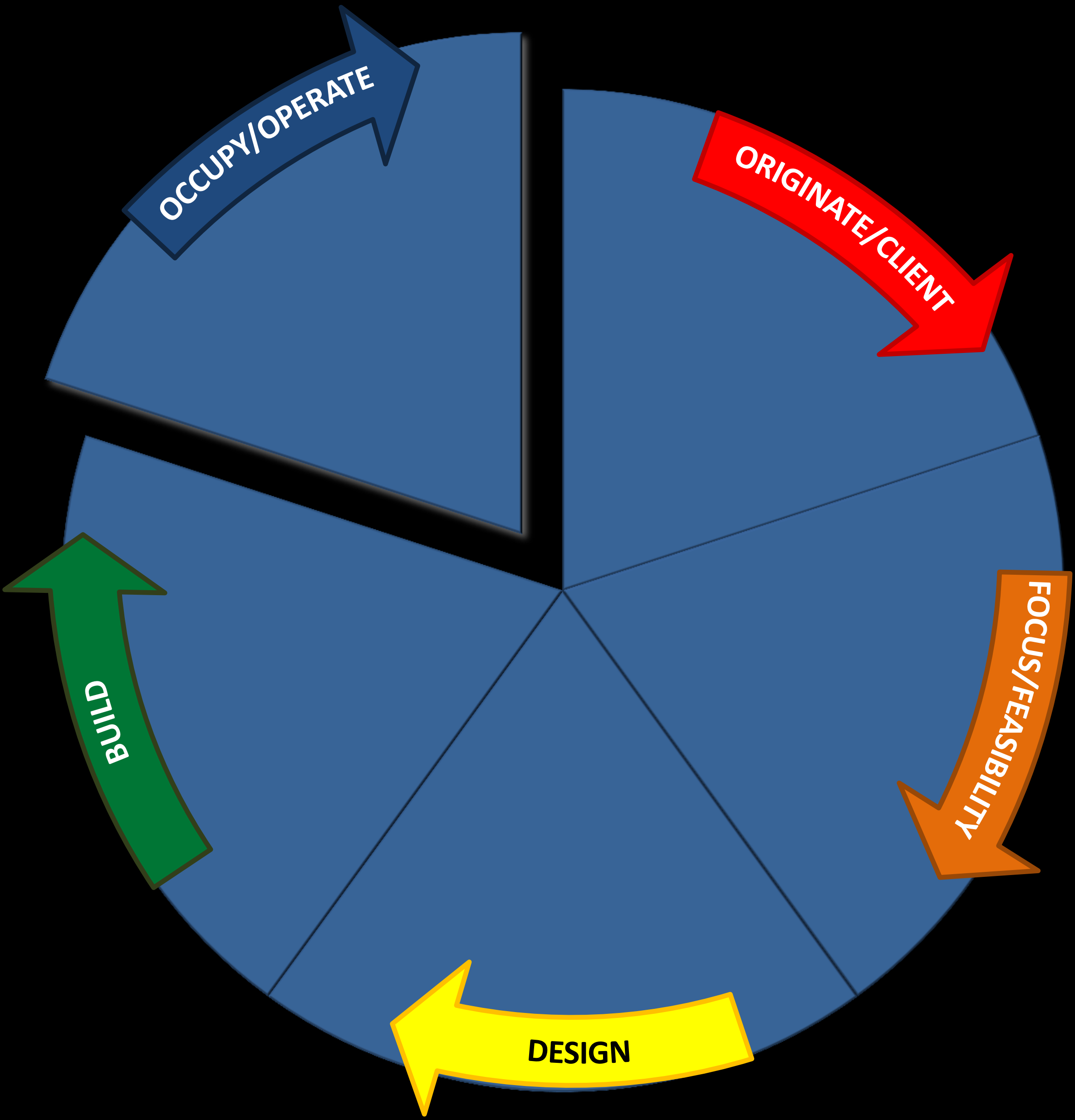
Design Phase

- Identify primary means of egress
- Fire resistance of elements of structure
- Compartment sizes and locations
- List of active systems required
- Outline strategy for response to fire
- Advanced fire modelling
- Marked-up drawings
- Liaison with AHJ
- Contribution to value engineering process



Build/Construction Phase

- Site Inspections
- Checks for compliance with fire strategy
- Attendance at commissioning of fire systems – *particularly for fire engineering solutions*
- As-built Fire Strategy
- Trouble-shooting



Occupy/Operate

- Periodic Audit
- Portfolio Management
- Fire safety training
- Phase Occupancy Strategy
- Personal Emergency Evacuation Plans - *schools*
- Operations and Maintenance Manuals – *testing of fire engineered designs*
- Training - *How does this fire engineered solution work in practice?*

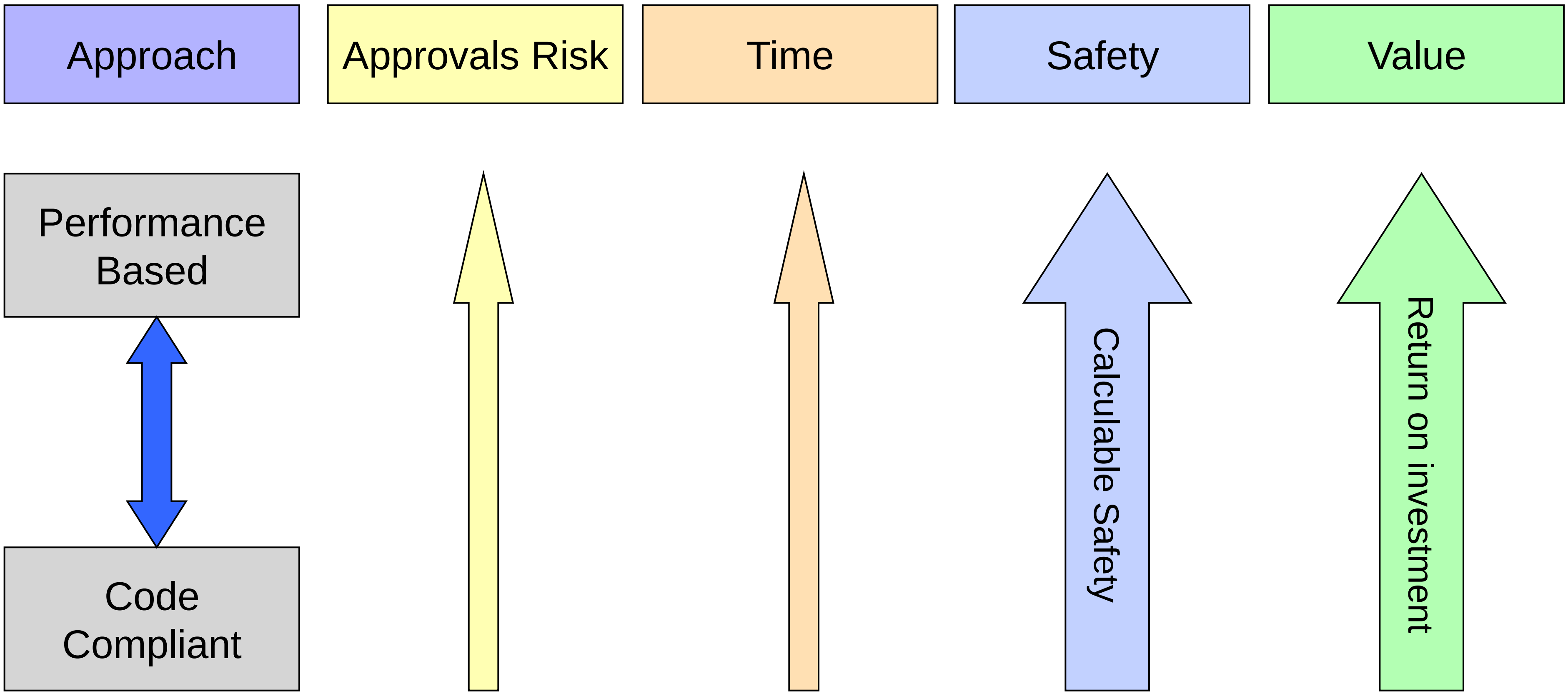
‘Connection’ to Fire Engineer

Performance Based Design

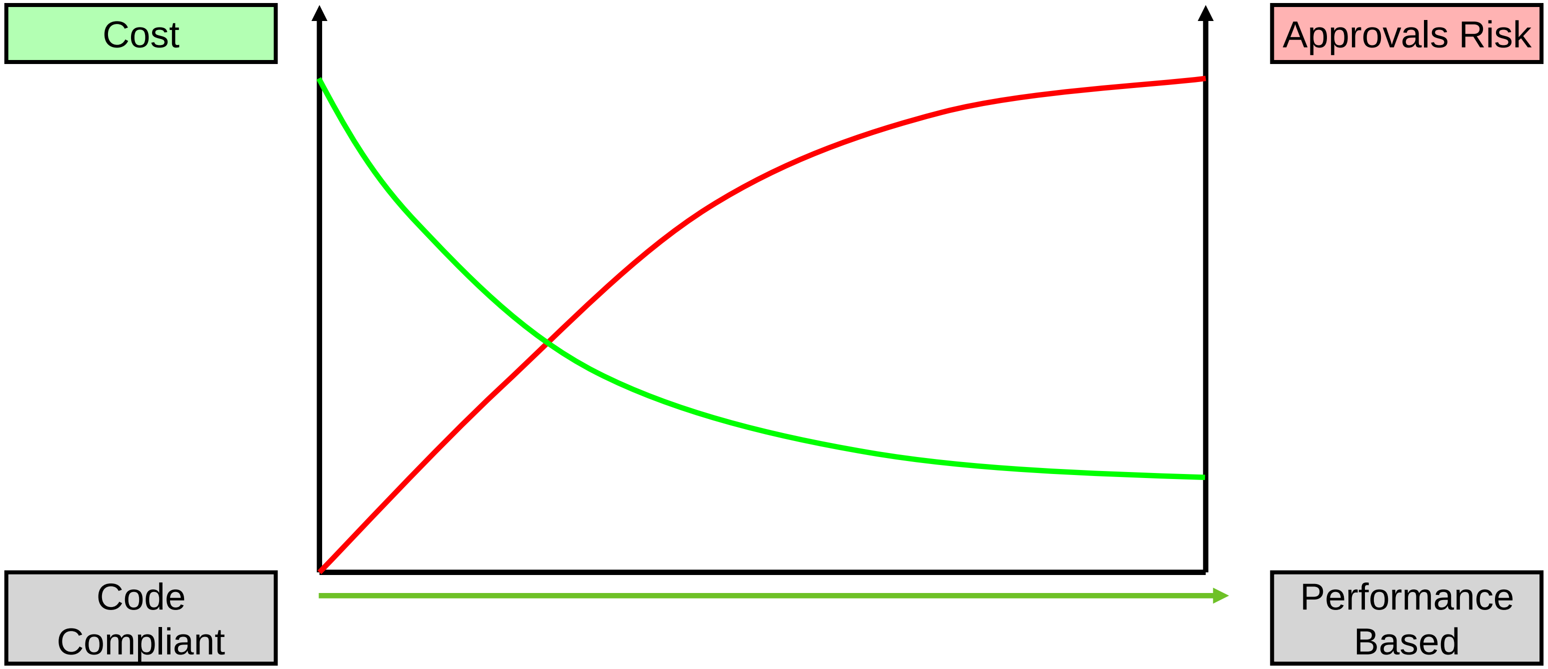
Tailored solutions to solve fire safety issues for which prescriptive solutions don't give satisfying results in the areas of:

- Life safety
- Robustness of Structures
- Architectural Vision
- Sustainability
- Cost

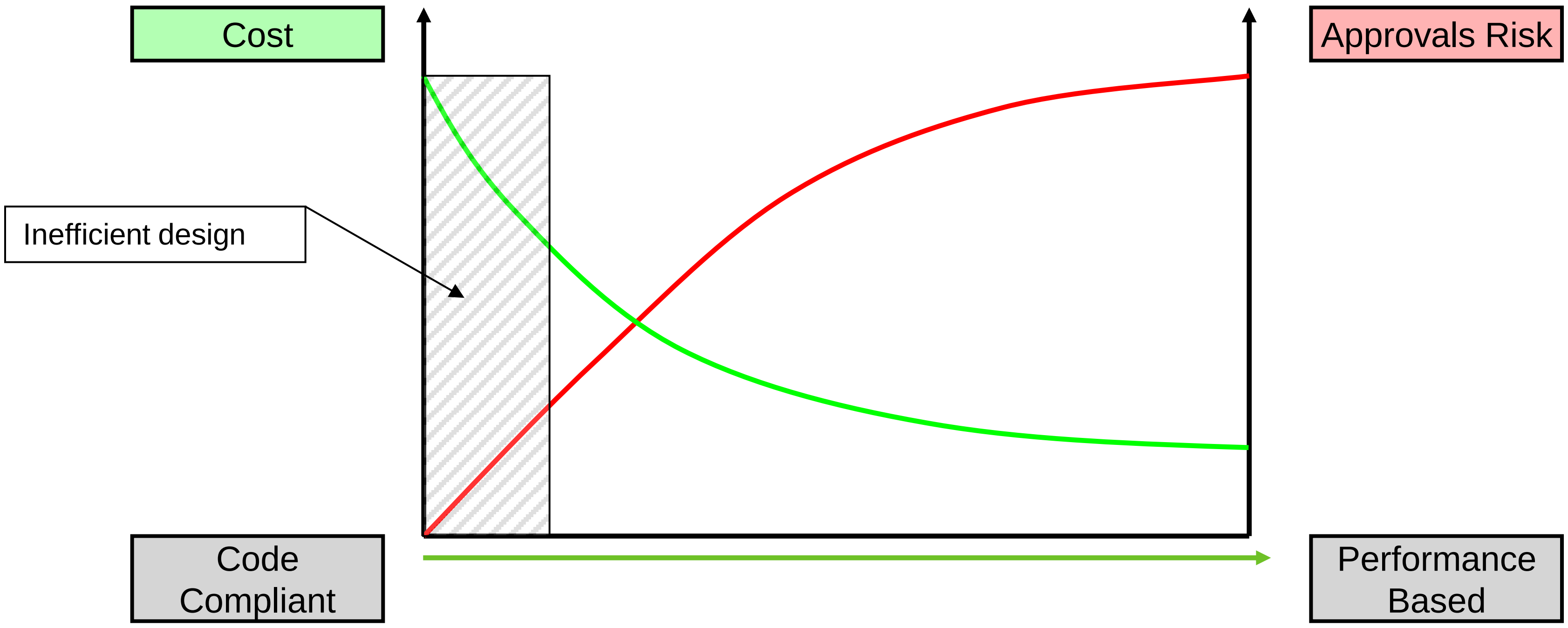
Performance Based Design



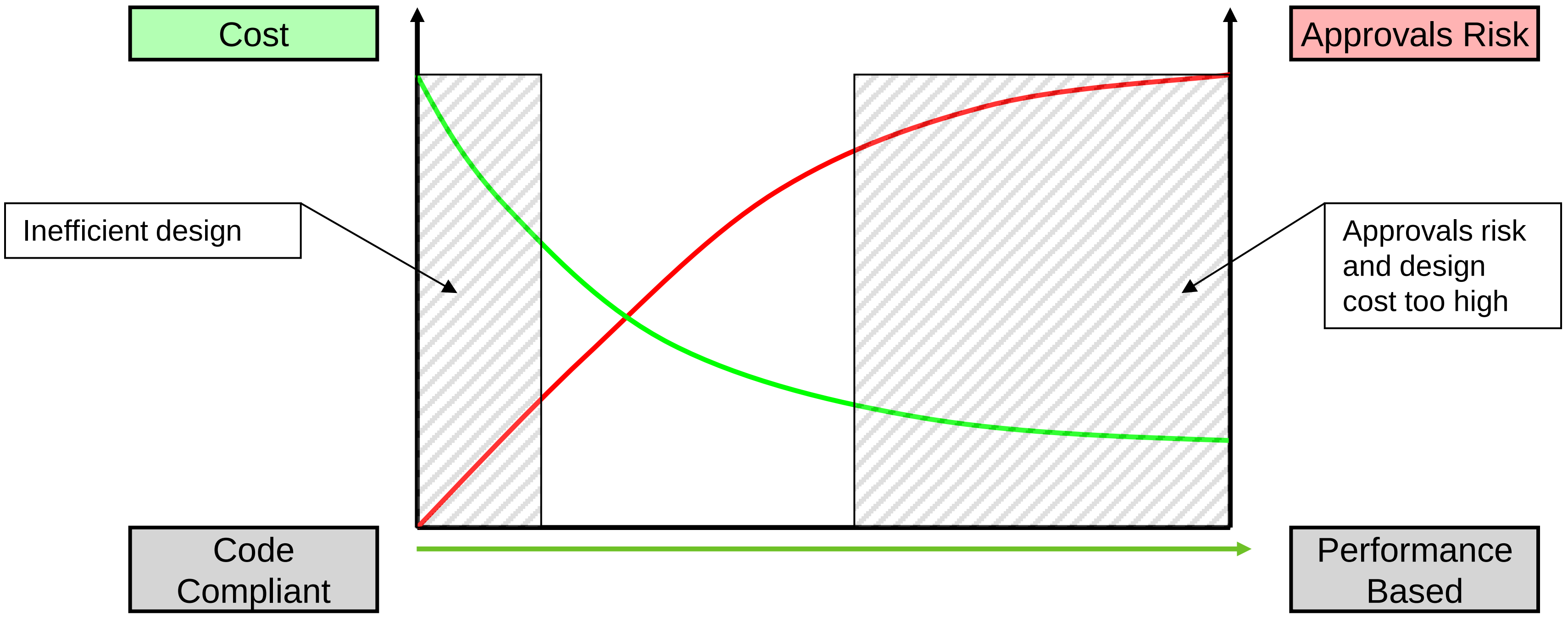
Performance Based Design



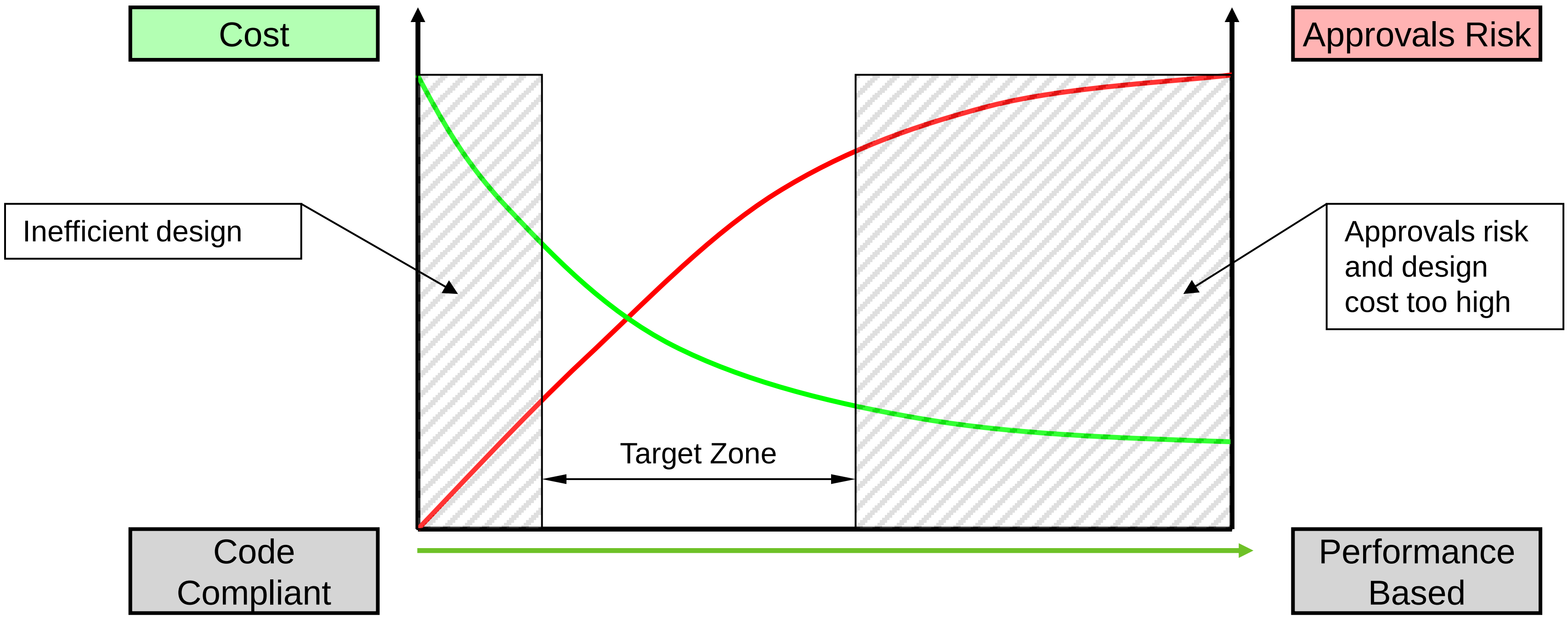
Performance Based Design



Performance Based Design



Performance Based Design



Performance Based Design - Process

1. Is performance based design required and applicable?

Scoping study

Test the market

2. Initial consultation

Consult stakeholder (Client, insurers, approving authority and fire brigade)

Set objectives

Agree acceptance criteria

Agree design fires scenarios

3. Conduct Analysis

Smoke and fire behaviour

People movement

Structural response

Performance Based Design - Process

4. Perform sensitivity studies

5. Prepare a detailed report

6. Gain building control approval

7. Construction drawings

8. Site inspection and performance testing

Fire Safety Objectives

Life Safety of people in the building

Protection of <u>other</u> property

Facilitate fire fighting

Property Protection

- Buildings
- Contents

Business / Operational Continuity

Protection of Brand / Image

Acceptance criteria

For structure:

- Stability of structure
- Containment of fire

For escape:

- Visibility
- Toxicity
- Temperature
- Air velocity and pressures

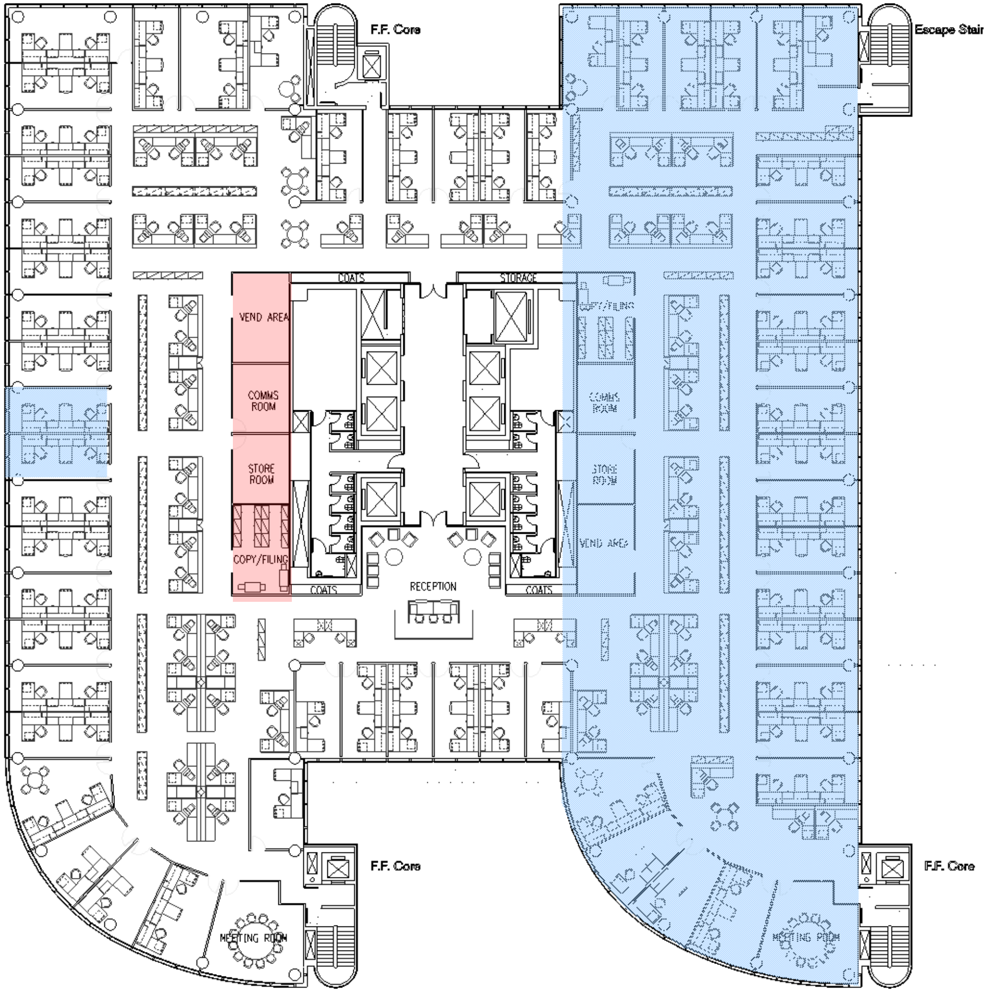
For fire fighting:

- Access
- Fire fighting systems

Determining the Design Fire Scenarios

Perform a Qualitative Risk and Hazard assessment

- Find a number of worst case design fire scenarios
- Also consider low possibility but high consequence event



Determine the Design Fire

Isolated Fires

- Develop in large open spaces or outside
- Fuel controlled

Compartment Fires

- Heat is conserved by surrounding structure
- Much higher temperatures than isolated fires
- Ventilation controlled

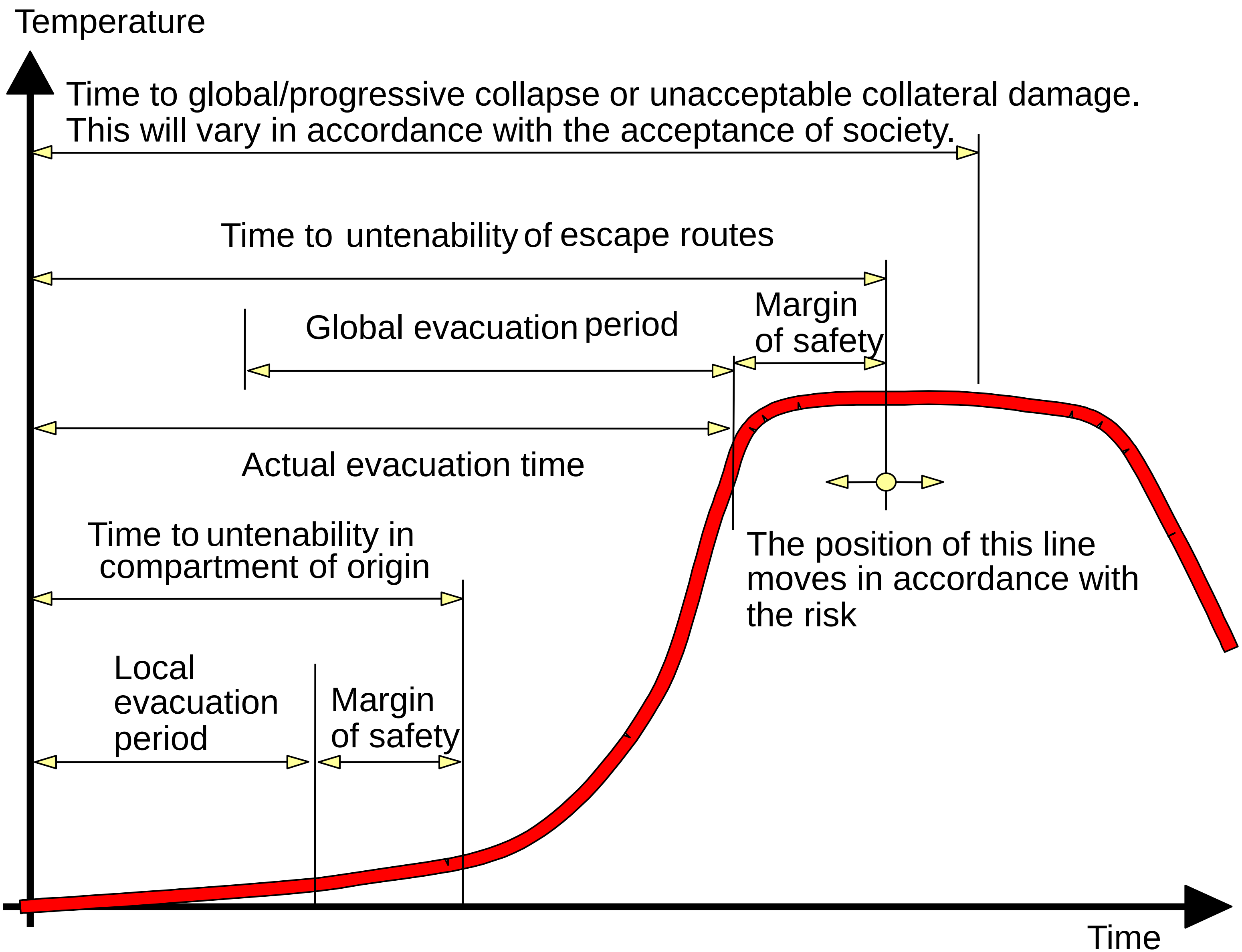
Agree with Stakeholders - Fire Engineering Brief (FEB)

Why?

- Performance based designs introduce risk

- Way to consult stakeholders early
- Aims to establish platform of principles for fire engineering to work from

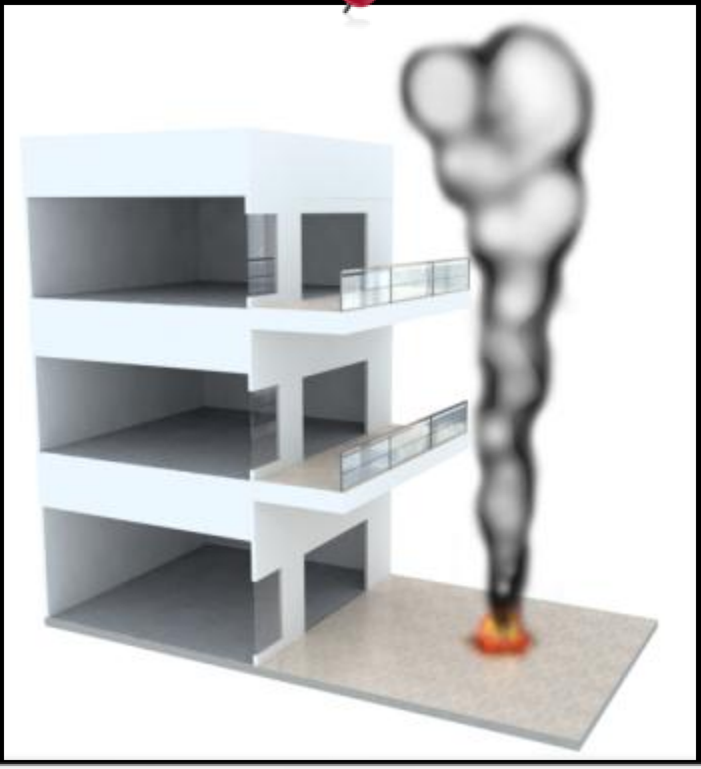
Time as Measure – ASET vs RSET



Fire & Smoke Modeling

Fire & Smoke Modeling

Hand Calculations



Axisymmetric Plume

Axisymmetric Plume

$$z_l = 0.533 Q_c^{\frac{2}{5}}$$

$$when\_z > z_1, m = (0.022 Q_c^{\frac{1}{3}} z^{\frac{5}{3}}) + 0.0042 Q_c$$

$$T_S = T_O + \frac{K_S Q_C}{m C_P}$$

$$\rho = \frac{144P}{R(T + 460)}$$

$$V = 60 \frac{m}{\rho}$$

$$V_{\max} = 452 \gamma d^{\frac{5}{2}} \left(\frac{T_S - T_O}{T_O} \right)^{\frac{1}{2}}$$

Fire & Smoke Modeling

Hand Calculations

Balcony Spill Plume

Balcony Spill Plume

$$m = 0.12(QW^2)^{\frac{1}{3}}(z_b + 0.25H)$$

$$\dot{m}_b = 0.31\dot{Q}^{\frac{1}{3}} W^{\frac{1}{5}}(z_b + 0.098W^{\frac{7}{15}} - 15)$$

$$m = \left[0.077(A_w H_w^{\frac{1}{2}})^{\frac{1}{3}}(z_w + a)^{\frac{5}{3}} \right] + 0.18 A_w H_w^{\frac{1}{2}}$$

$$T_S = T_O + \frac{K_S Q_C}{m C_P}$$

$$\rho = \frac{144P}{R(T + 460)}$$

$$V = 60\frac{m}{\rho}$$

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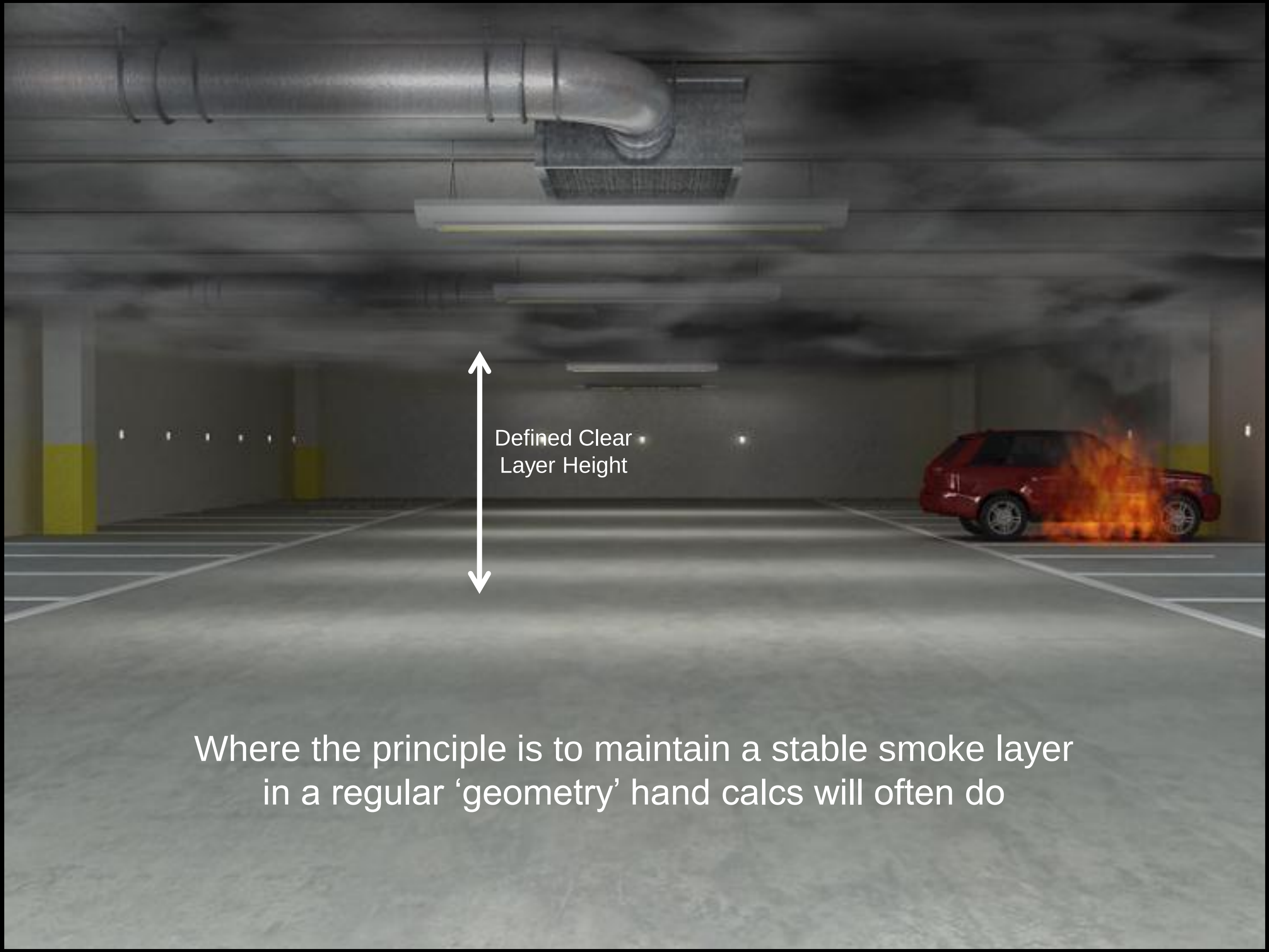
Fire & Smoke Modeling

Hand Calculations



Fire & Smoke Modeling

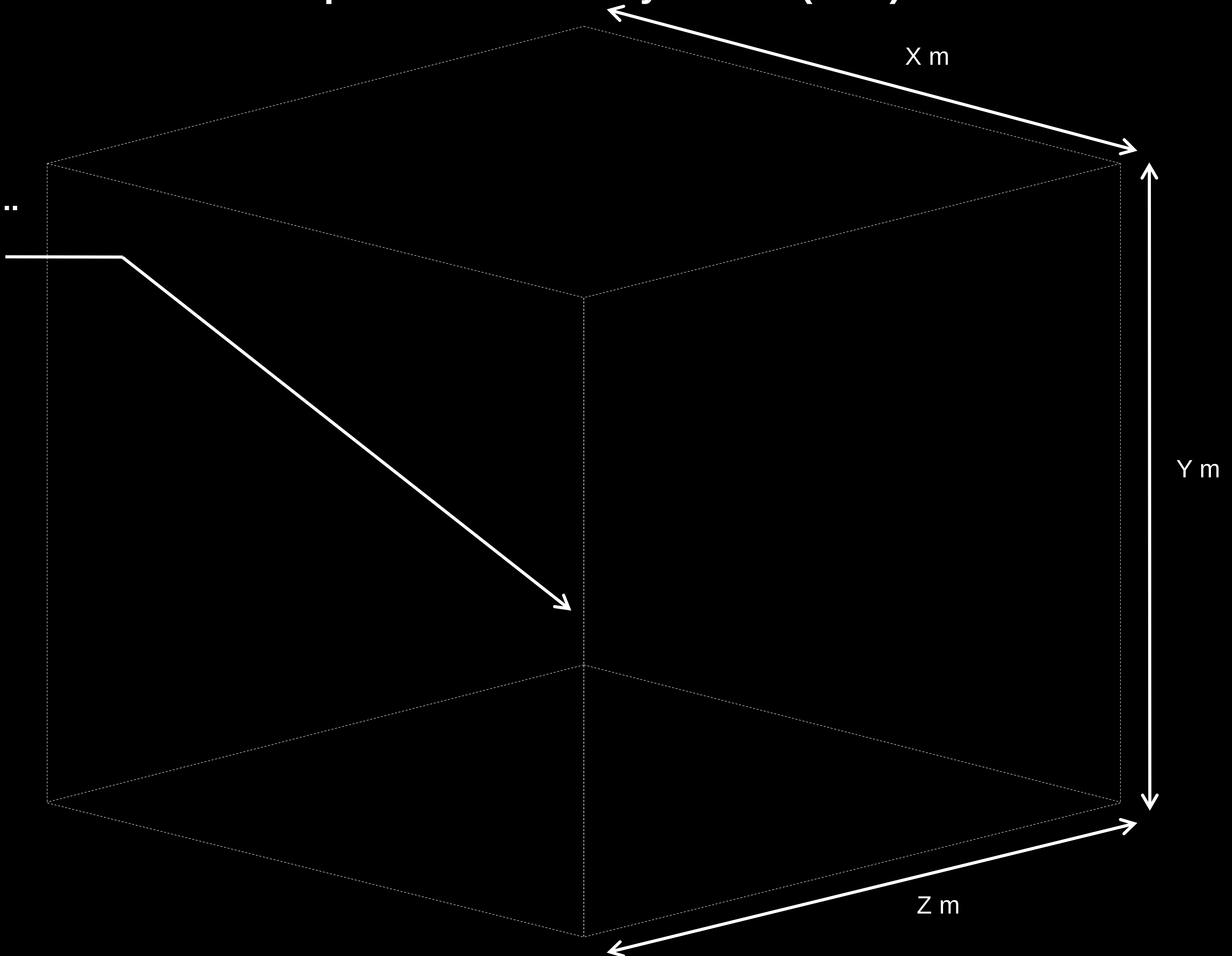
Computational Fluid Dynamics (CFD)

Fire & Smoke Modeling

Computational Fluid Dynamics (CFD)

Define……..

Geometry



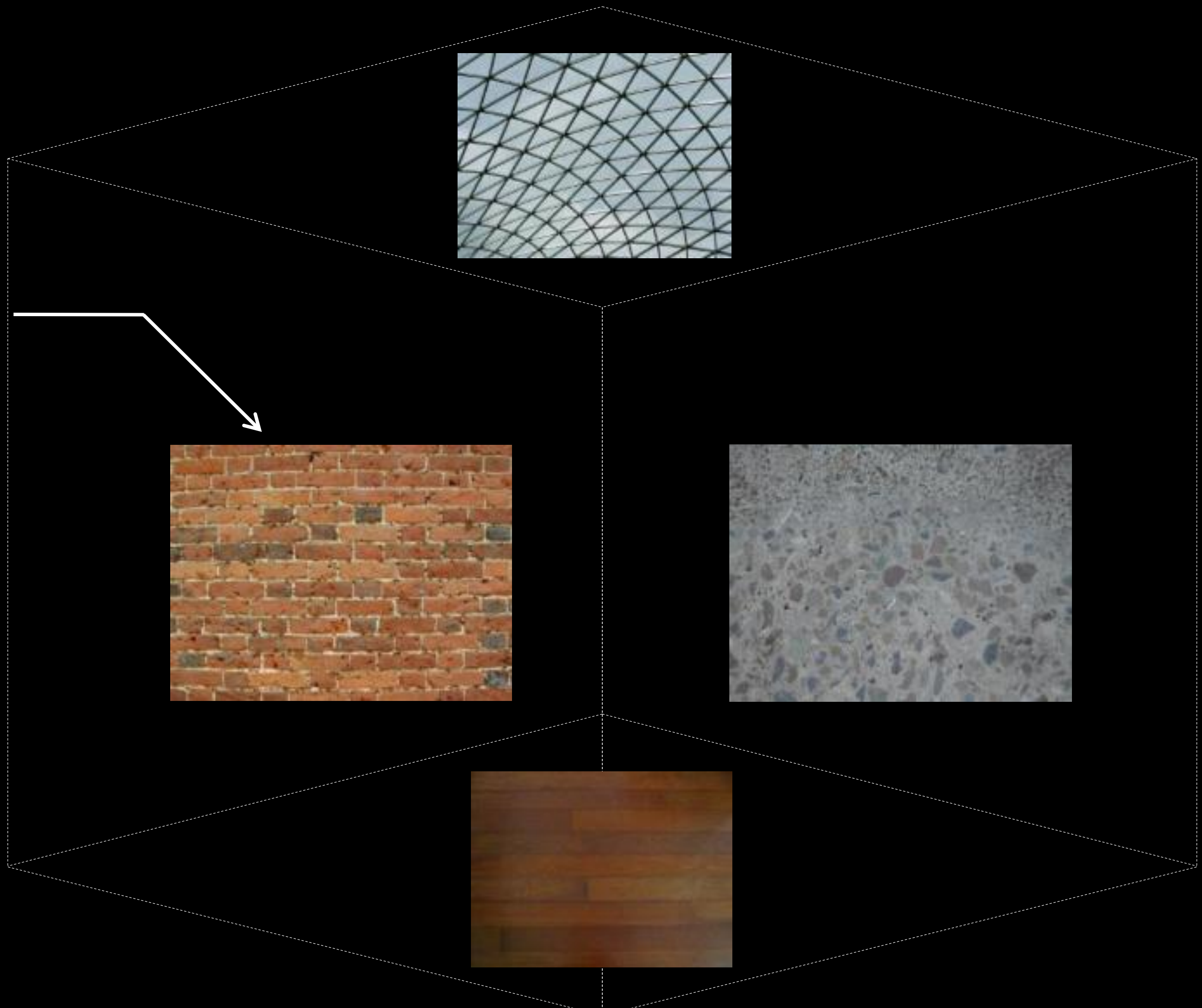
Fire & Smoke Modeling

Computational Fluid Dynamics (CFD)

Define……..

Geometry

Boundary Materials



Fire & Smoke Modeling

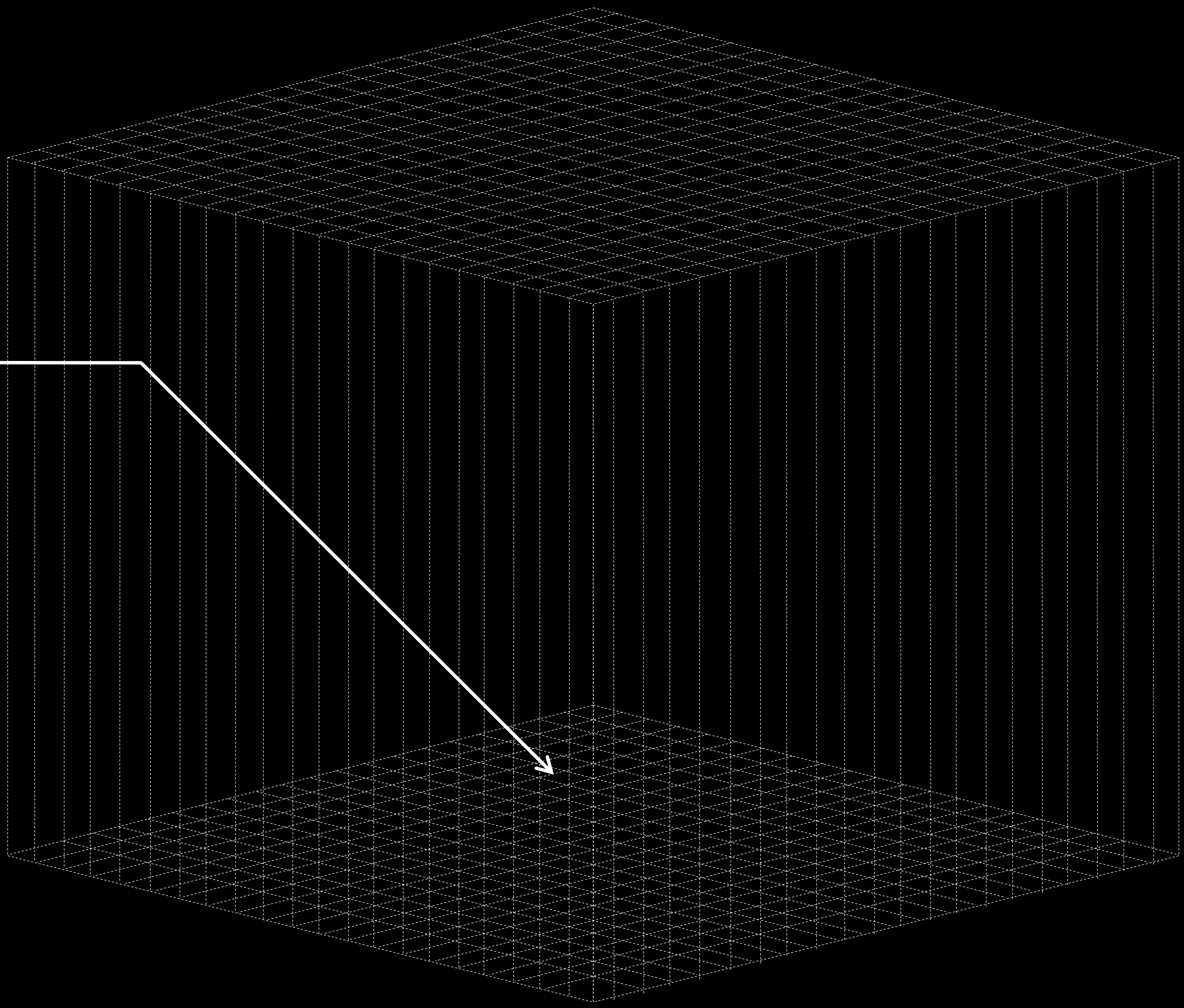
Computational Fluid Dynamics (CFD)

Define……..

Geometry

Boundary materials

Mesh



Fire & Smoke Modeling

Computational Fluid Dynamics (CFD)

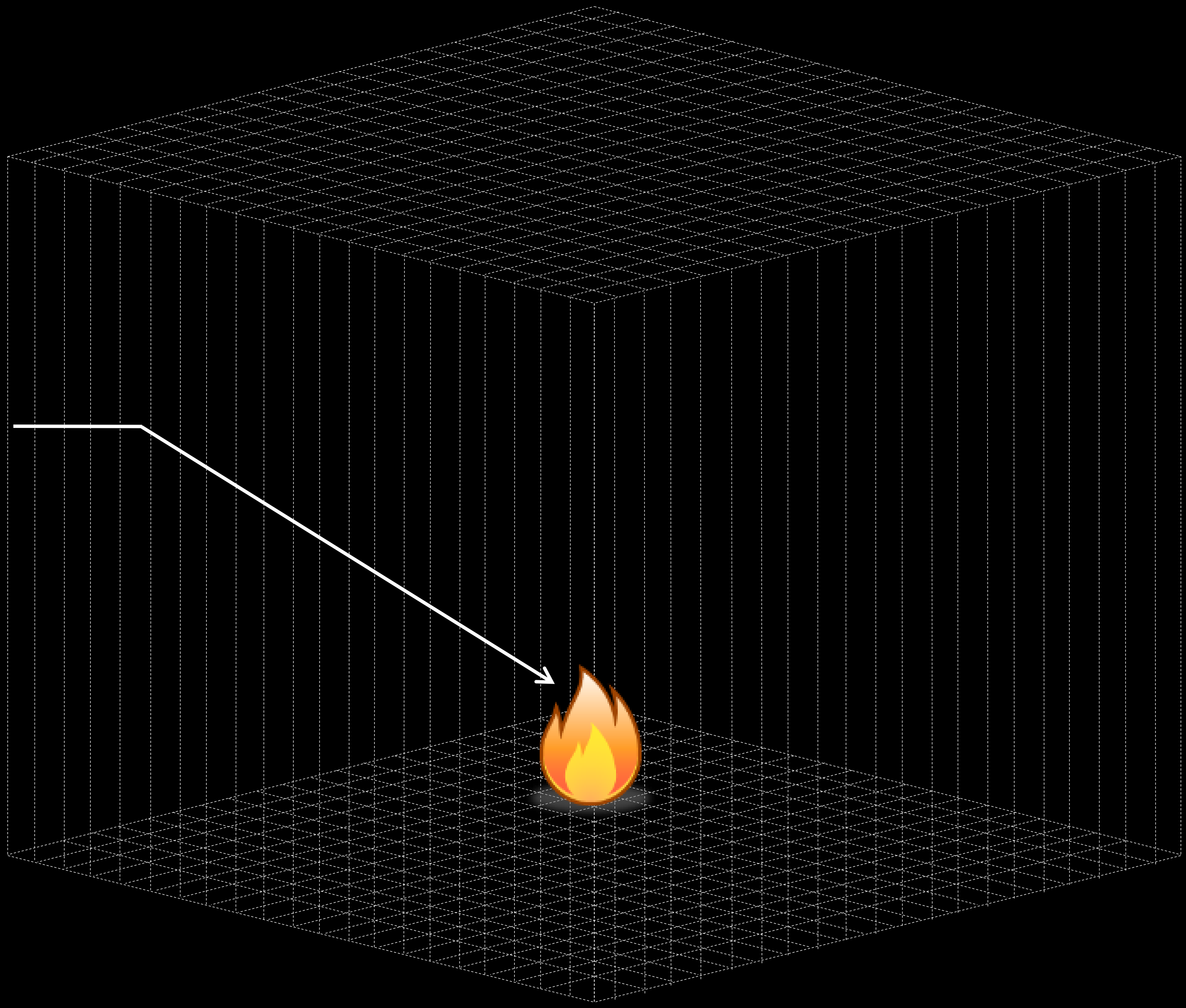
Define……..

Geometry

Boundary materials

Mesh

Fire Location/size



Fire & Smoke Modeling

Computational Fluid Dynamics (CFD)

Define……..

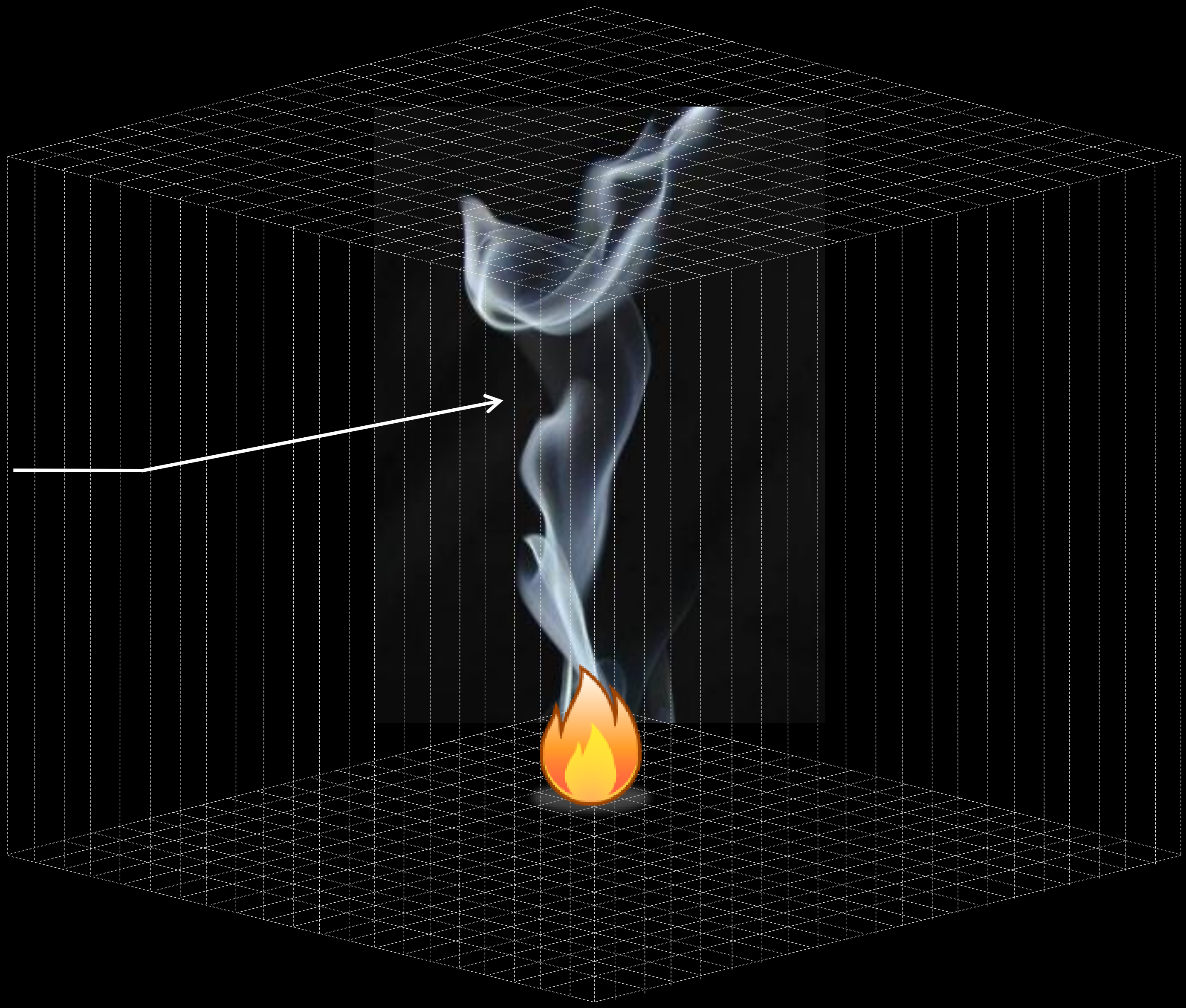
Geometry

Boundary materials

Mesh

Fire Location/size

Soot Yield

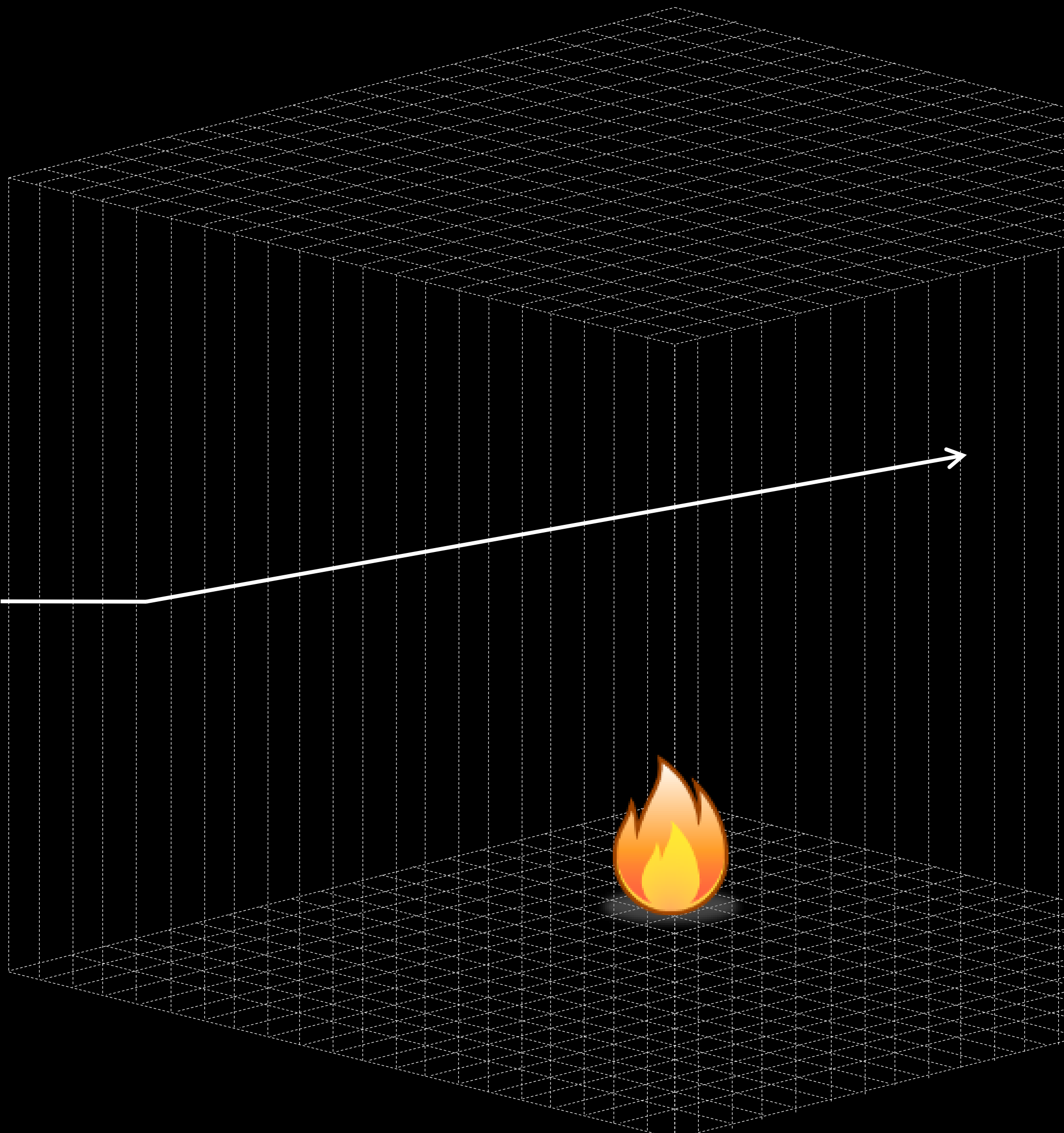


Fire & Smoke Modeling

Computational Fluid Dynamics (CFD)

Define……..

- Geometry
- Boundary materials
- Mesh
- Fire Location/size
- Soot Yield
- Extract Provisions



Fire & Smoke Modeling

Computational Fluid Dynamics (CFD)

Define……..

Geometry

Boundary materials

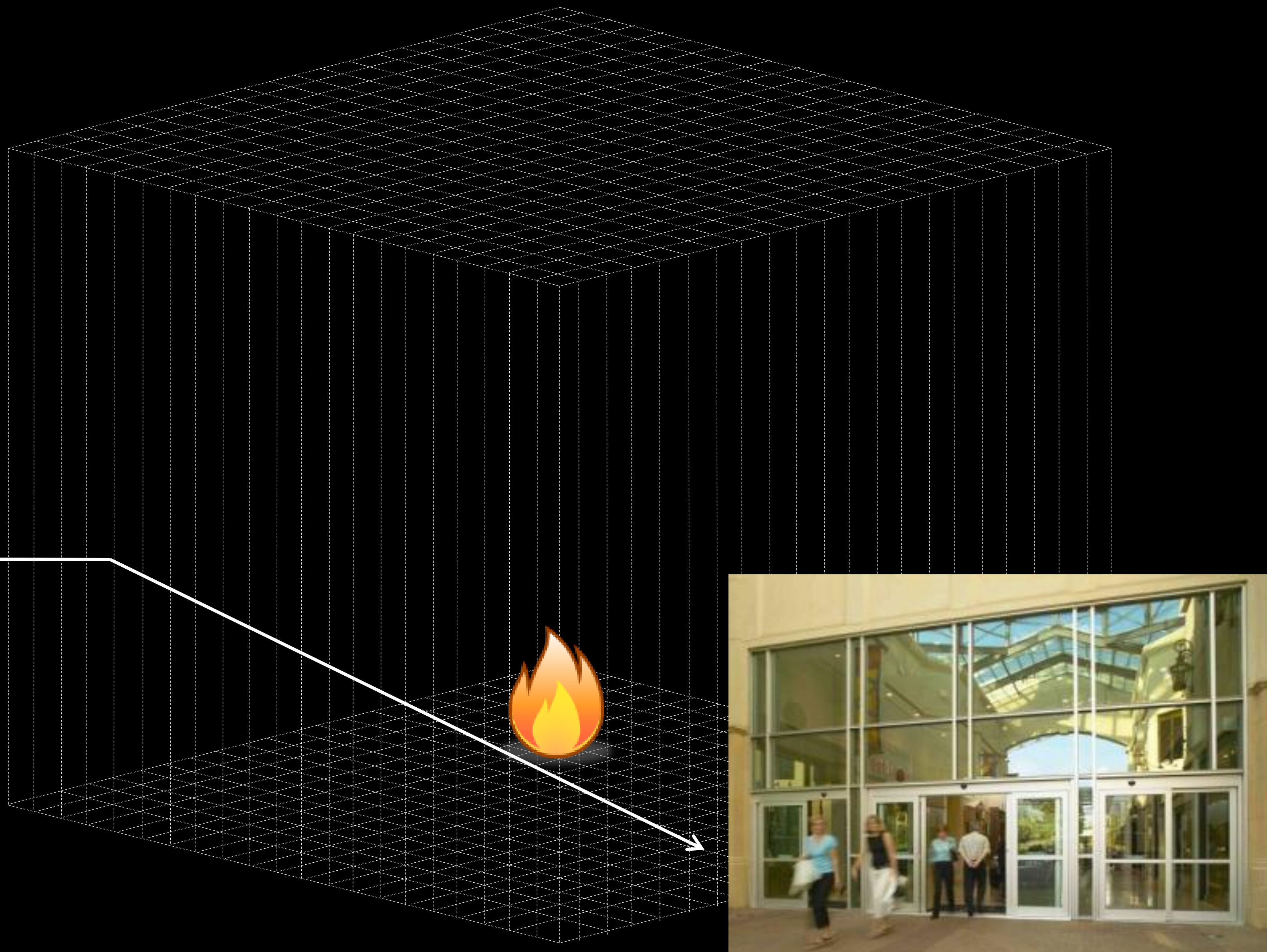
Mesh

Fire Location/size

Soot Yield

Extract Provisions

Replacement Air



Fire & Smoke Modeling

Computational Fluid Dynamics (CFD)

Define……..

Geometry

Boundary materials

Mesh

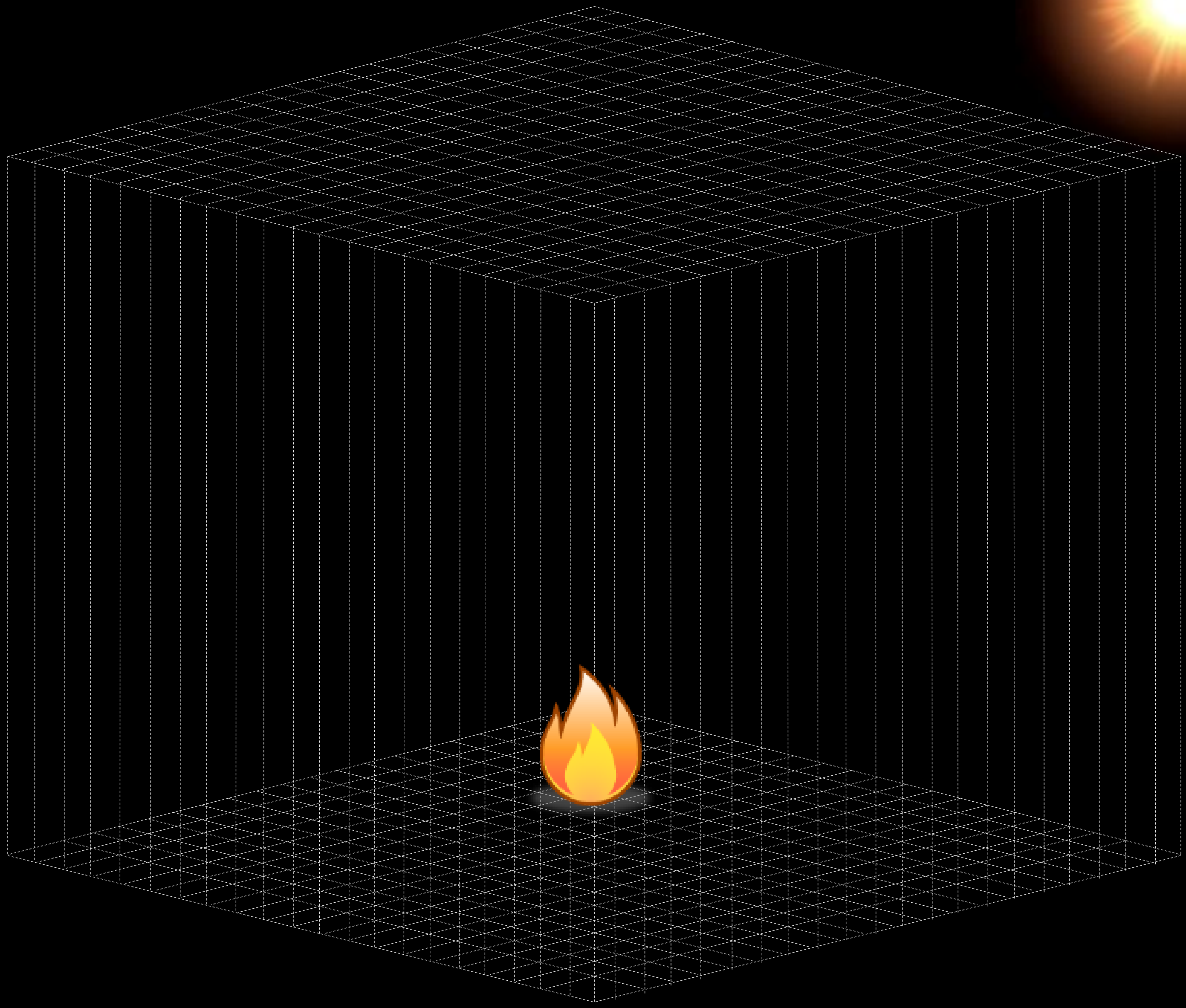
Fire Location/size

Soot Yield

Extract Provisions

Replacement Air

External Temp



Fire & Smoke Modeling

Computational Fluid Dynamics (CFD)

Define……..

Geometry

Boundary materials

Mesh

Fire Location/size

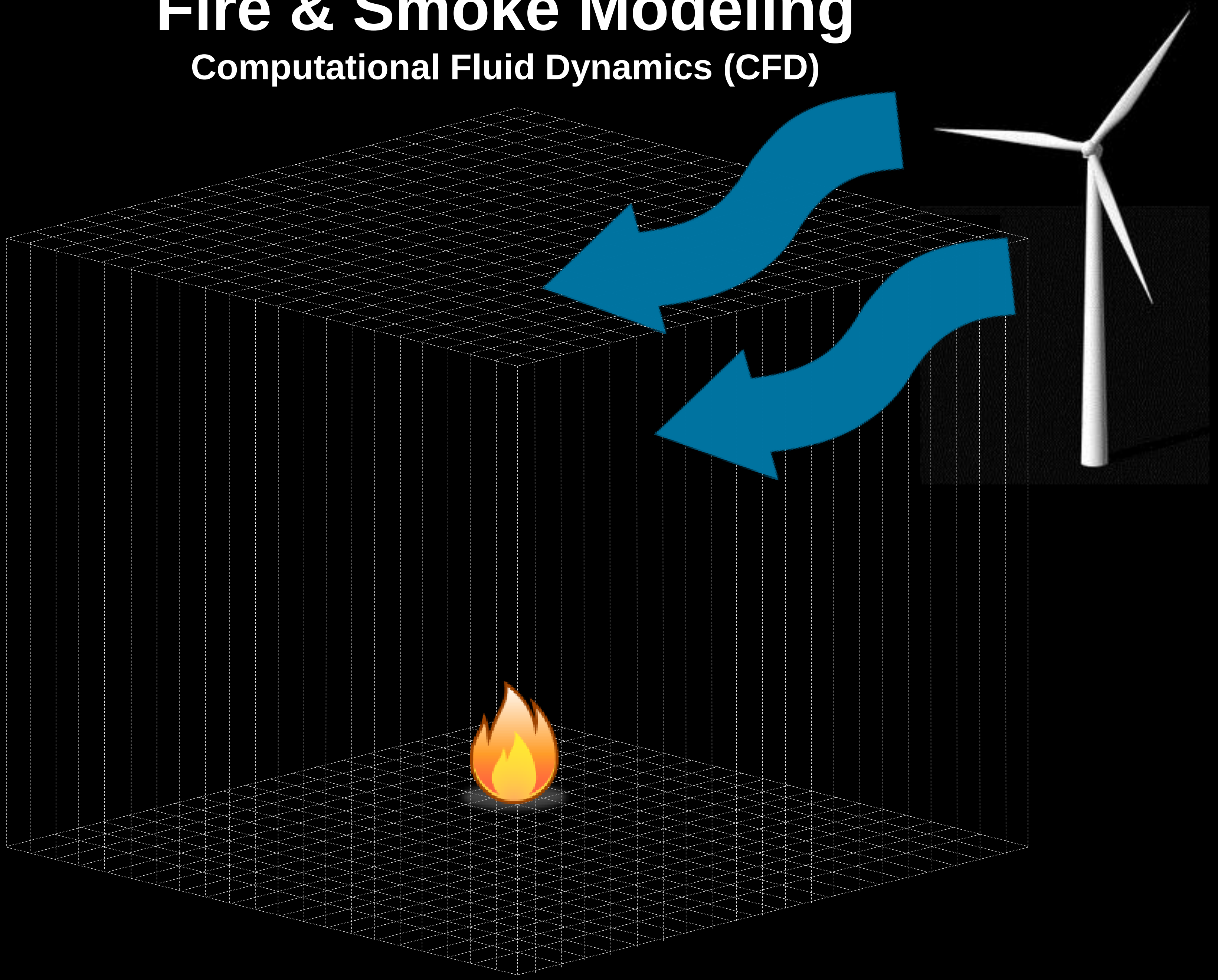
Soot Yield

Extract Provisions

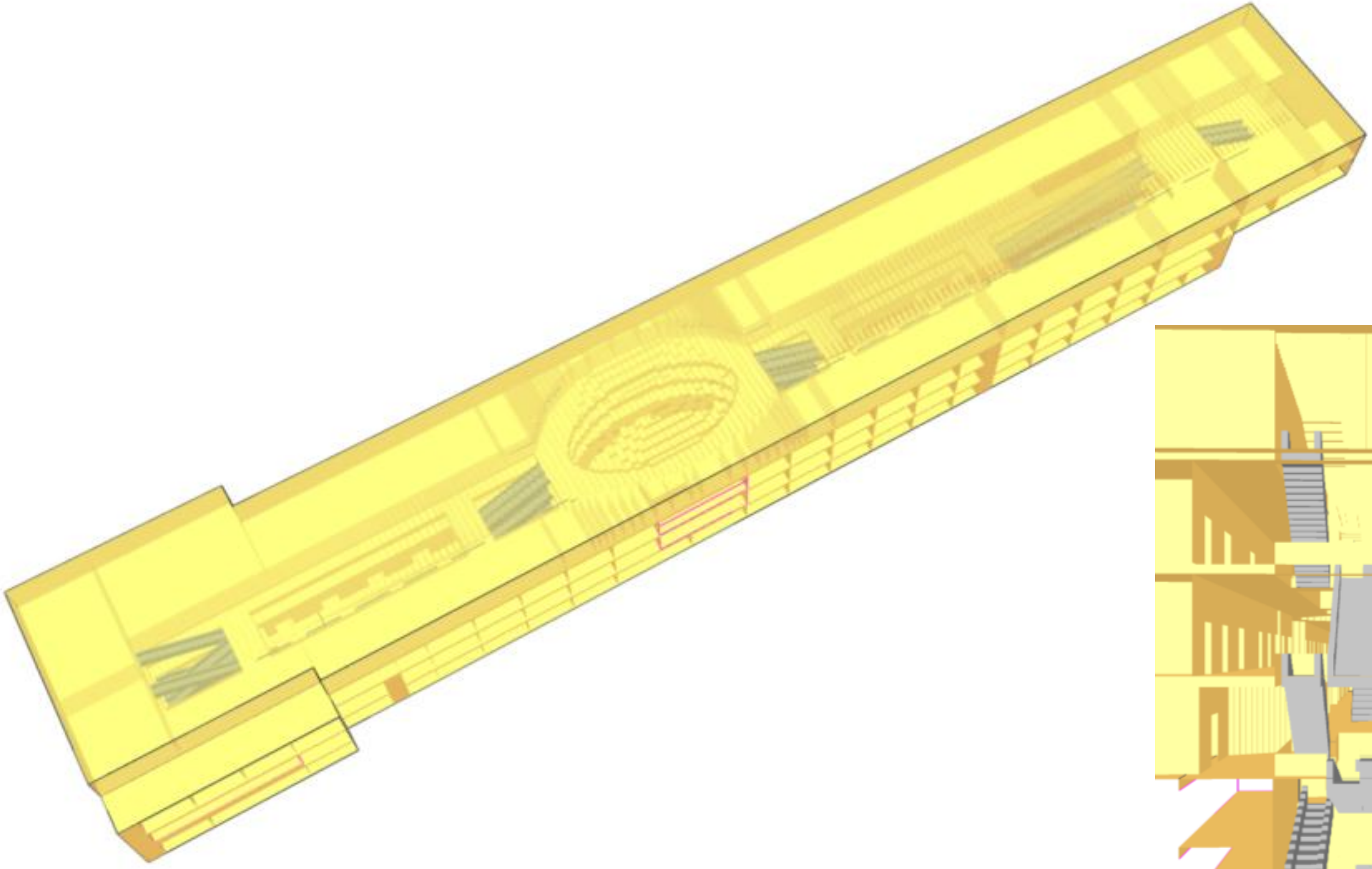
Replacement Air

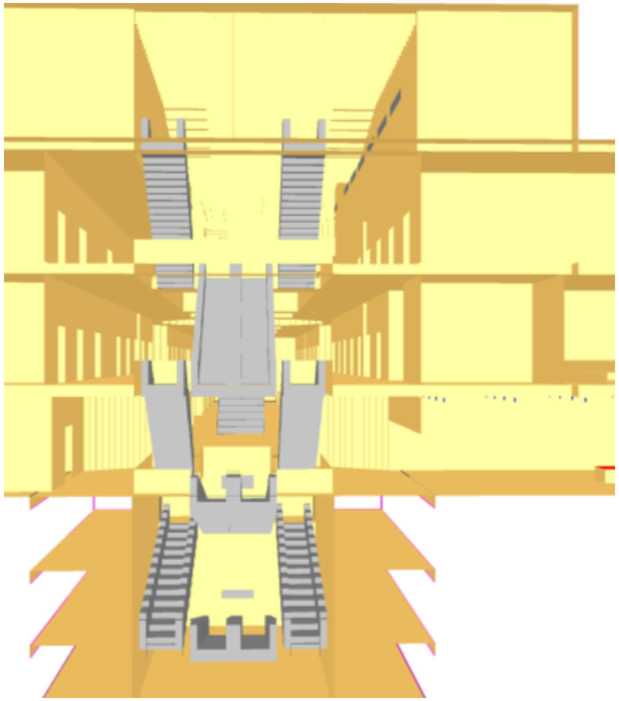
External Temp

Wind Conditions

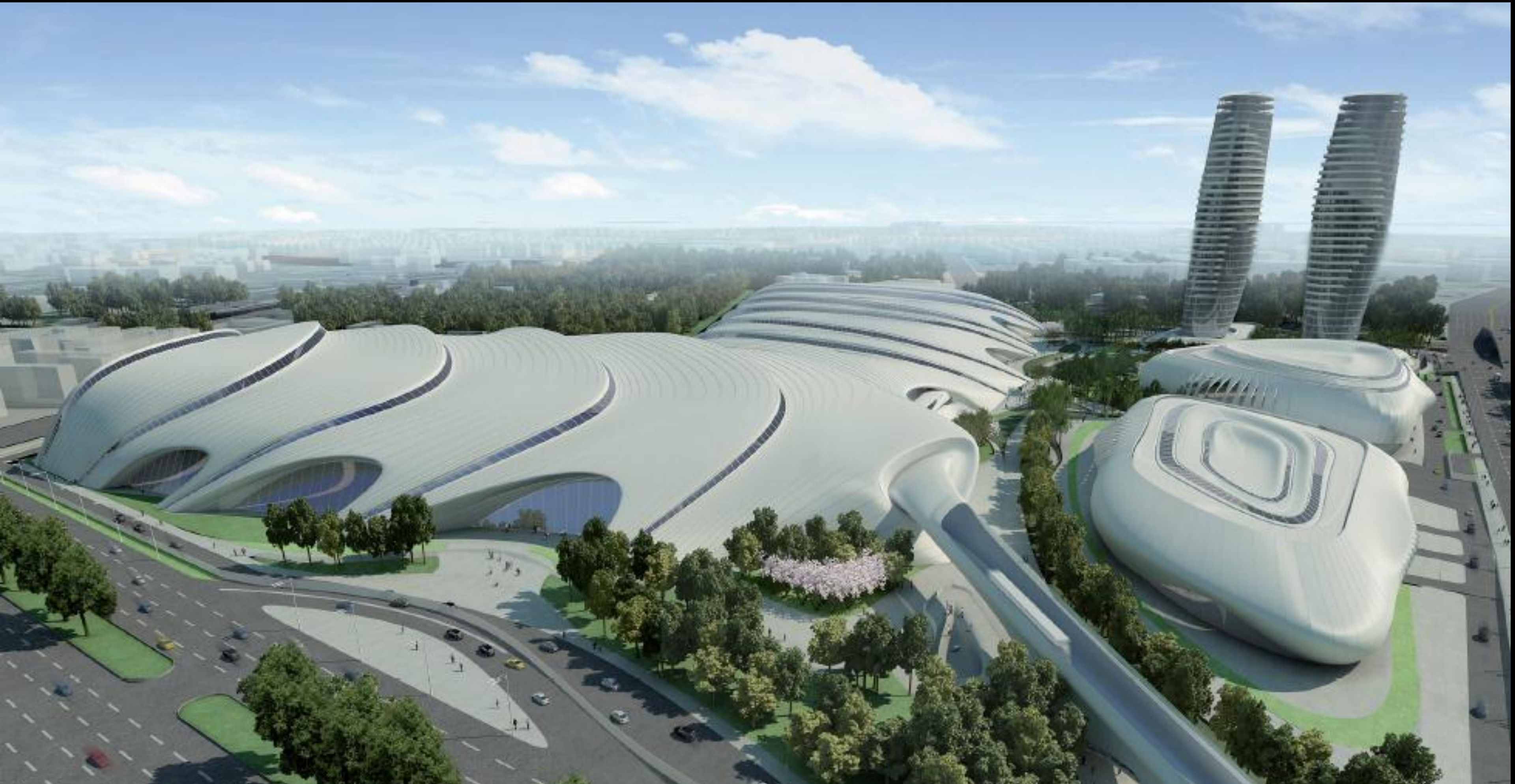


CFD Assessment – Example of a Shopping Mall





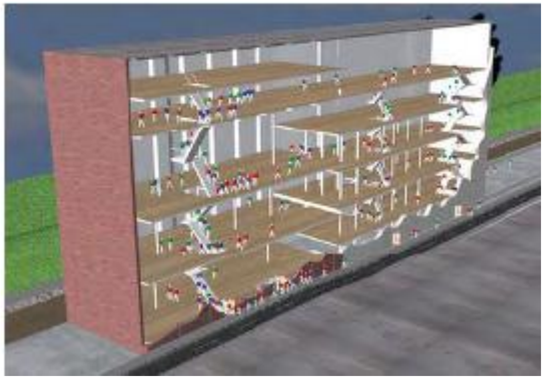
Egress Modeling



Egress Modelling

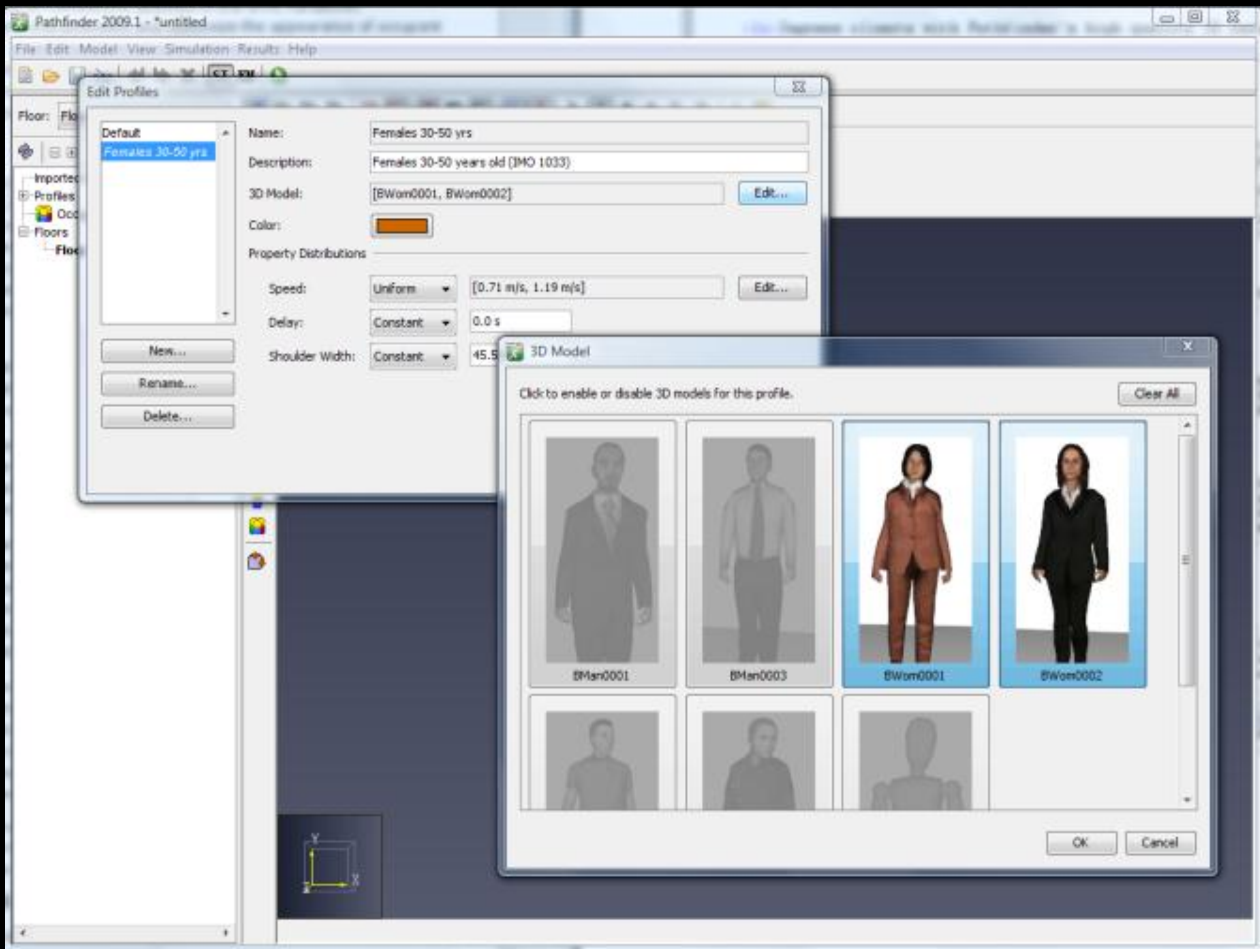
There are different approaches to egress modelling:

- Follow prescriptive escape width and distance provisions in codes
- Use simple flow calculations by hand
- Use network models (Steps,…)
- Use agent based egress modelling (Exodus,…)



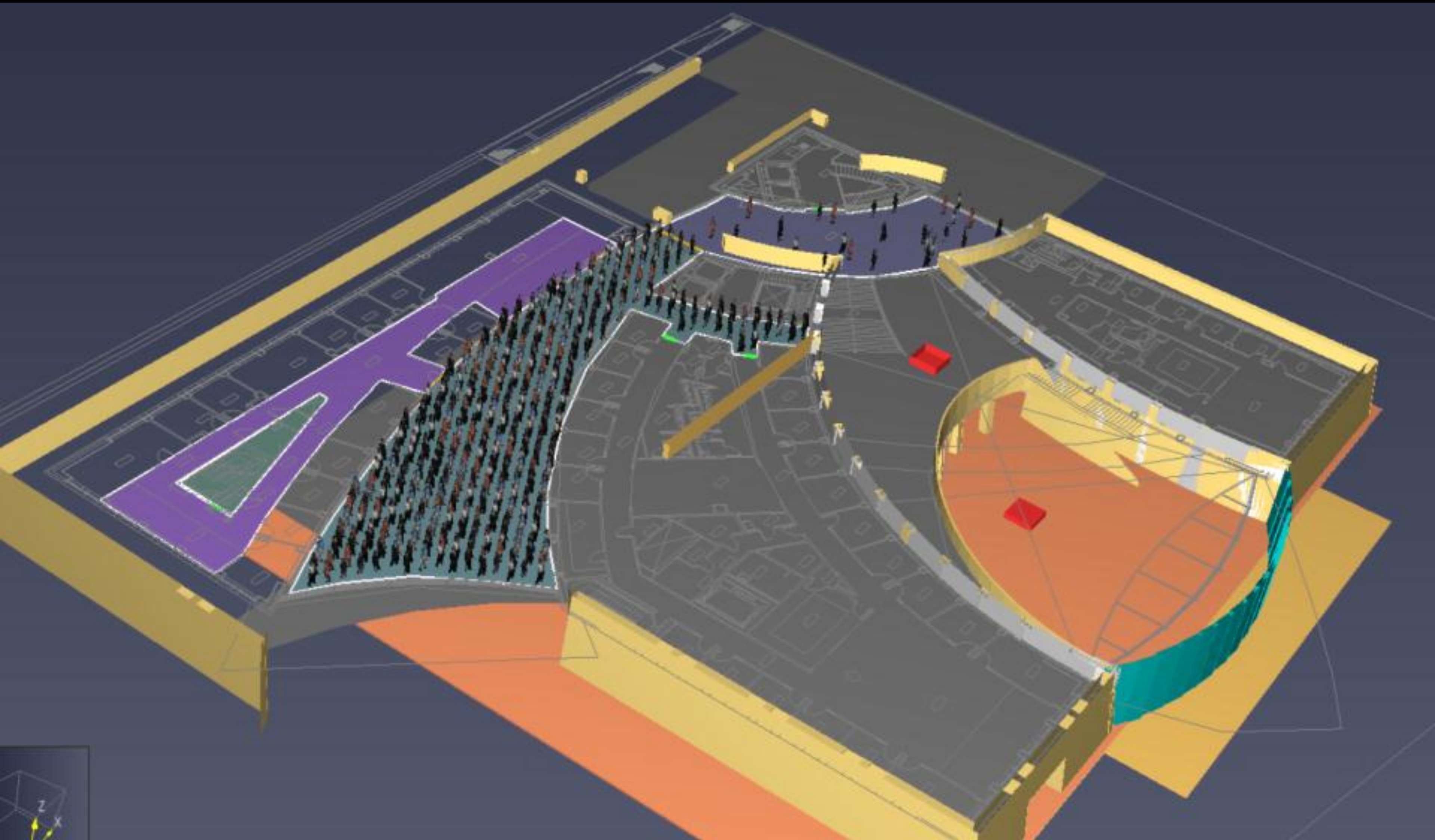
Define & Populate Geometry

Determine Population Characteristics

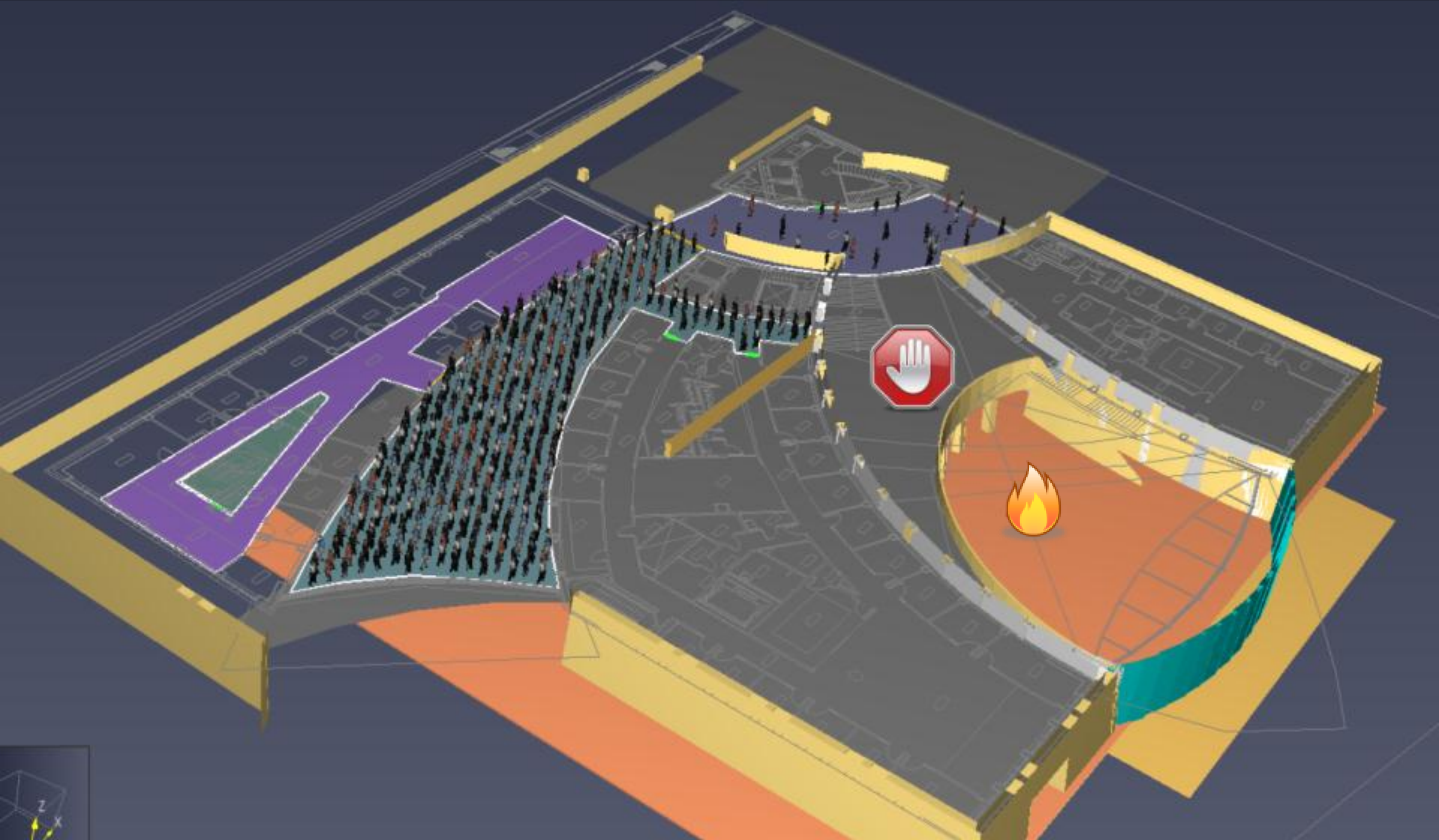


- Age/Gender
- Staff/Public
- Mobility (disabled occupant)
- Walking speed
- Distance to exit
- Flow rate though doors
- Flow rates down/up stairs
- Decision making algorithms;
  - Pre movement time
  - Nearest exit
  - Main exit
  - Follow crowd
  - Redistribution upon queuing

Fill Geometry

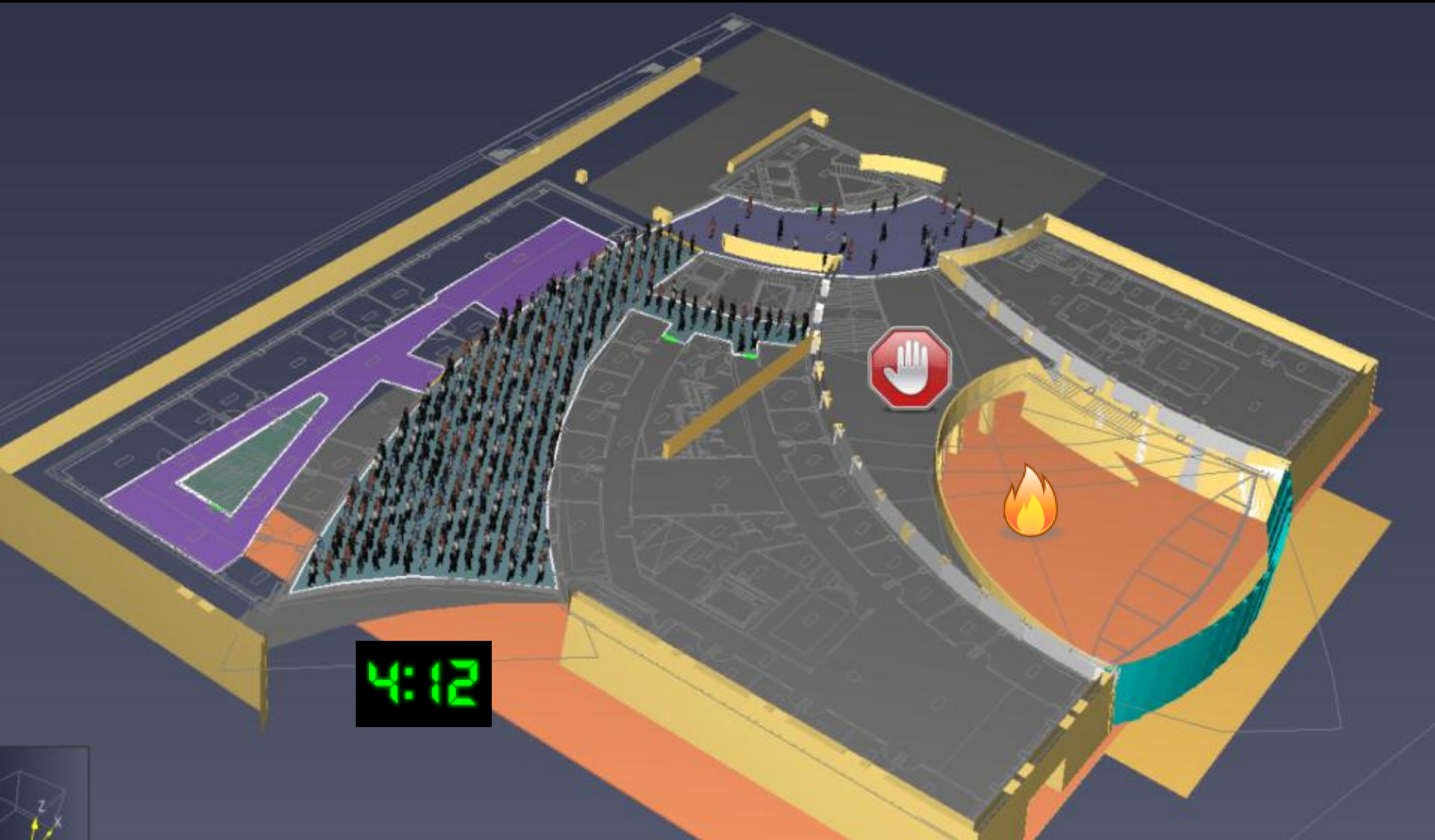


Define Fire Location



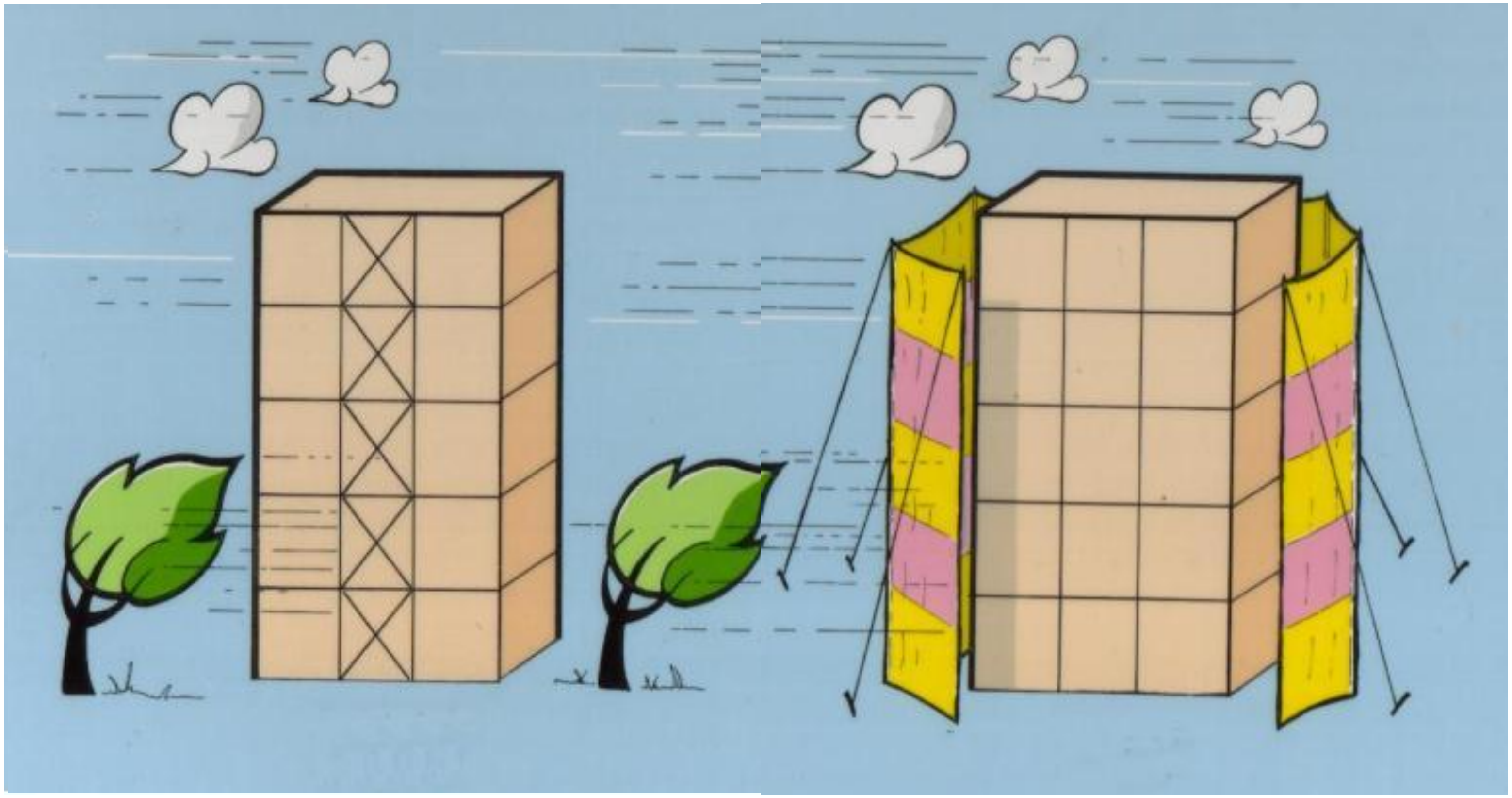
Egress Modeling

Time to Evacuate + Factor of Safety **<** Time to untenable Conditions



Structural Fire Engineering Design Methods

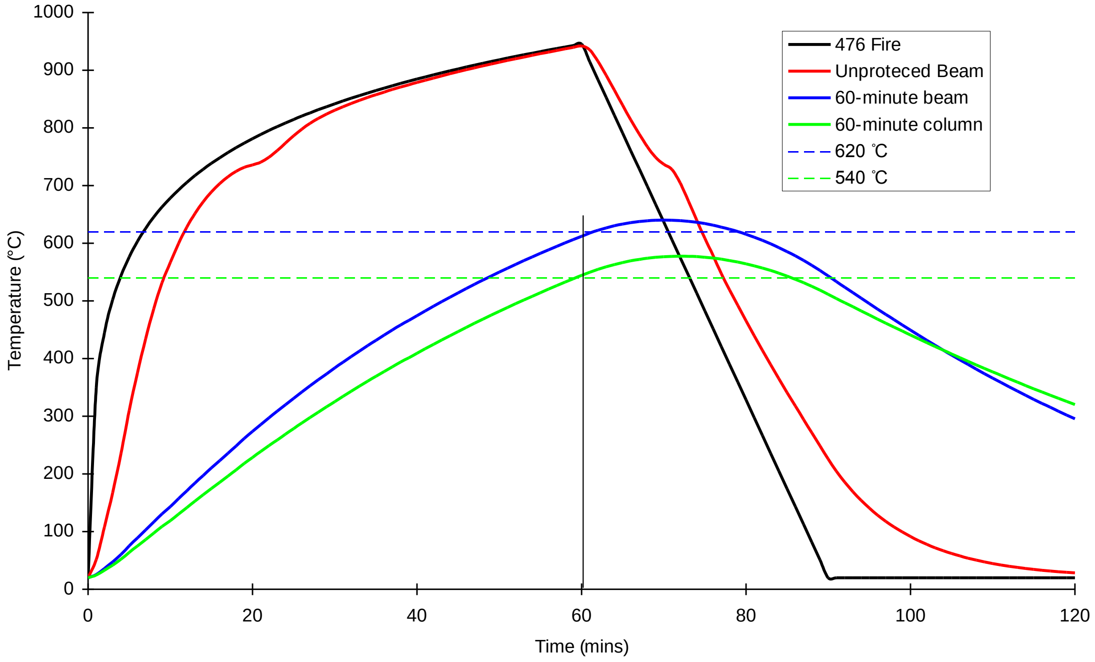
Designing for Wind

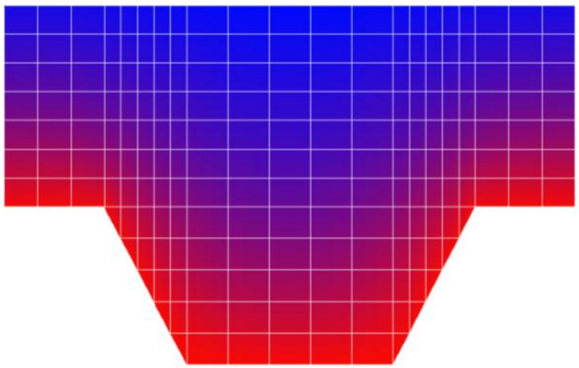


Design to resist wind **Protect from wind**

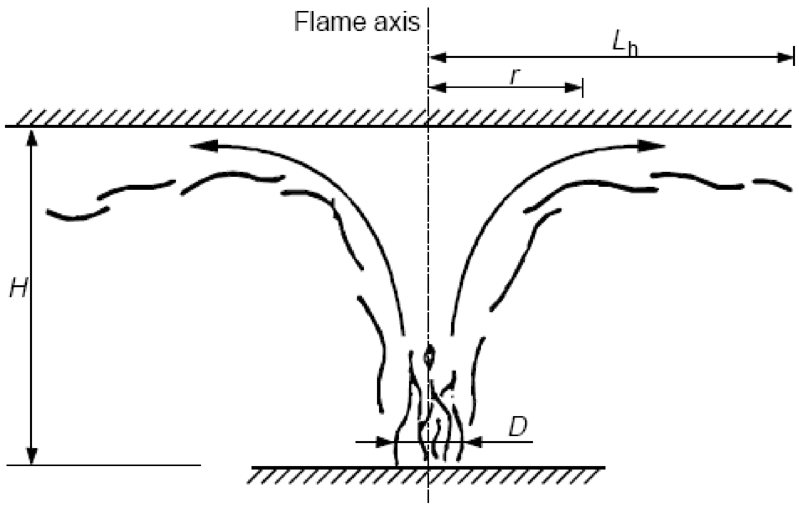
Heat transfer from fire to structure - compartment fire

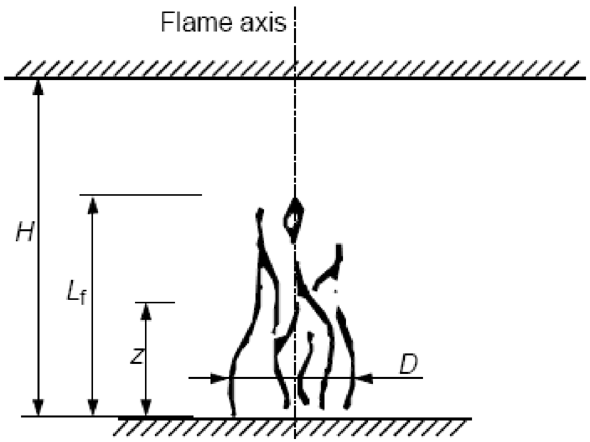
1. Table 9 and 10 in BS5950-8: Temperature depending on flange thickness.
2. Simple heat transfer method in Eurocode 3-1.2 for protected and unprotected steel members depending on section factor.
3. Finite element software: SAFIR, TASEF, ANSYS, ABAQUS



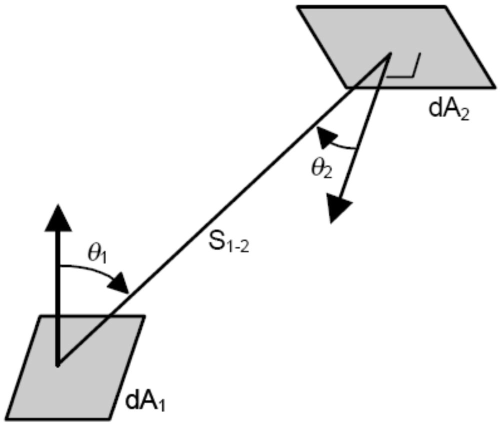


Heat transfer from fire to structure – localised fire





Radiation
Convection if member is in the plume
View factor calculations for radiation!



Structural Responds – Fire Limit State

A fire limit state should be treated as an ***Accidental Limit State*** with its own associated partial factors

Load Factors (γ_f) - Table 2 BS5950-8

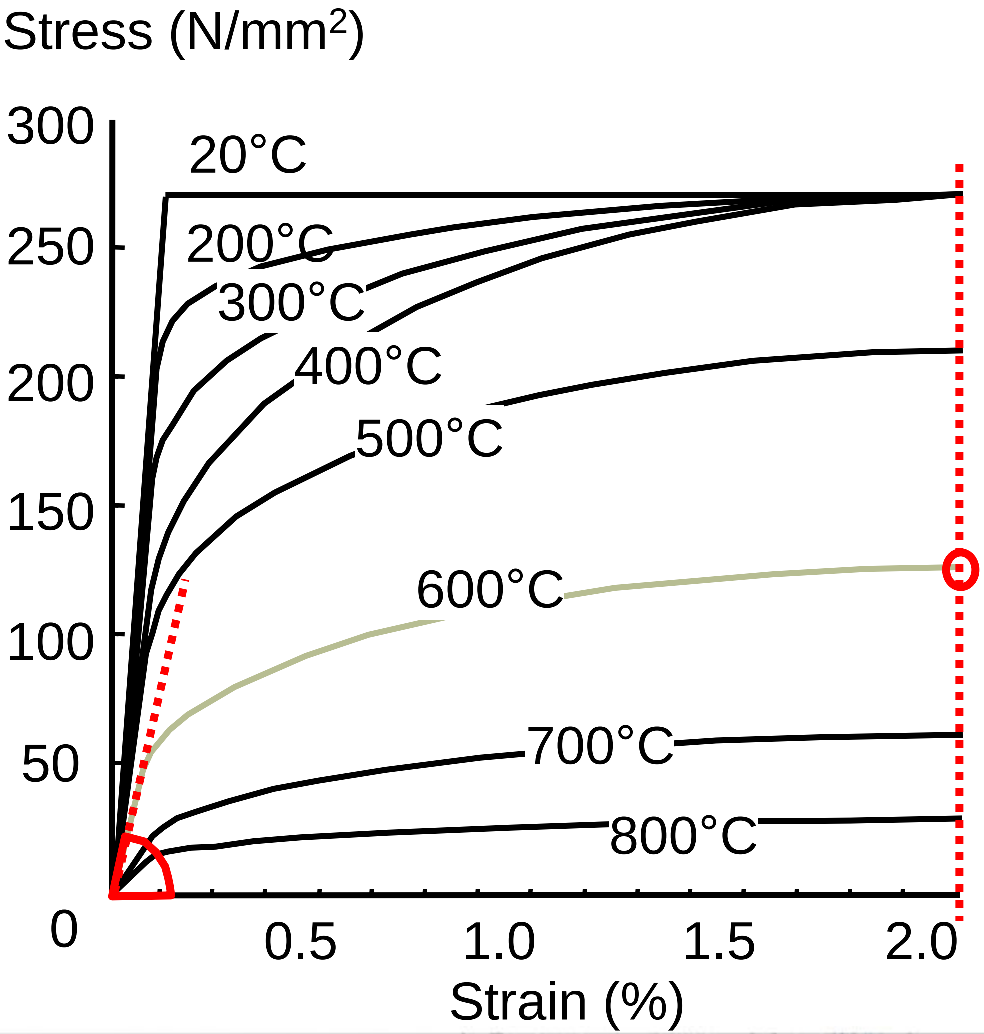
• Dead Loads	1.0
• Imposed Loads (permanent)	1.0
• Imposed Loads (non-permanent)	0.8
for commercial offices	0.5
• Wind Loads	0.33

Steel stress-strain curves at high temperatures

- Strength/stiffness reduction factors for elastic modulus and yield strength (2% strain).

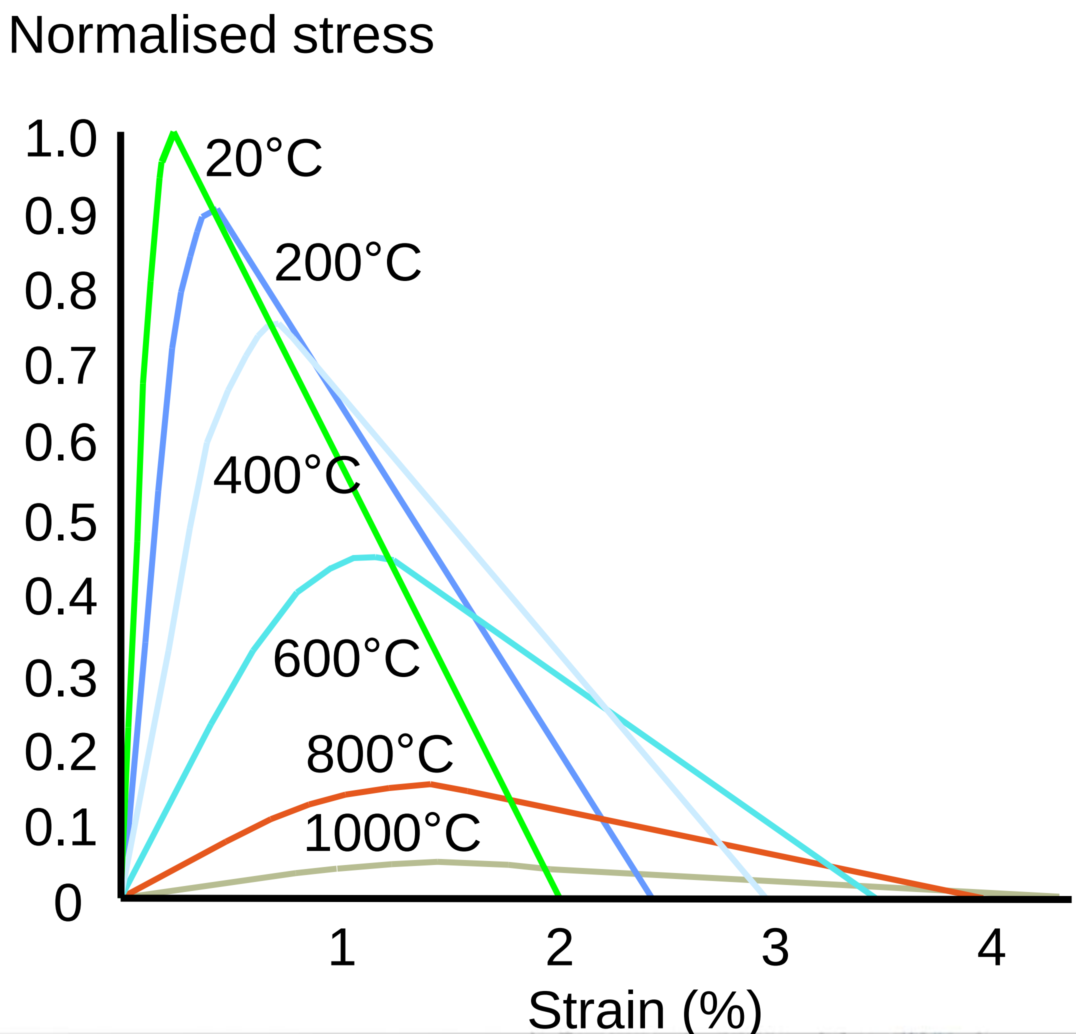
- Elastic modulus at 600°C reduced by about 70%.

- Yield strength at 600°C reduced by over 50%.



Concrete stress-strain curves at high temperatures

- Concrete also loses strength and stiffness from 100°C upwards.
- Does not regain strength on cooling.
- High temperature properties depend mainly on aggregate type used.
- Spalling for dense and high-strength concretes.



Limiting Temperature Method

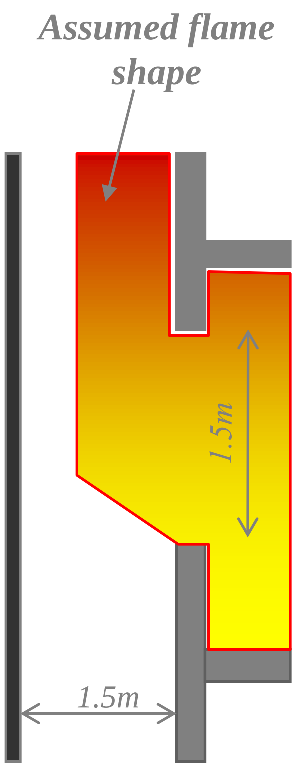
The *Design temperature* is the temperature which the section will reach at the prescribed fire resistance time. It is based on member type and fire resistance

The *Limiting temperature* is the temperature at which the section is deemed to fail. It is based on member type, thermal gradient and Load Ratio

Limiting Temperature > Design Temperature

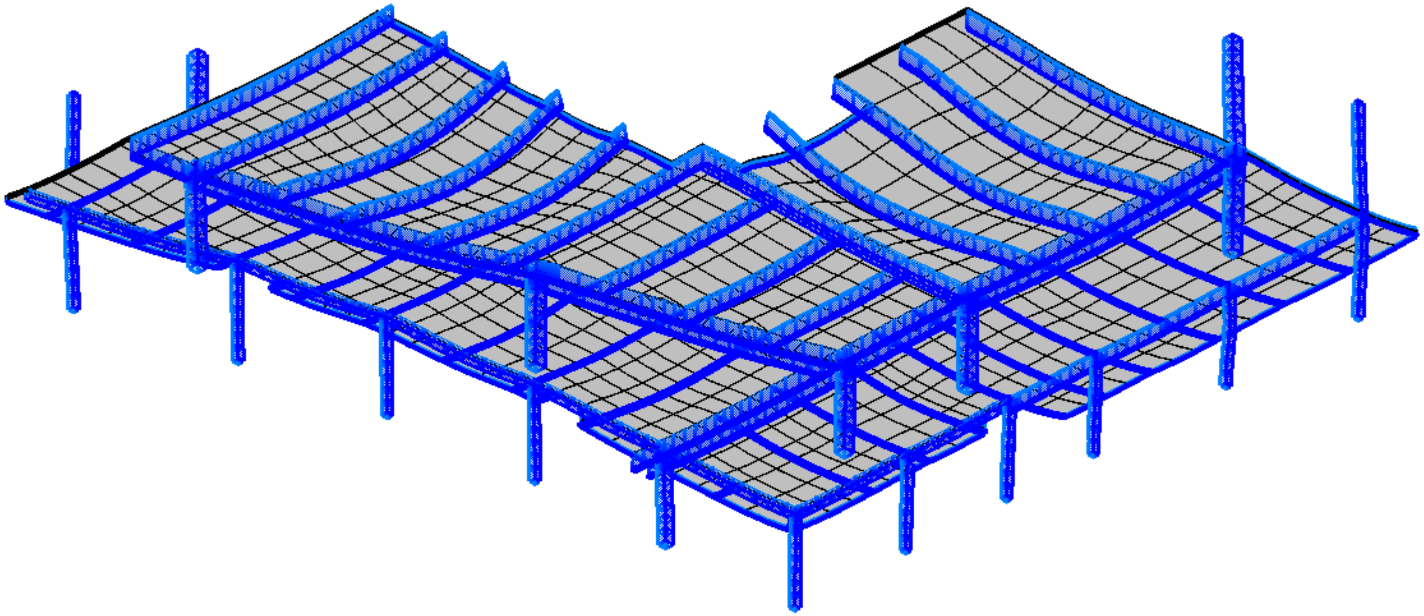
External Steelwork calculations

- Assessing flames breaking out of windows.
- If distance between window and steel is large enough no fire protection is needed.
- Simple methods have been published by SCI and are repeated in the Eurocodes.
- Significant assumptions are made in the simplified approach in terms of:
  - Fire development in compartment
  - Flame and smoke plume shape
  - Effects of wind
  - Heat transfer parameters
- For significant projects a series of CFD analyses could be used to perform a more realistic assessment.



Finite Element Analysis – Vulcan

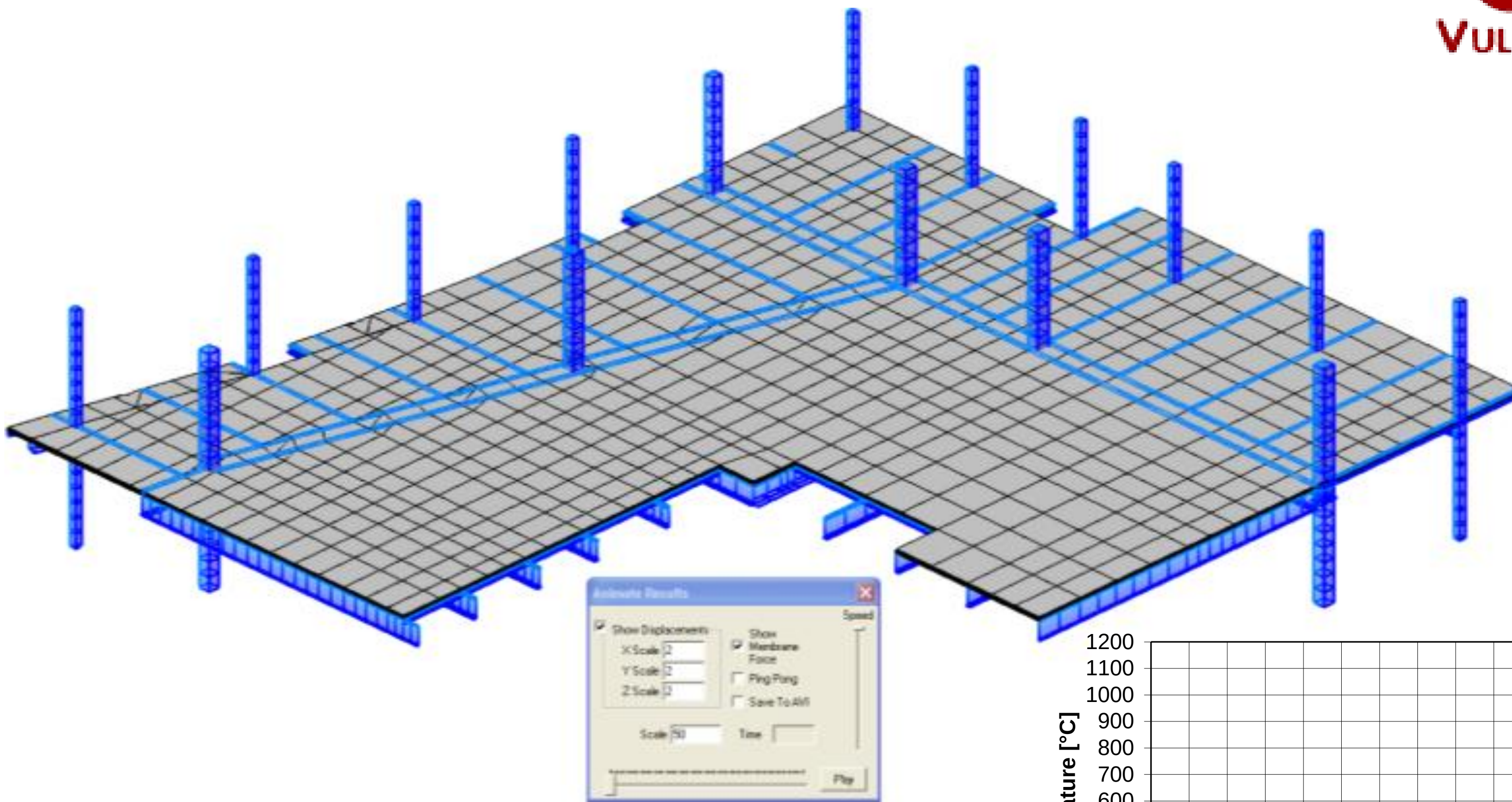
Vulcan is a non-linear finite element program developed by the University of Sheffield and Buro Happold.

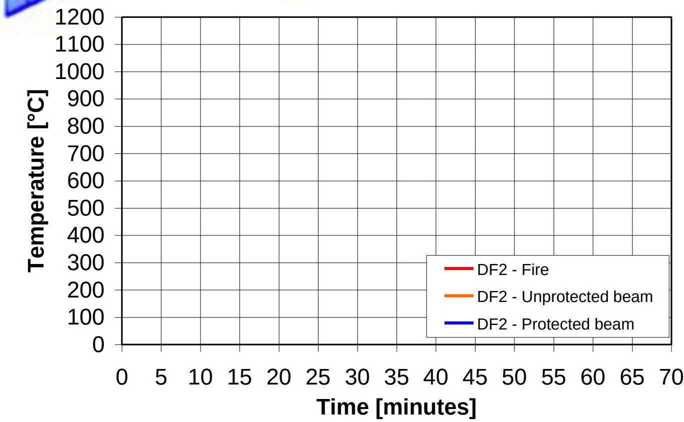


- Whole building analysis
- Can be applied to any composite steel-framed building
- Real non-linear material behaviour
- Real structural behaviour
- Exact fire protection requirements calculated for any steel member

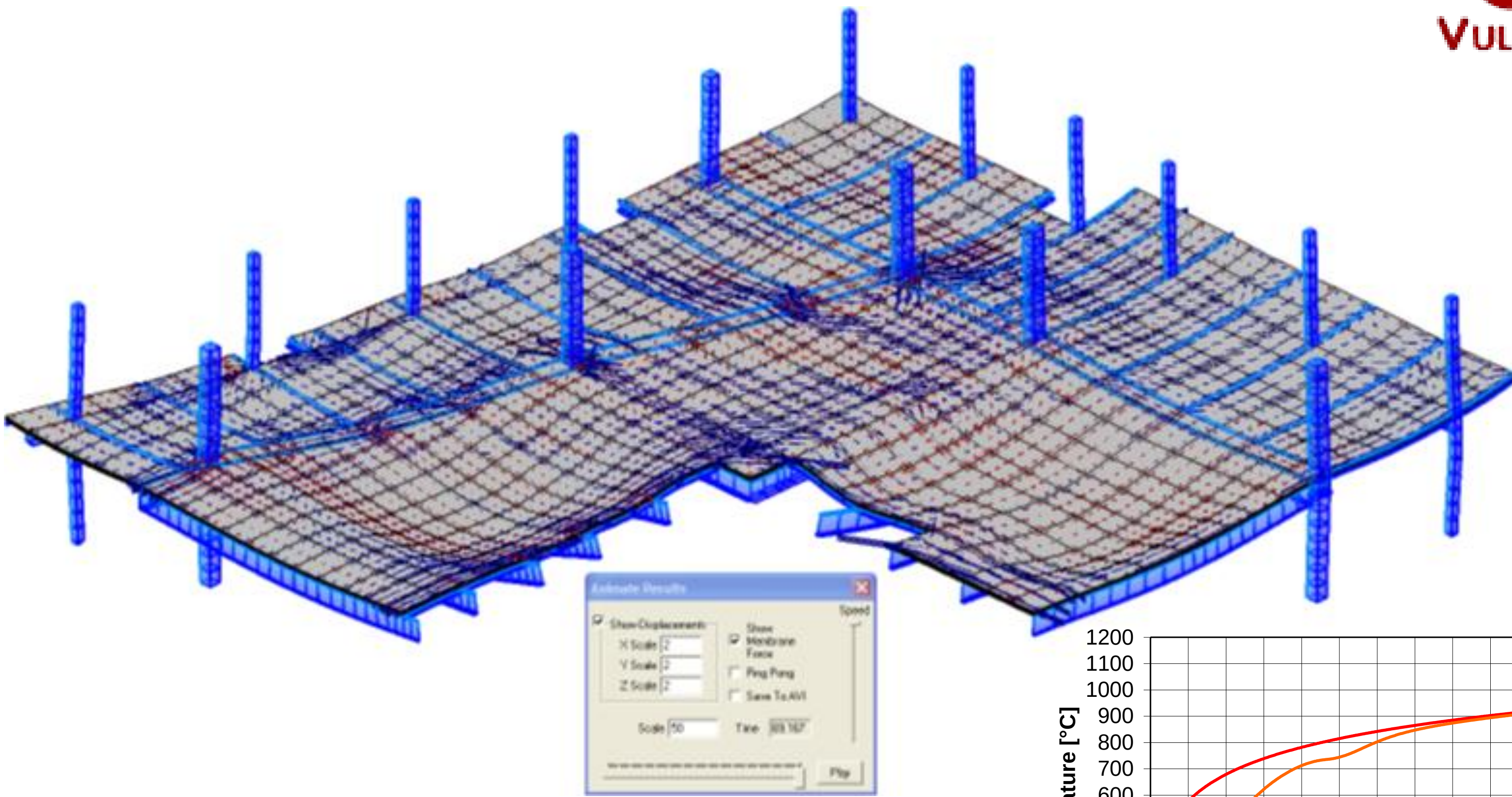
Fire behaviour of a composite floor slab

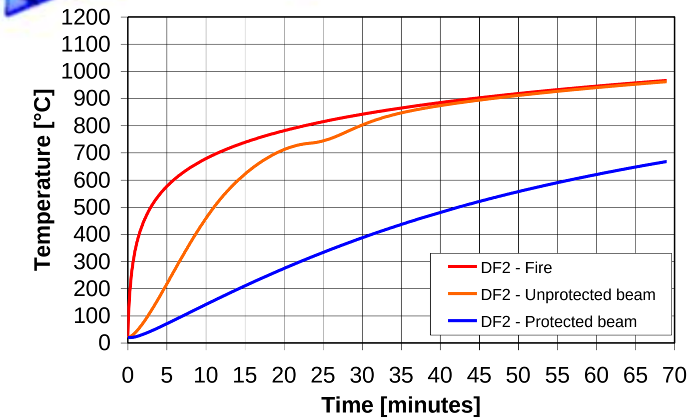
VULCAN



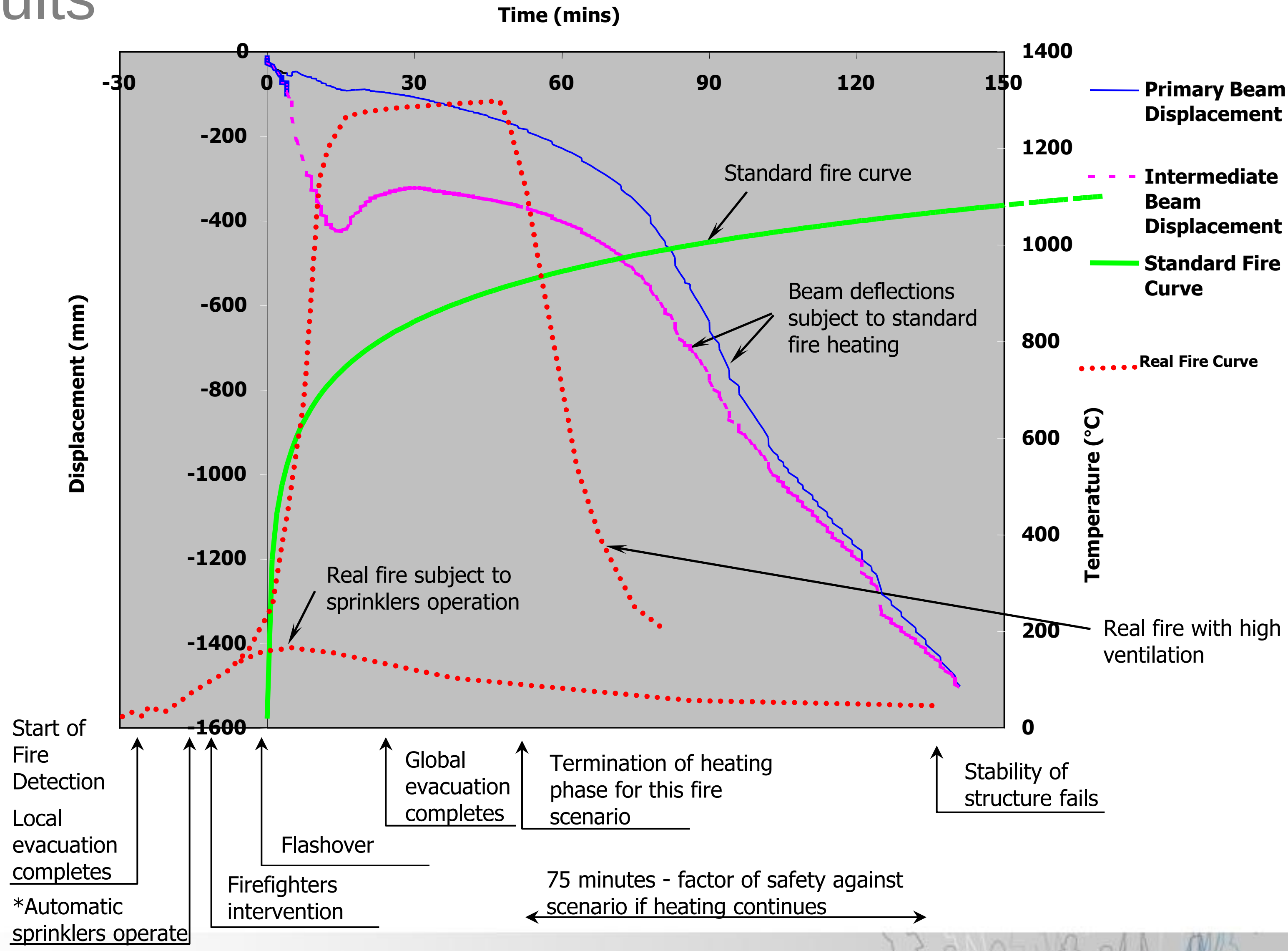


Fire behaviour of a composite floor slab





Results



Time (mins)
-30
0
30
60
90
120
150
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
Displacement (mm)
1400
1200
1000
800
600
400
200
0
Temperature (°C)
Primary Beam Displacement
Intermediate Beam Displacement
Standard Fire Curve
Real Fire Curve
Standard fire curve
Beam deflections subject to standard fire heating
Real fire subject to sprinklers operation
Real fire with high ventilation
Start of Fire Detection
Local evacuation completes
*Automatic sprinklers operate
Firefighters intervention
Flashover
Global evacuation completes
Termination of heating phase for this fire scenario
Stability of structure fails
75 minutes - factor of safety against scenario if heating continues

Sensitivity Study

- It is essential that sufficient sensitivity studies are performed to ensure that a robust solution.
- The input parameter and boundary conditions need to be varied beyond the normal design assumptions.
- Check for sudden changes in behaviours - ‘Cliff edge analysis’

Reporting and Quality Control of Assessment

Reporting:

- Detailed documentation of all assumptions and input variable with appropriate references
- Full results in calculations reports
- Summary report for stakeholders

Checking:

- 4 eyes concept
- Design reviews and sanity checks by senior staff
- Third party checking

Site Inspections and Performance Tests

- Site inspections are essential for performance based solutions during construction and after completion.
- Testing of mechanical systems – smoke test
- Trial evacuations

Case Study 1

United States Institute of Peace
Washington DC

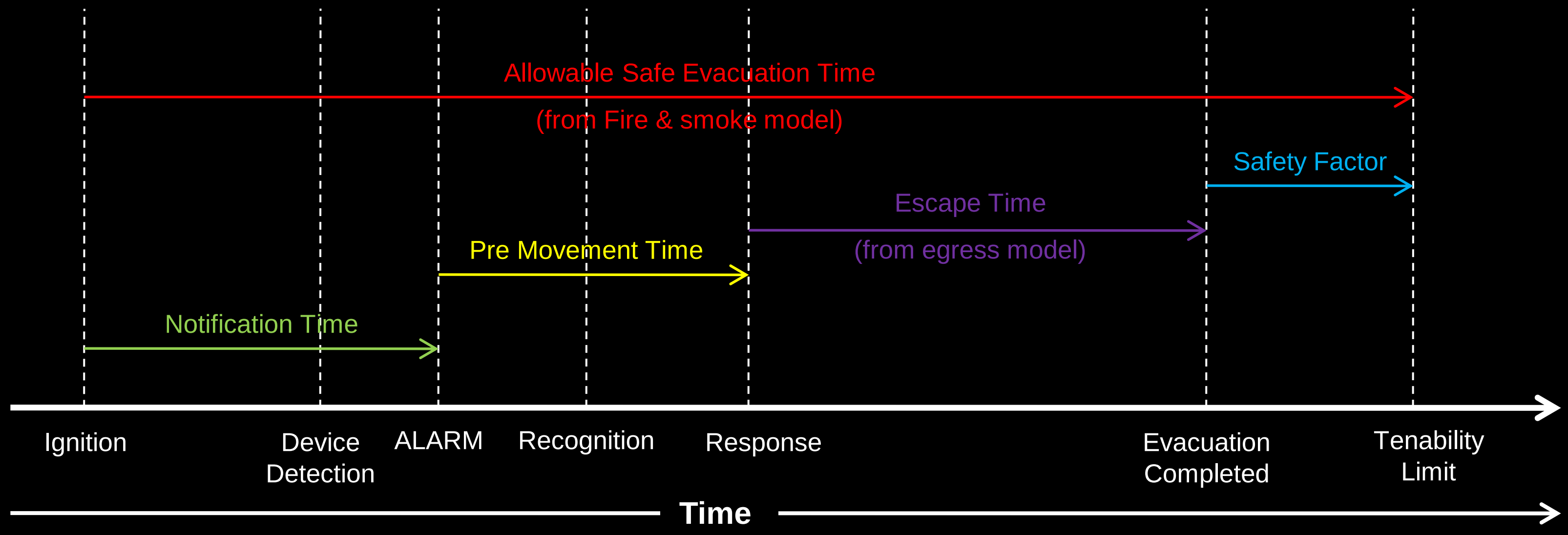

UNITED STATES INSTITUTE OF PEACE

Study Purpose

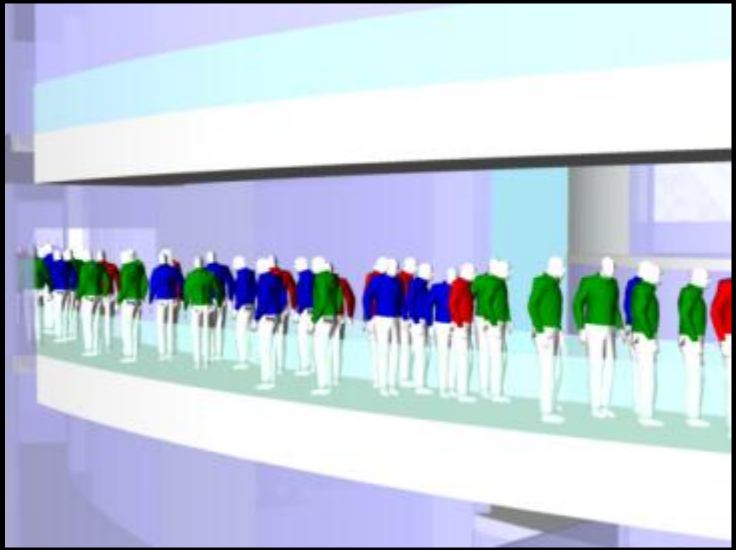
Provide safe environment for atrium occupants with **reduced smoke extract**

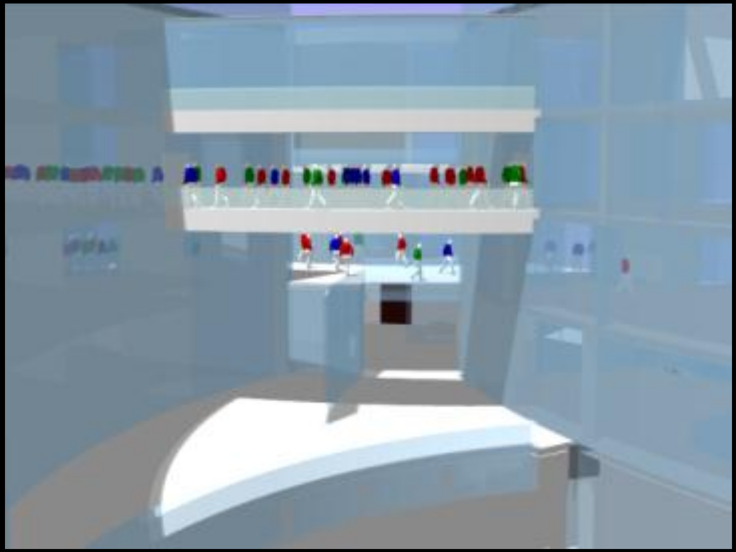
Escape Time + Safety Factor < Untenable Fire Conditions

Compare Fire & Smoke Model Vs Egress Model



Egress Model (Bridge)

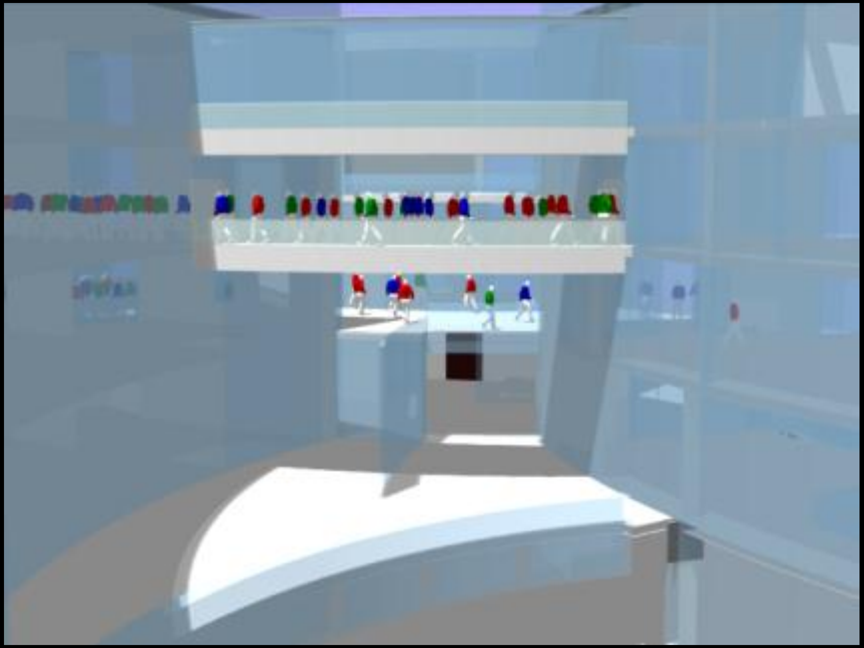


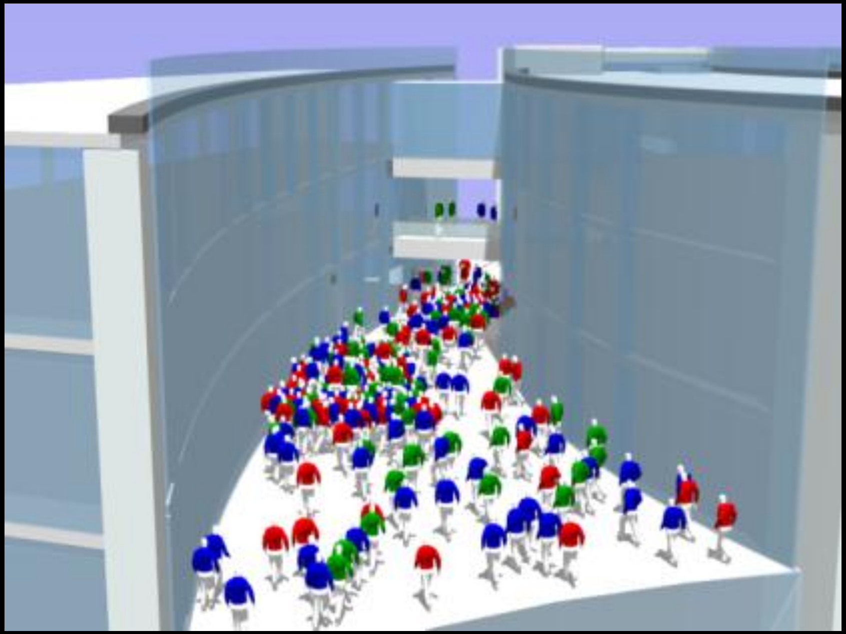


Egress Model Scenarios

Scenario 1: South Atrium →

Time for occupants to egress a fully occupied Level 4 open bridge within the South Atrium

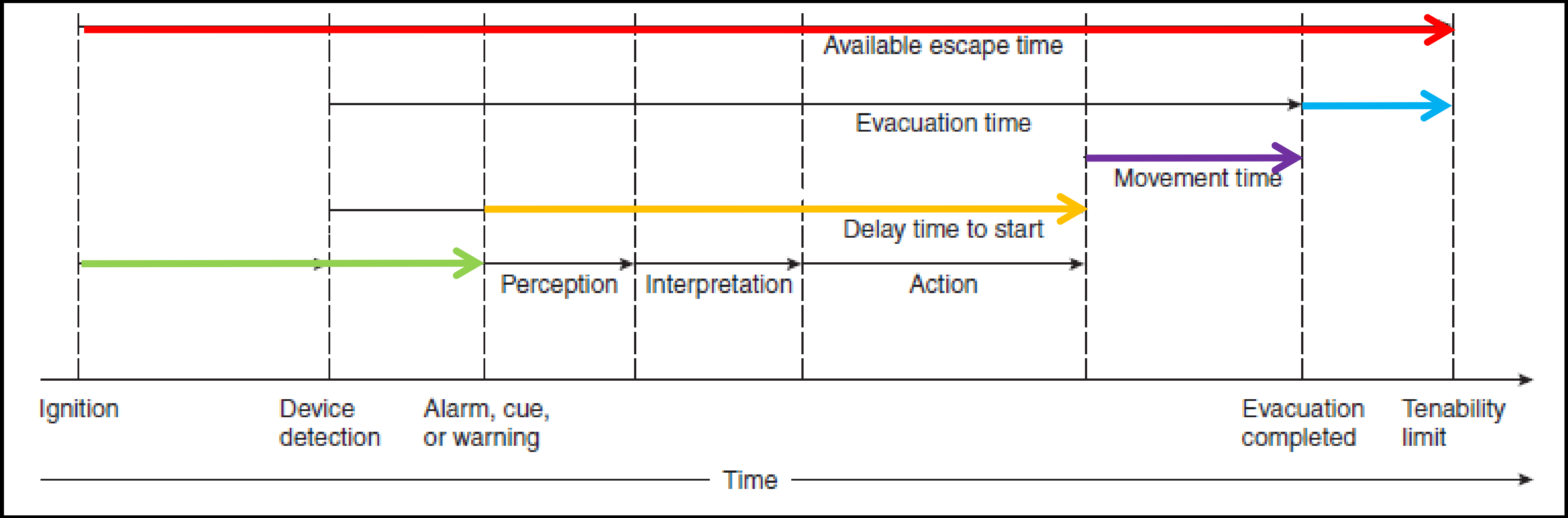




← **Scenario 2: North Atrium**

Time for occupants to egress the Level 3 North Atrium base

Evacuation Timeline (Scenario 1)



Time from fire ignition to detection – **60 seconds** (taken from live smoke test Dec 2010)

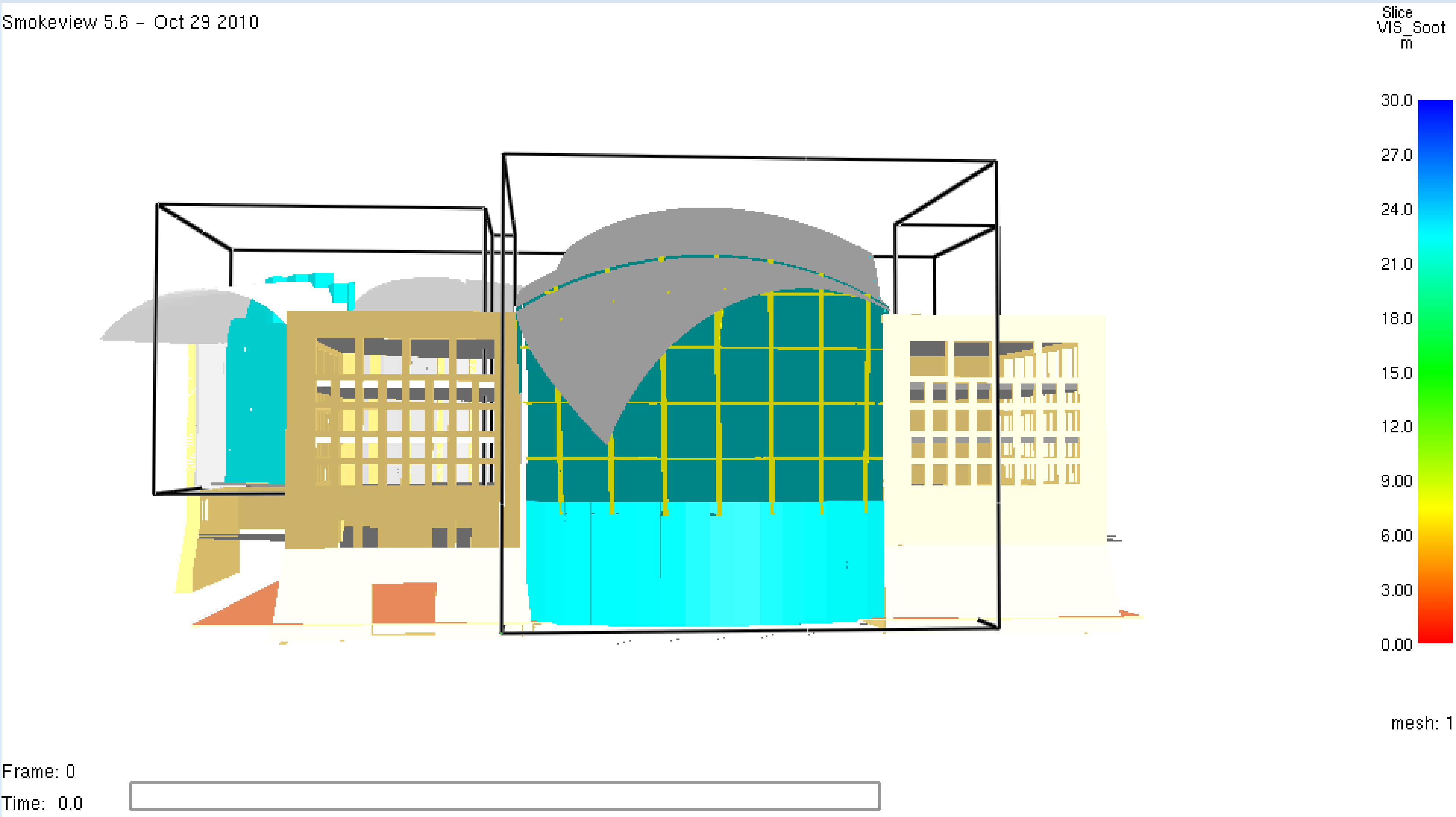
Delay time to start of egress – **30 seconds** (SFPE Handbook Table 3-13.1)

Egress model time – **67 seconds** (1m:07s)

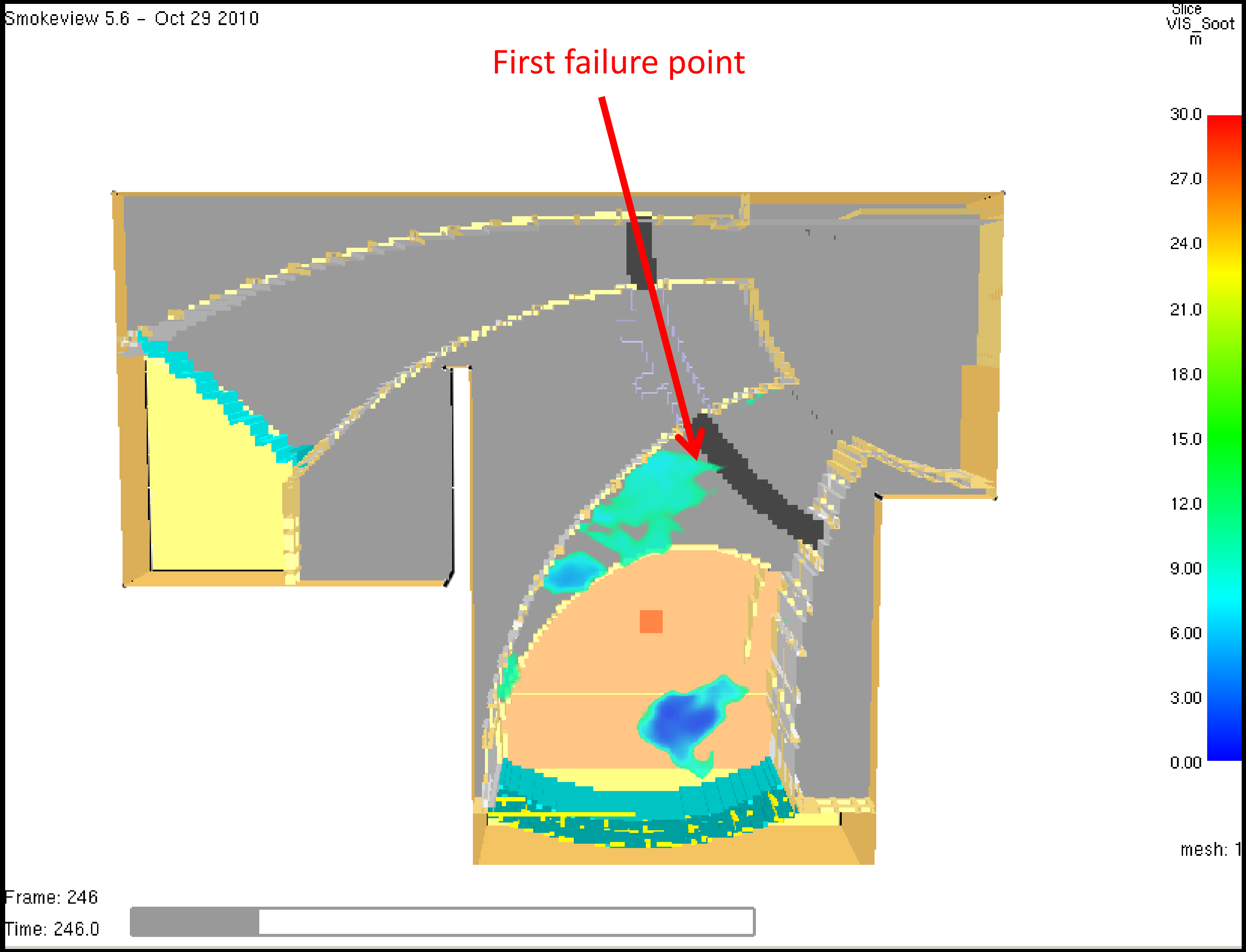
Safety Factor : 50% of egress model time - **34 seconds**

TOTAL EVACUATION TIME = 191 seconds (3m:11s)

Results – Fire Model 4th Floor



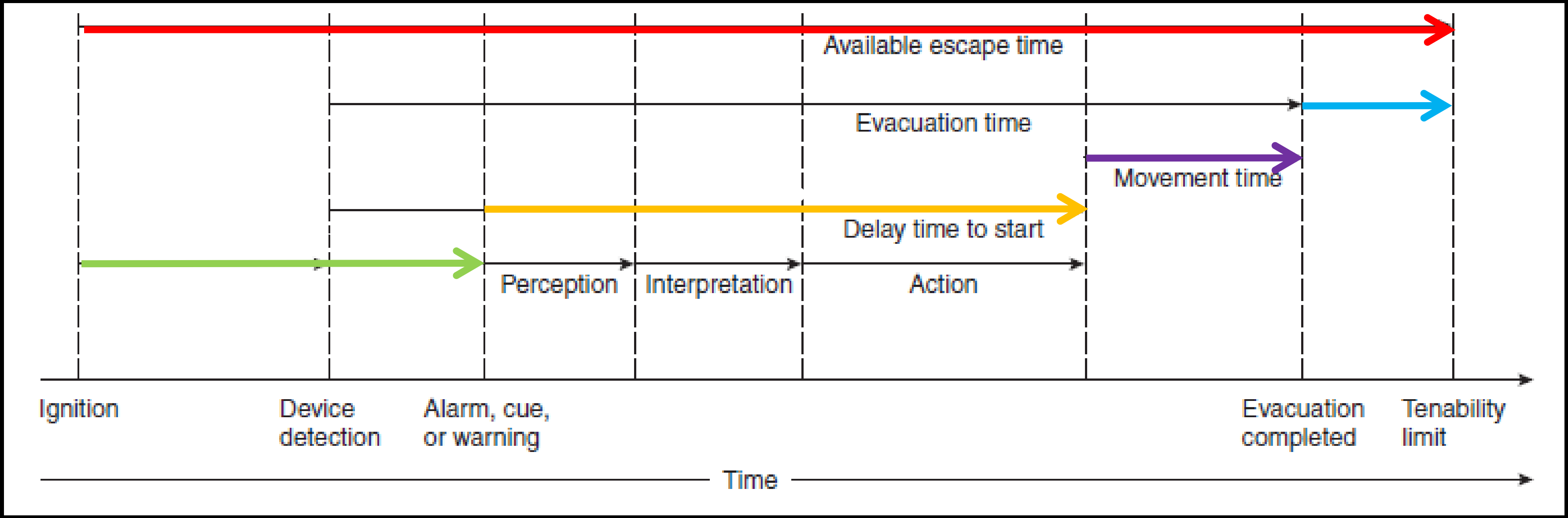
Results – Fire Model 4th Floor



Conditions maintained tenable for 245 seconds

Scenario 2 Egress Model

Evacuation Timeline (Scenario 2)




Time from fire ignition to detection – **60 seconds** (taken from live smoke test Dec 2010)

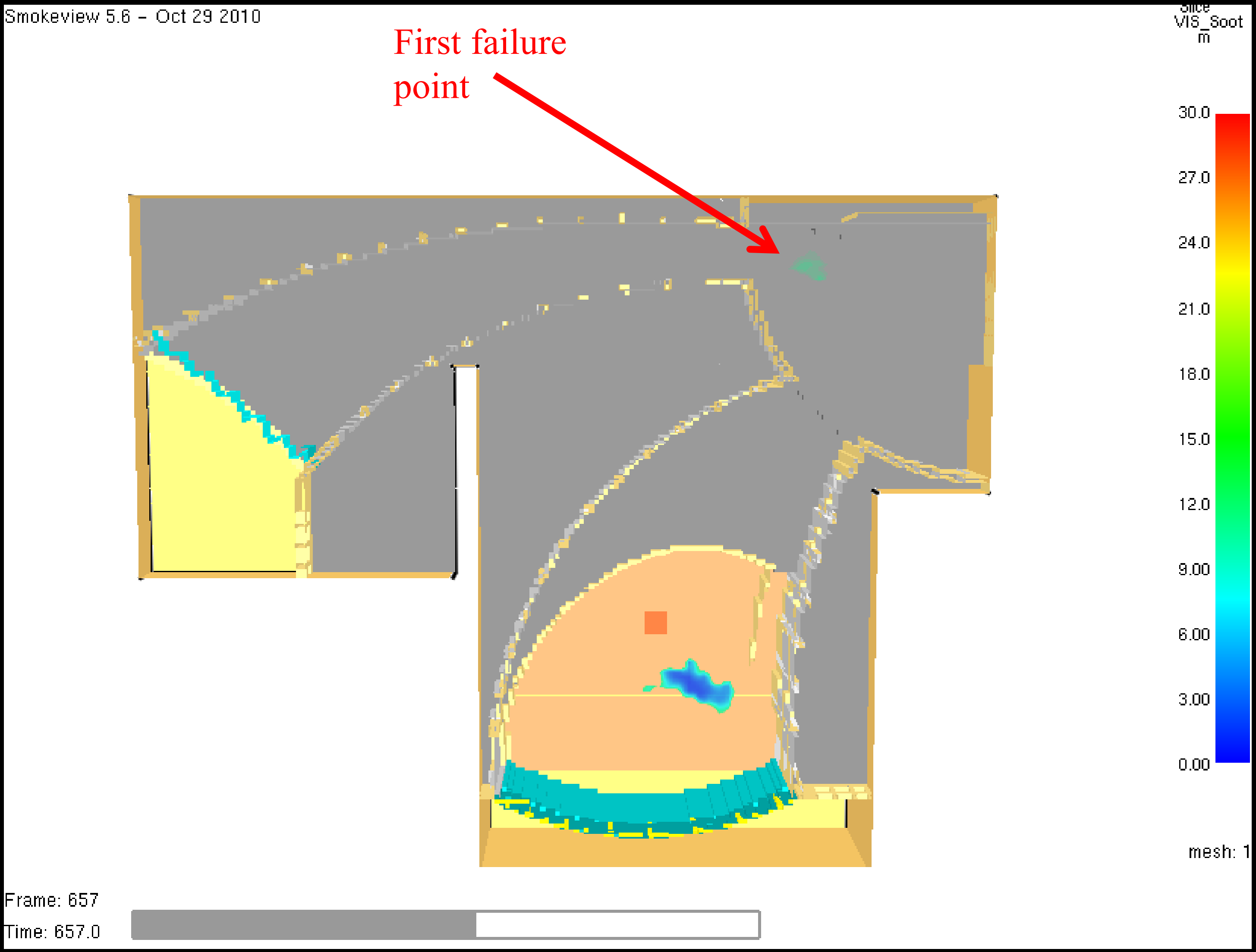

Delay time to start of egress – **90 seconds** (SFPE Handbook Table 3-13.1)


Egress model time – **156 seconds** (2m:26s) [61s for North Link Bridge]


Safety Factor : 50% of egress model time - **78 seconds**

TOTAL EVACUATION TIME = 384 seconds (6m:24s)

Results – Fire Model 3rd Floor



Conditions maintained tenable for 657 seconds

RSET Vs ASET Conclusions

Scenario	Total Egress Time (+ 50% code Safety Factor)	Time to Untenable Conditions	Additional Safety Factor (over the req'd 50% by code)
1	191 s (3m:11s)	245s (4m:05s)	54s (22%)
2	384 s (6m:24s)	657 s (10m:57s)	273s (42%)

Safe conditions are maintained for longer periods than the minimum required safe egress times by means of smoke control

Project Examples:

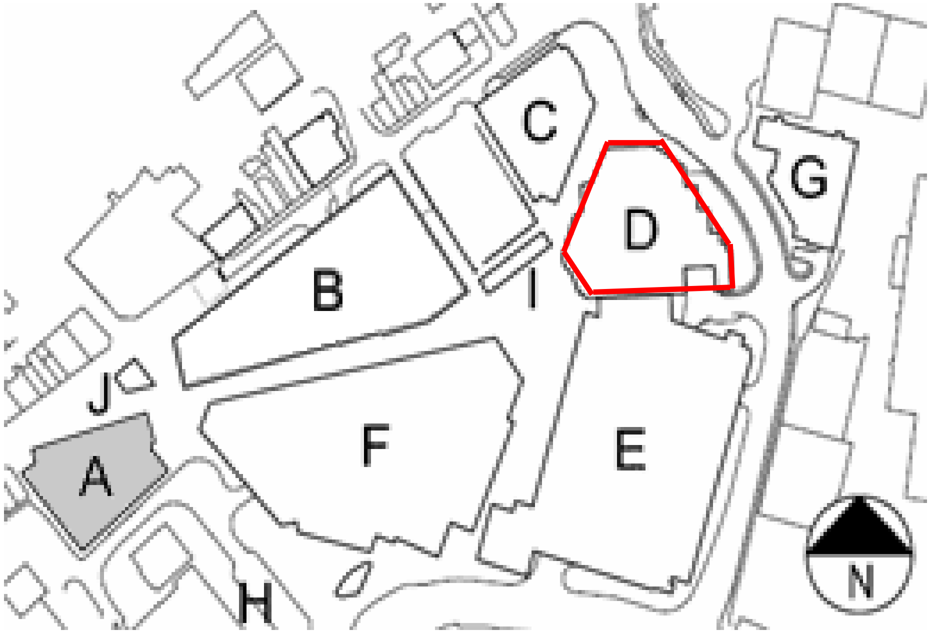
The Rock Triangle, Bury





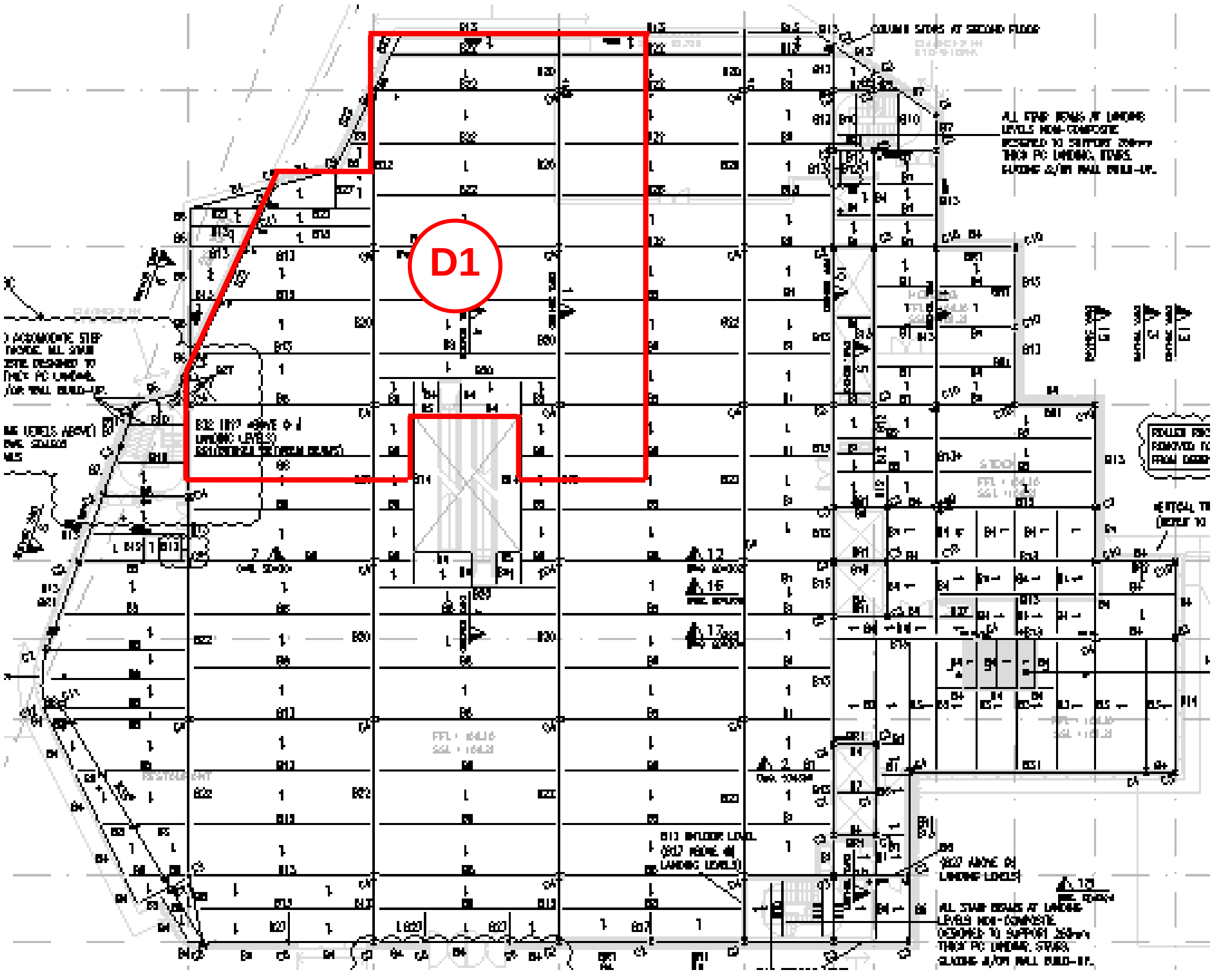


Building Description



- £150m retail, leisure and residential development in Bury, UK.
- 10 Buildings forming a new city centre
- Block D – Debenhams Store
- 3 story composite steel frame
- Cell beams
- Fire resistance period: 60 minutes

Overview of a floor plate

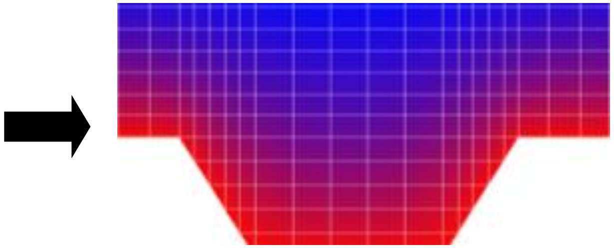


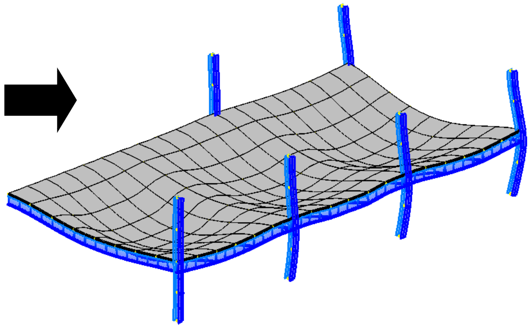
Location of *Vulcan* model

Methodology and Process

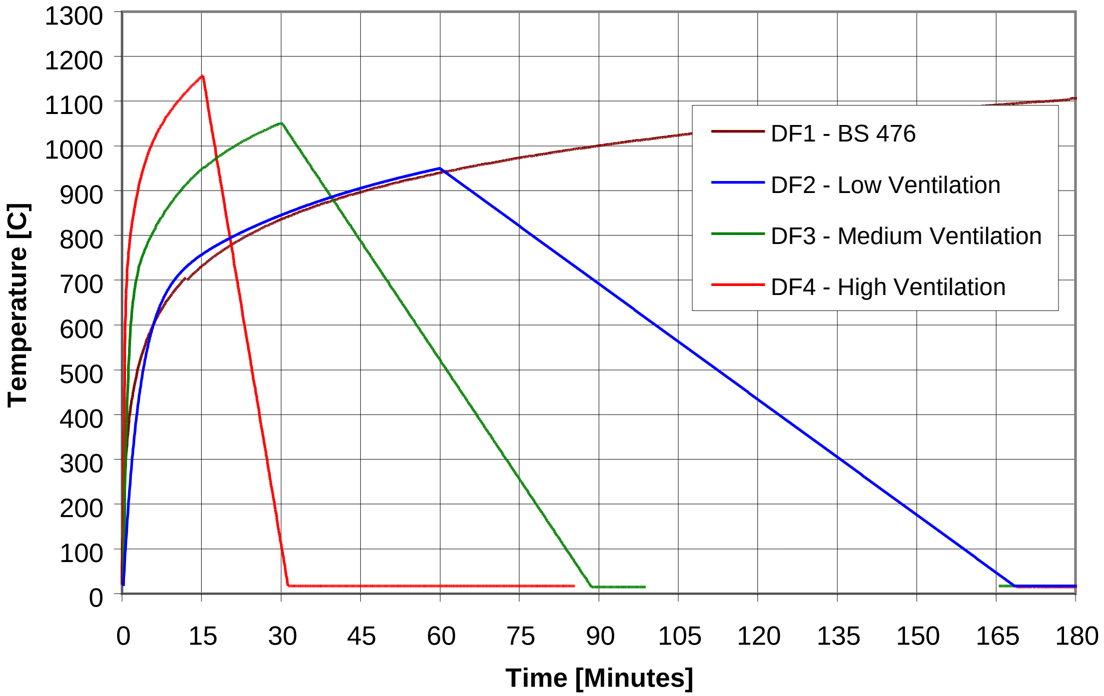
Show an equivalent standard of performance to what is seen to be acceptable in prescriptive guidance.

1. Agree methodology with Stakeholders
2. Develop design fires (including cooling)
3. Develop assessment criteria
4. Build geometry of the sub-frames and analyse for different fires
5. Assess connection forces
6. Write a detailed report
7. Present and negotiate with Building Control





Design Fires



DF1-Standard Fire

DF2-Slow Fire

- Worst Parametric Fire
- Largest vertical deflections of protected beams
- Critical for columns

DF3-Medium Fire

DF4-Fast Fire

Hottest fire **/** Early deflections of unprotected beams **/**

Largest connection forces

Acceptance Criteria

Stability	–	checked by Vulcan
Integrity	–	controlled over deflection limits
Insulation	–	normally not a problem in composite slabs

<table>
<tr><th>Design Fire</th><th>Assessment Period</th><th>Acceptance Criteria</th></tr>
<tr><td>DF1 – Low Ventilation
(No Cooling)</td><td>60 minutes</td><td rowspan="4">Check for runaway deflections

Deflection of protected beams < Span/20

Deflection of slab < Span/20 (compartment floor)

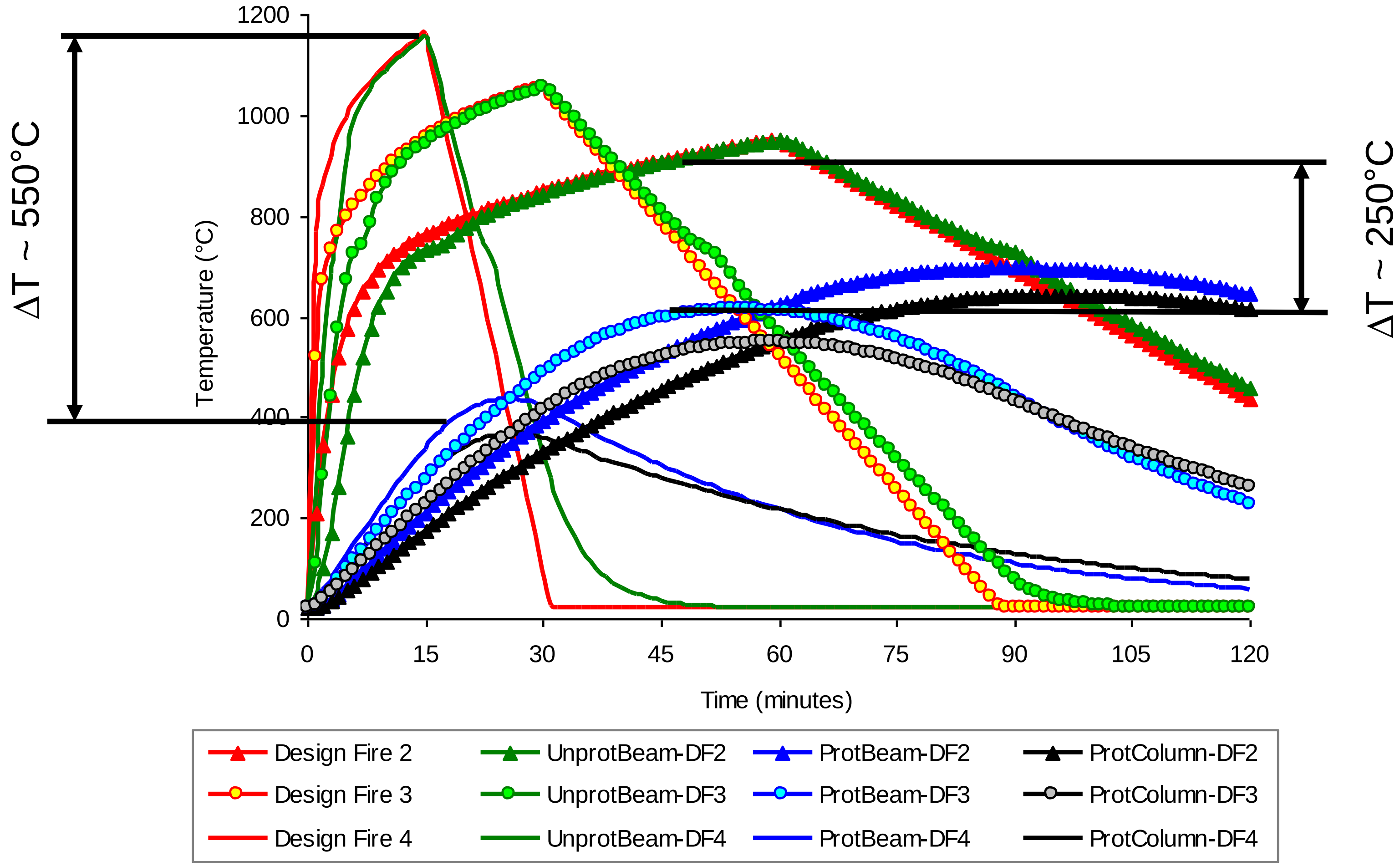
Deflection of slab < Span/10 (non-compartment floor)

Connection forces to be provided.</td></tr>
<tr><td>DF2 – Low Ventilation
(With Cooling)</td><td rowspan="3">60 minutes
(compartment floor)

Entire fire duration (non-compartment floor)</td></tr>
<tr><td>DF3 – Medium Ventilation
(With Cooling)</td></tr>
<tr><td>DF4 – High Ventilation
(With Cooling)</td></tr>
</table>

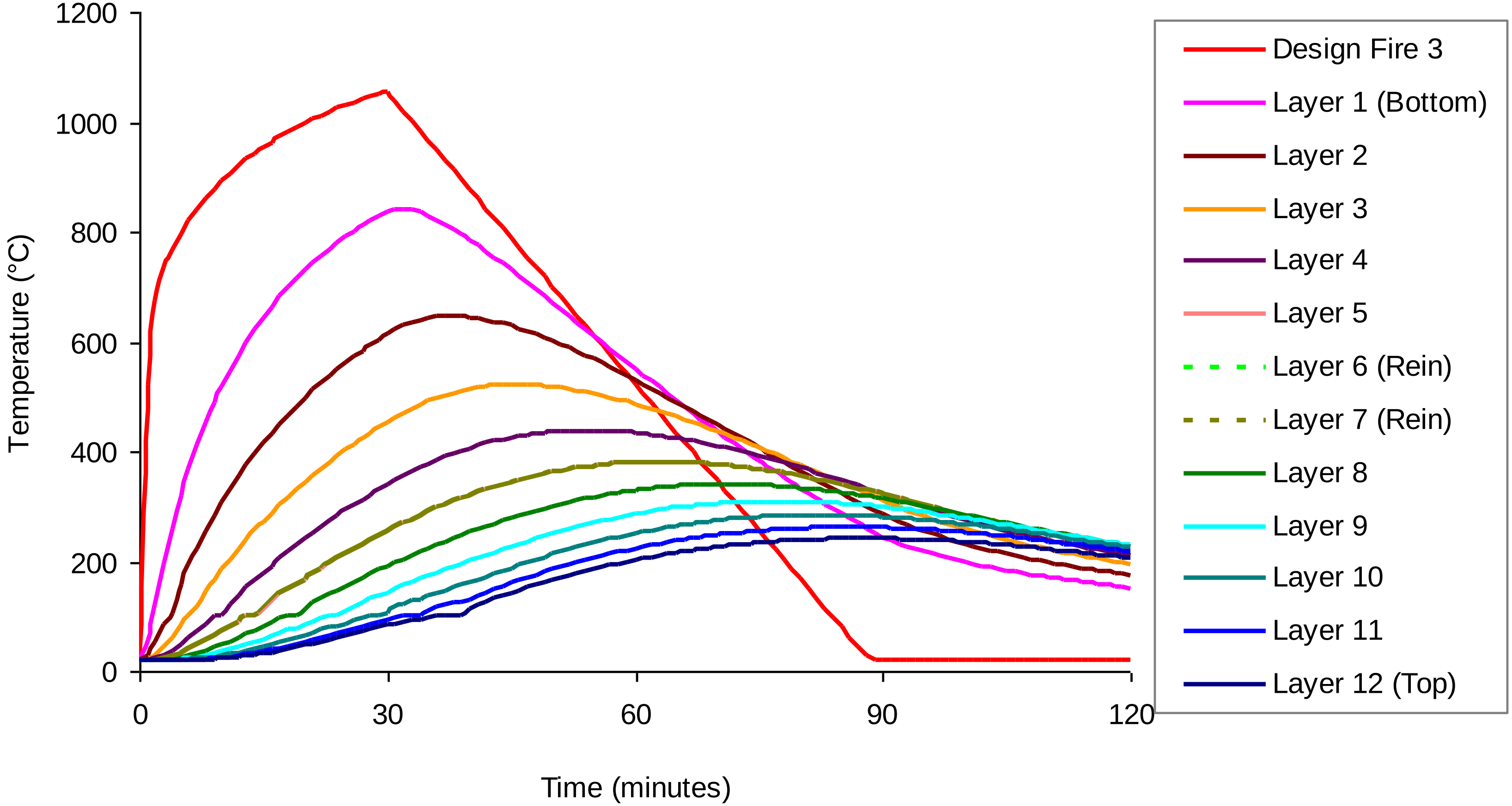
Material Temperatures

Typical steel temperatures calculated by using EC3-1.2 heat transfer calculations for each part of the section

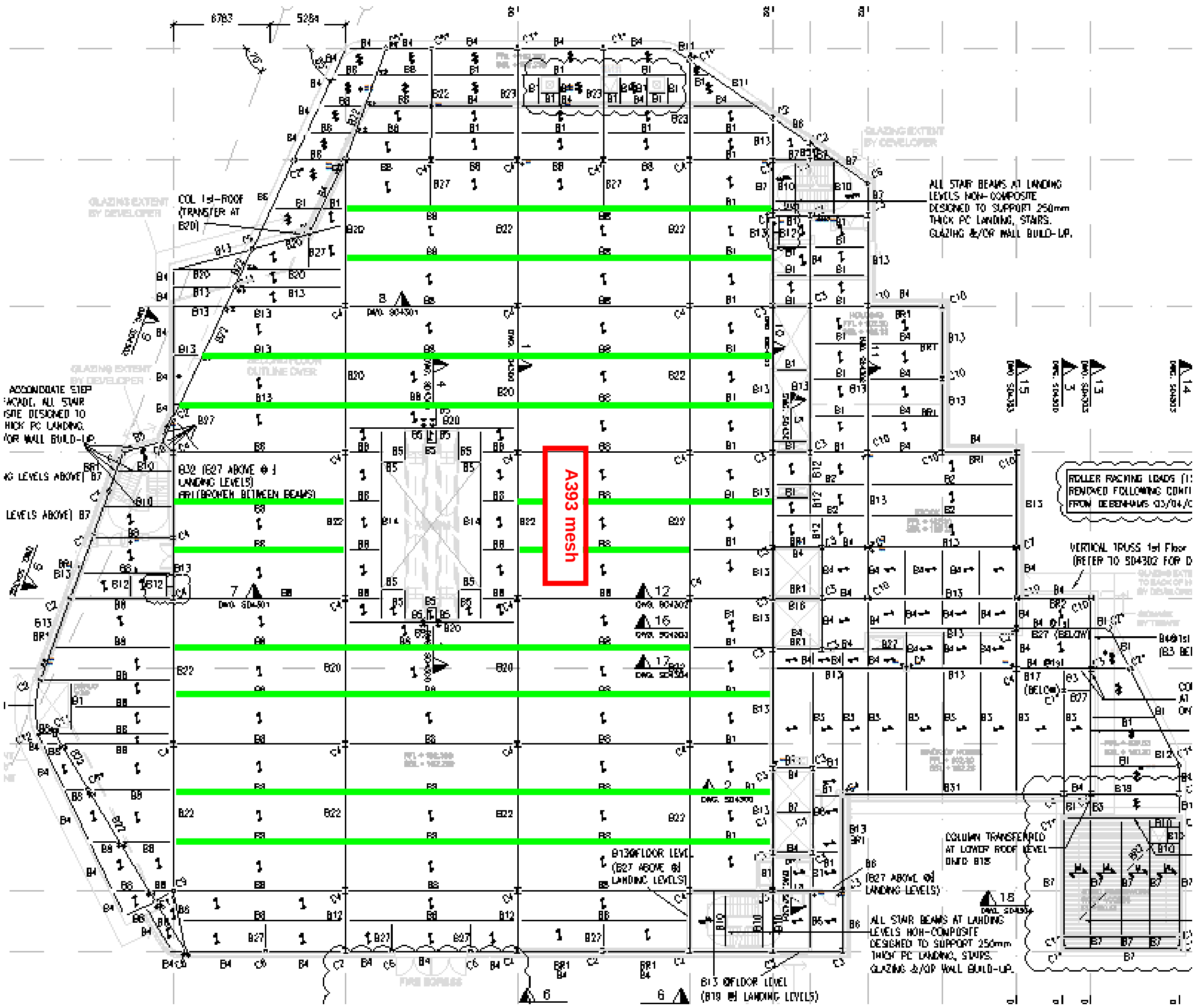


Material Temperatures

Typical concrete slab temperatures



Proposed Fire Protection Regime

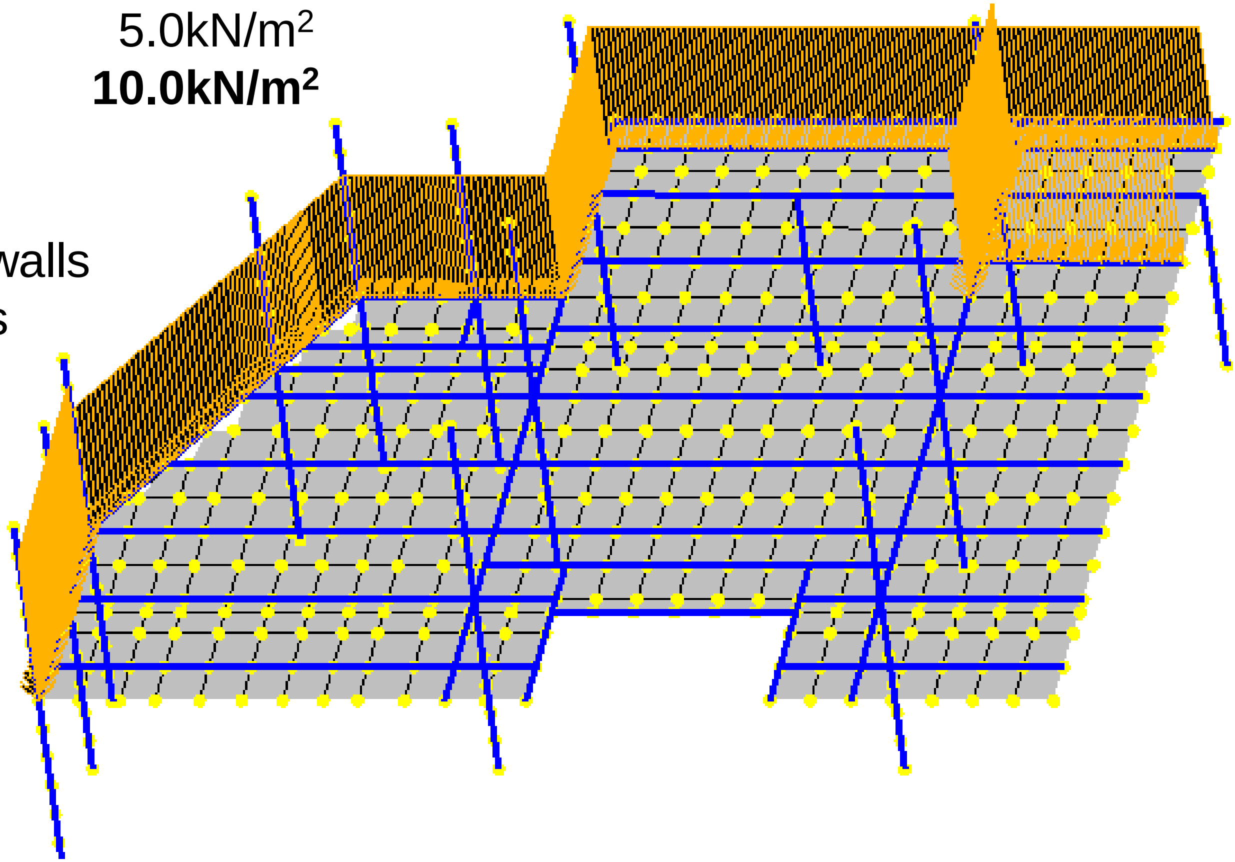


Vulcan Model - Loading

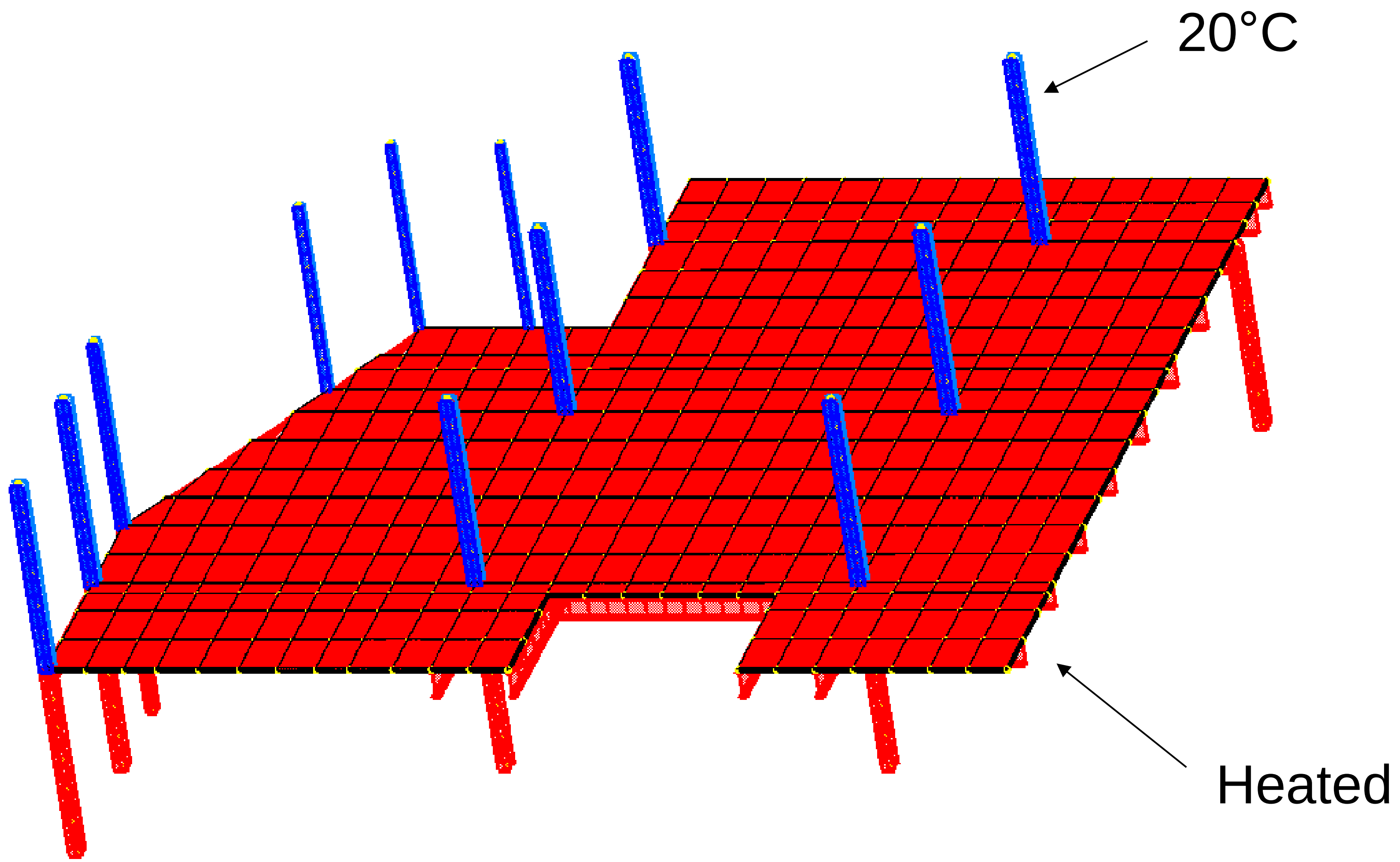
Floor Loads:

Dead Load	6.0kN/m^2
Non-perm. Live Load	5.0kN/m^2
FLS = 6.0 + 0.8 x 5.0 =	**10.0kN/m^2**

+ Line loads for façade
+ Line loads for internal walls
+ Point loads on columns

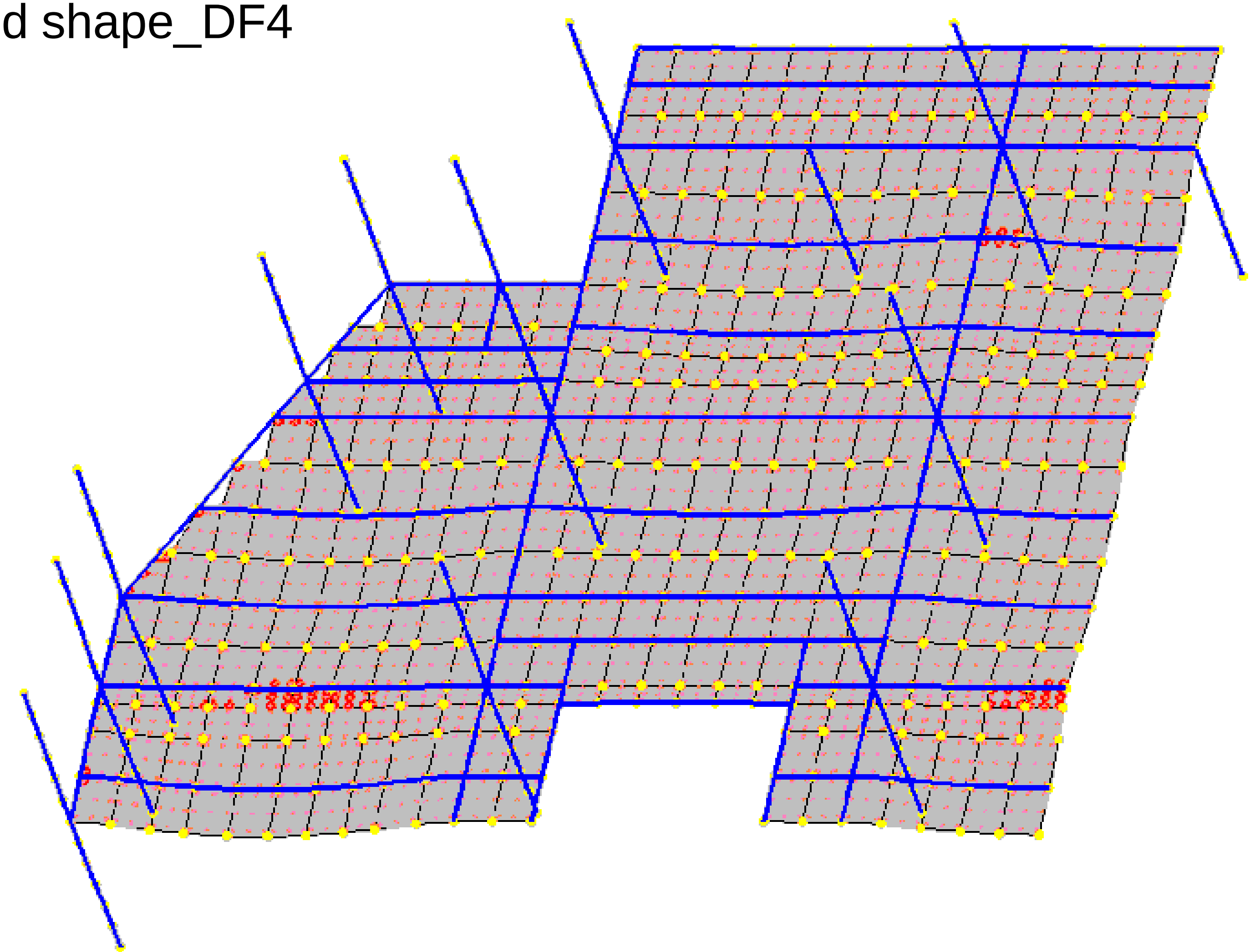


Heating regime



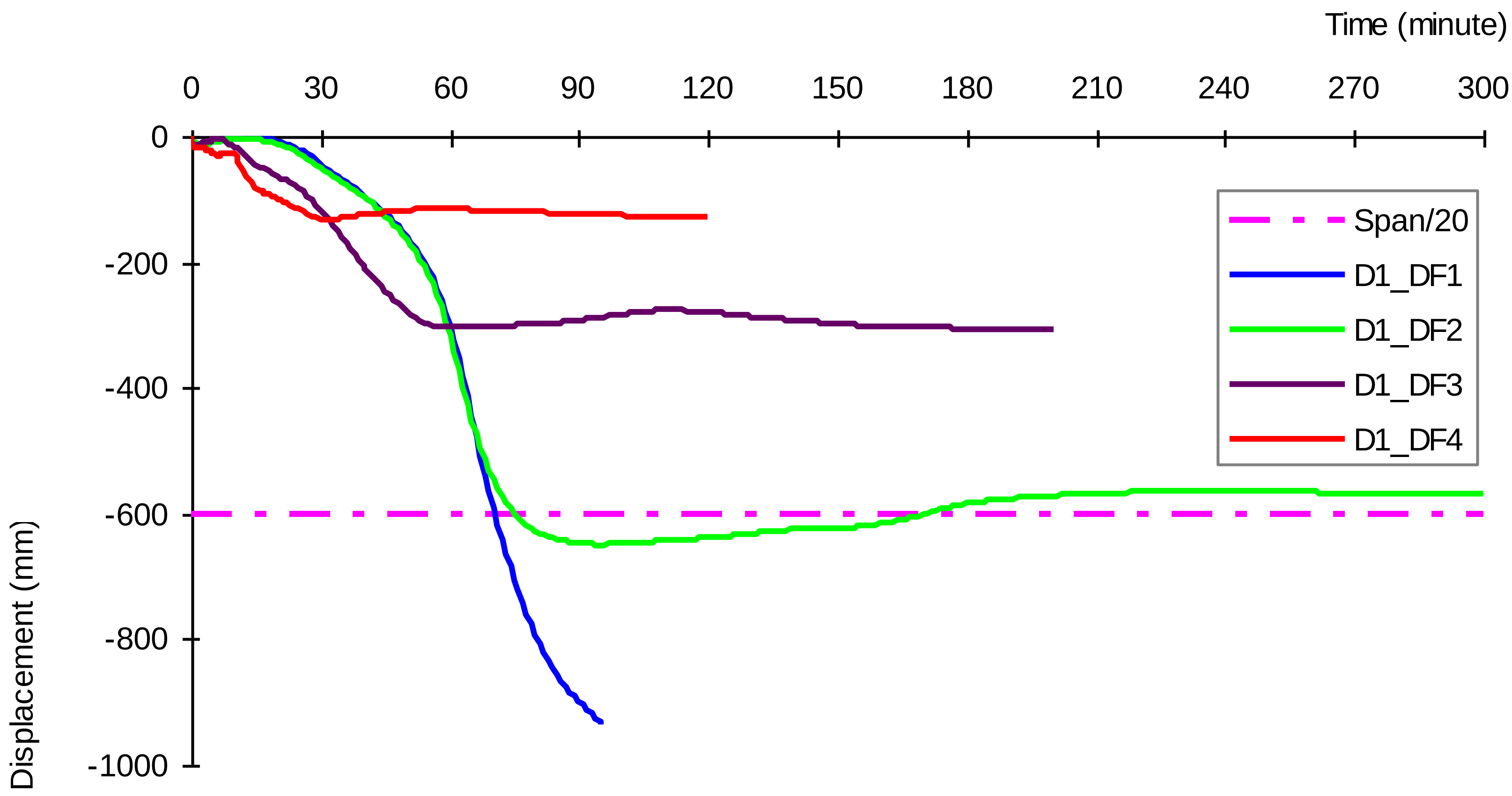
SFE Analyses and Results

Deflected shape_DF4



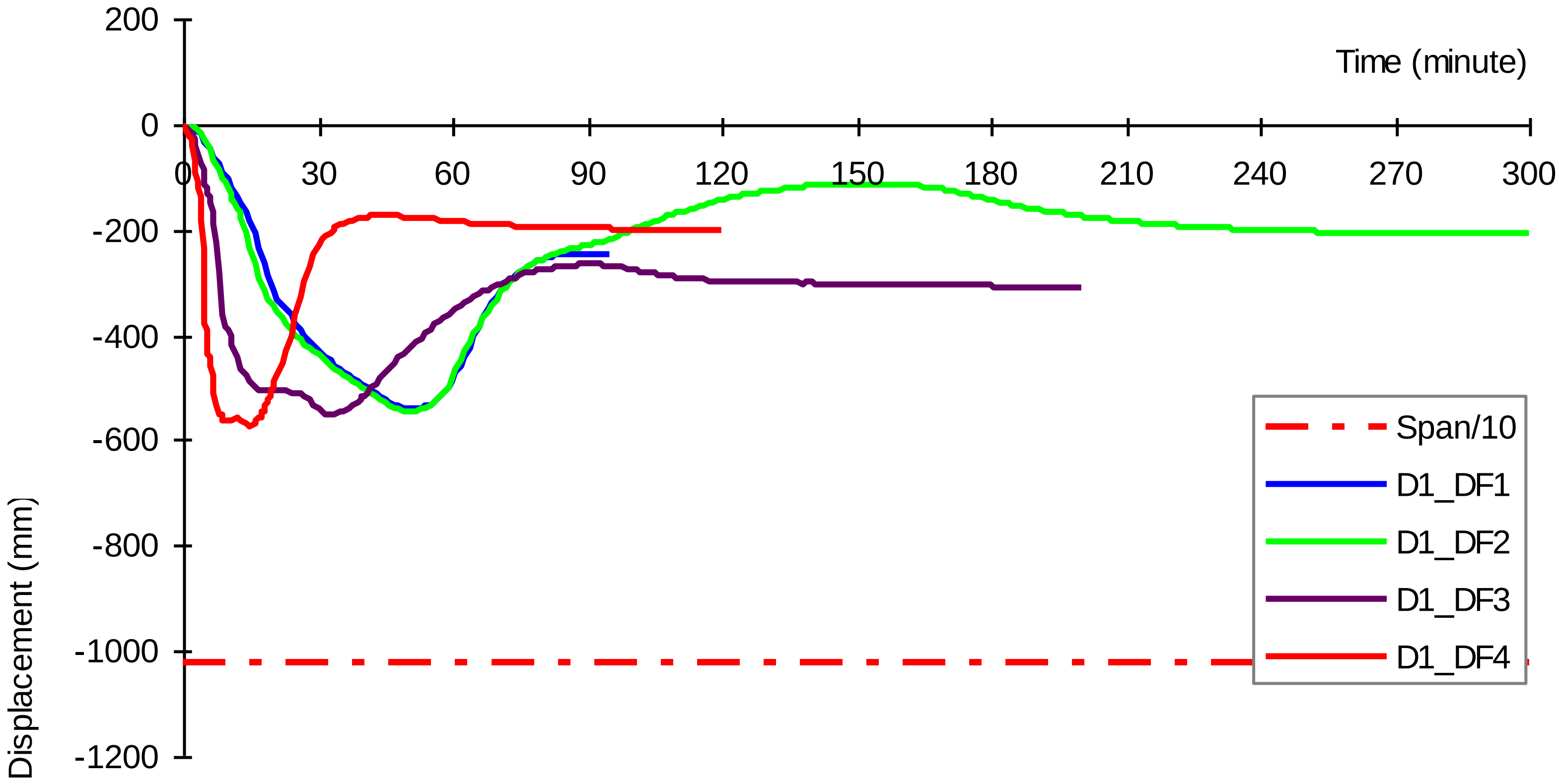
SFE Analyses and Results

Max protected beam deflections

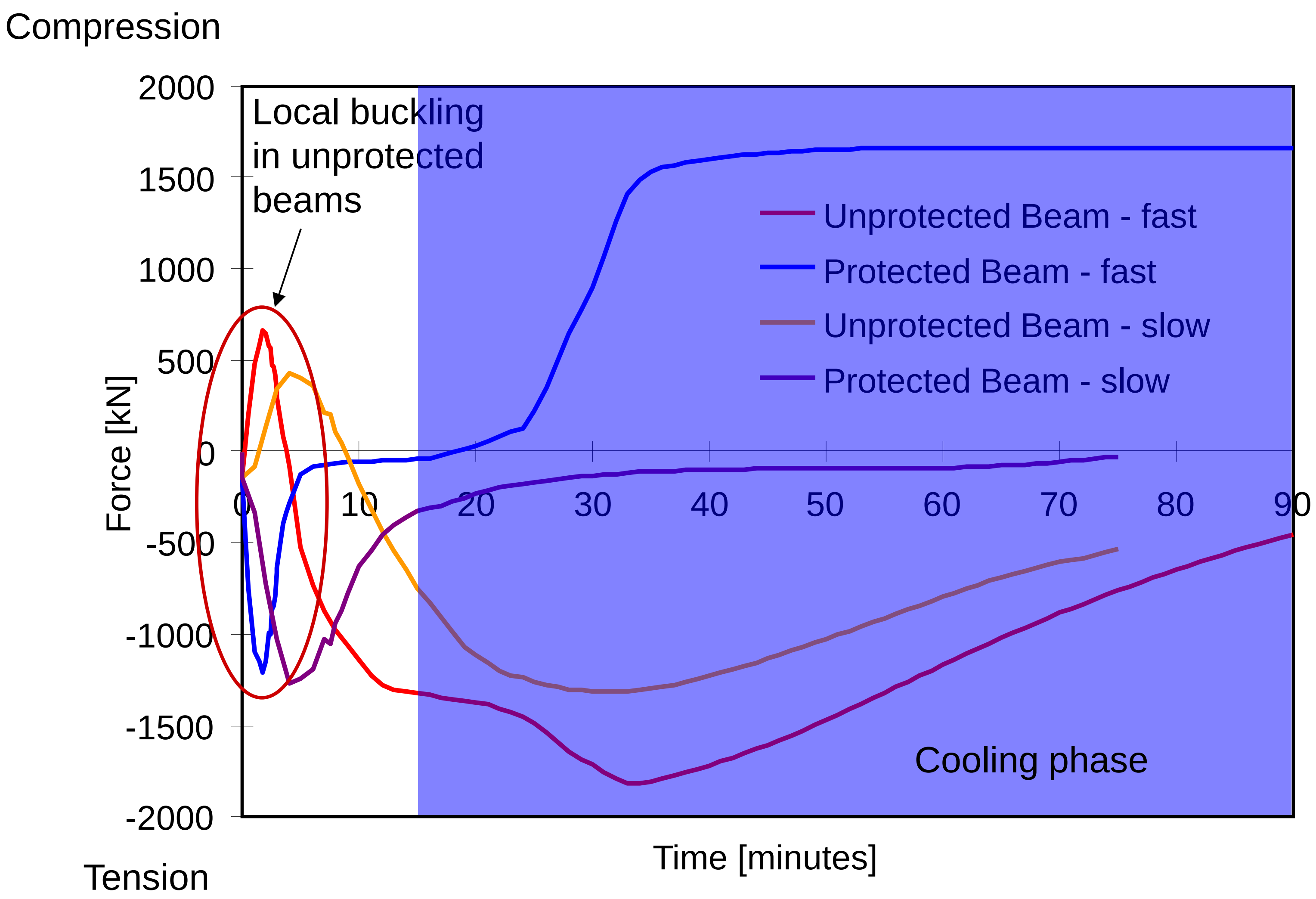


SFE Analyses and Results

Max differential slab deflections

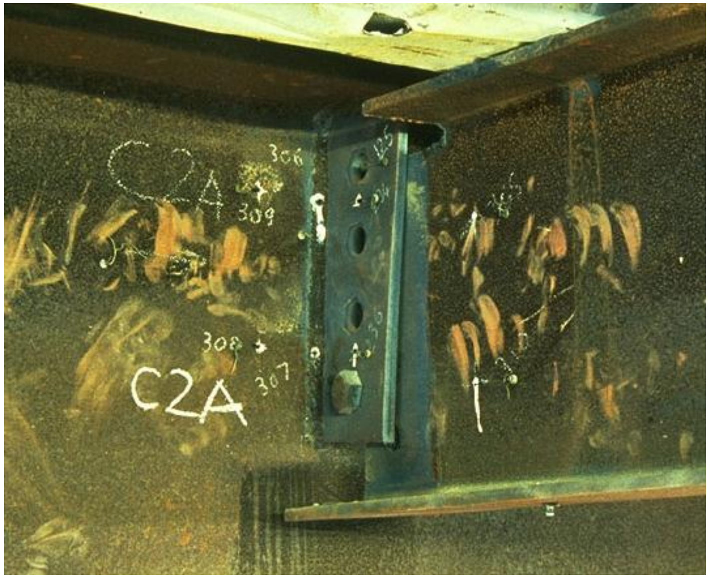


Connection forces



Connections in Fire - Cardington

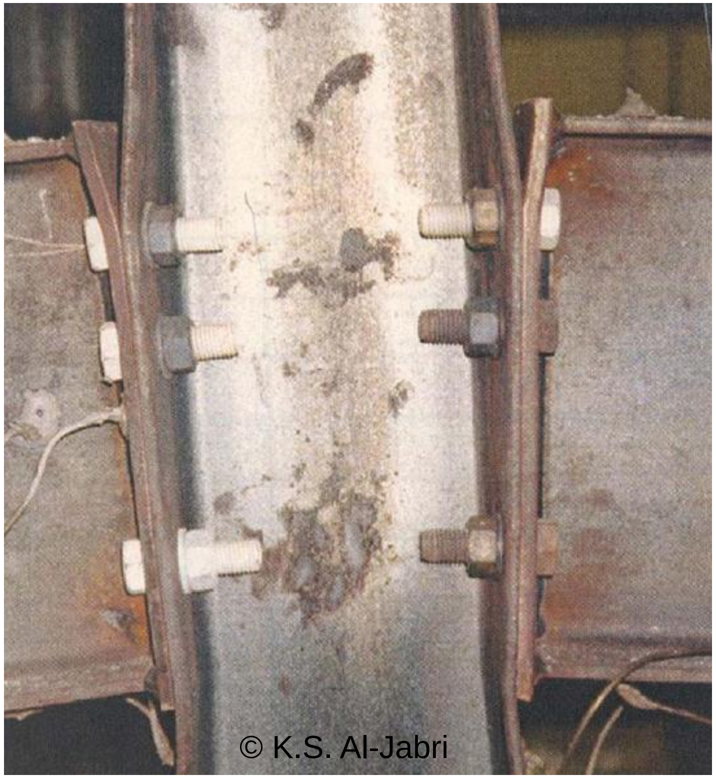
Lower flange buckling occurred during early stages of fire – thermal expansion



Bolt failure occurred during cooling phase

Connections in Fire

Double web cleat for unprotected beams

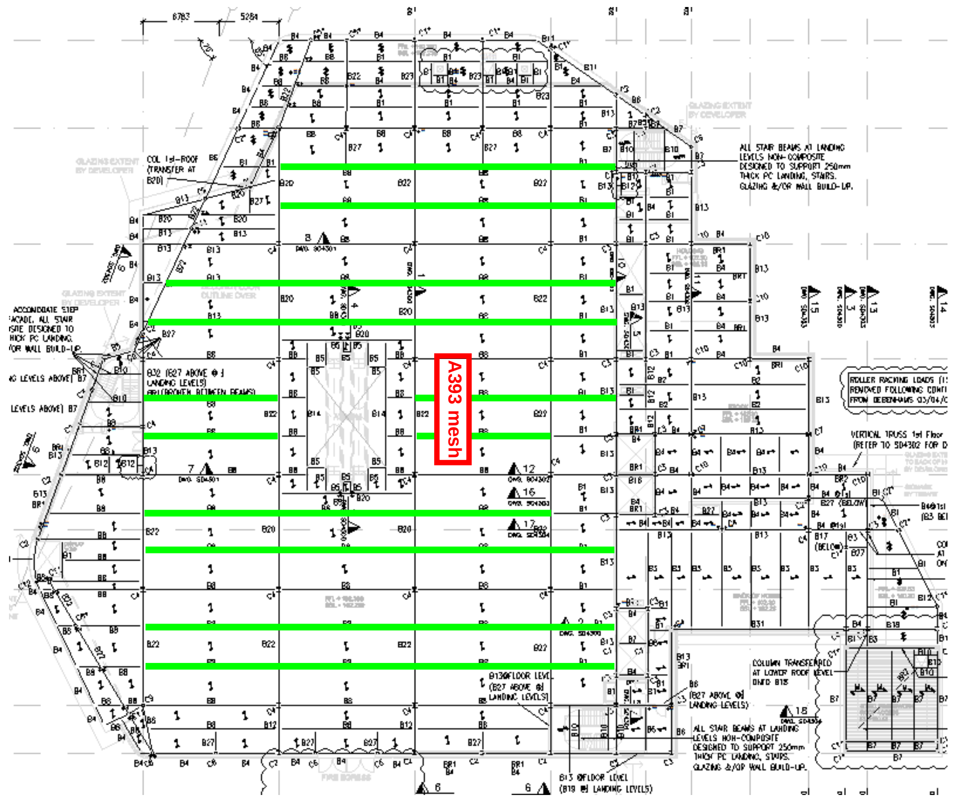


Endplate connections to protected beams framing into columns

Site Pictures

Conclusions

- About 30% of floor beams can be unprotected
- Some protected secondary beams needed to be stronger
- Reinforcement mesh in slab increased
- Connection design influenced
- Significant cost savings



ME Hotel, London





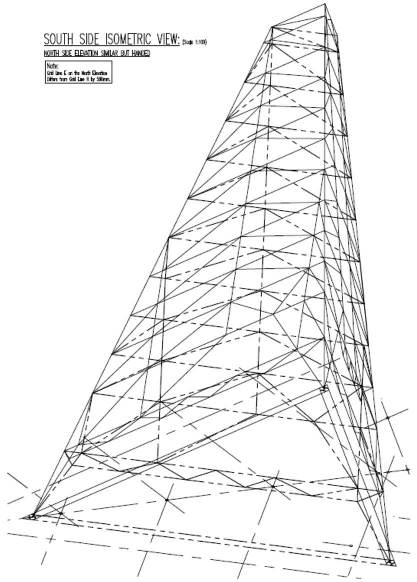


ME Hotel – Aldwych London

Client: MELIÃ HOTELS INTERNATIONAL

Architects: **Foster + Partners**

10 storey refurbished hotel and residential building with central atrium

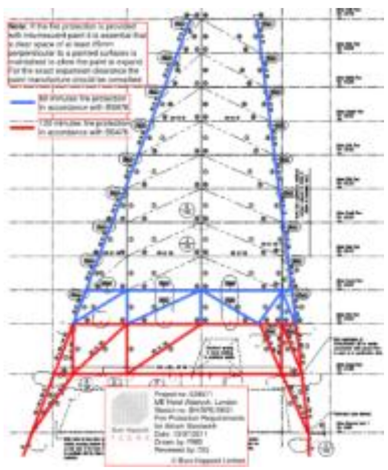


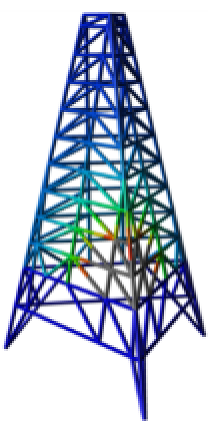
Assessment Methodology

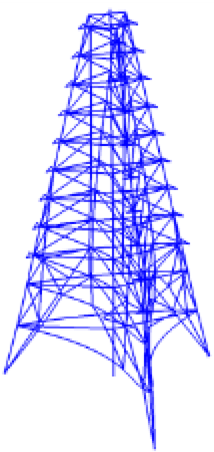
Hazard identification and risk assessment

Structural response modelling at elevated temperature

- Define design fire
- Determine fire protection scheme
- Calculate the heat transfer of the structure
- Calculate the response of the structure at the elevated temperature
- Assessment criteria – Global stability



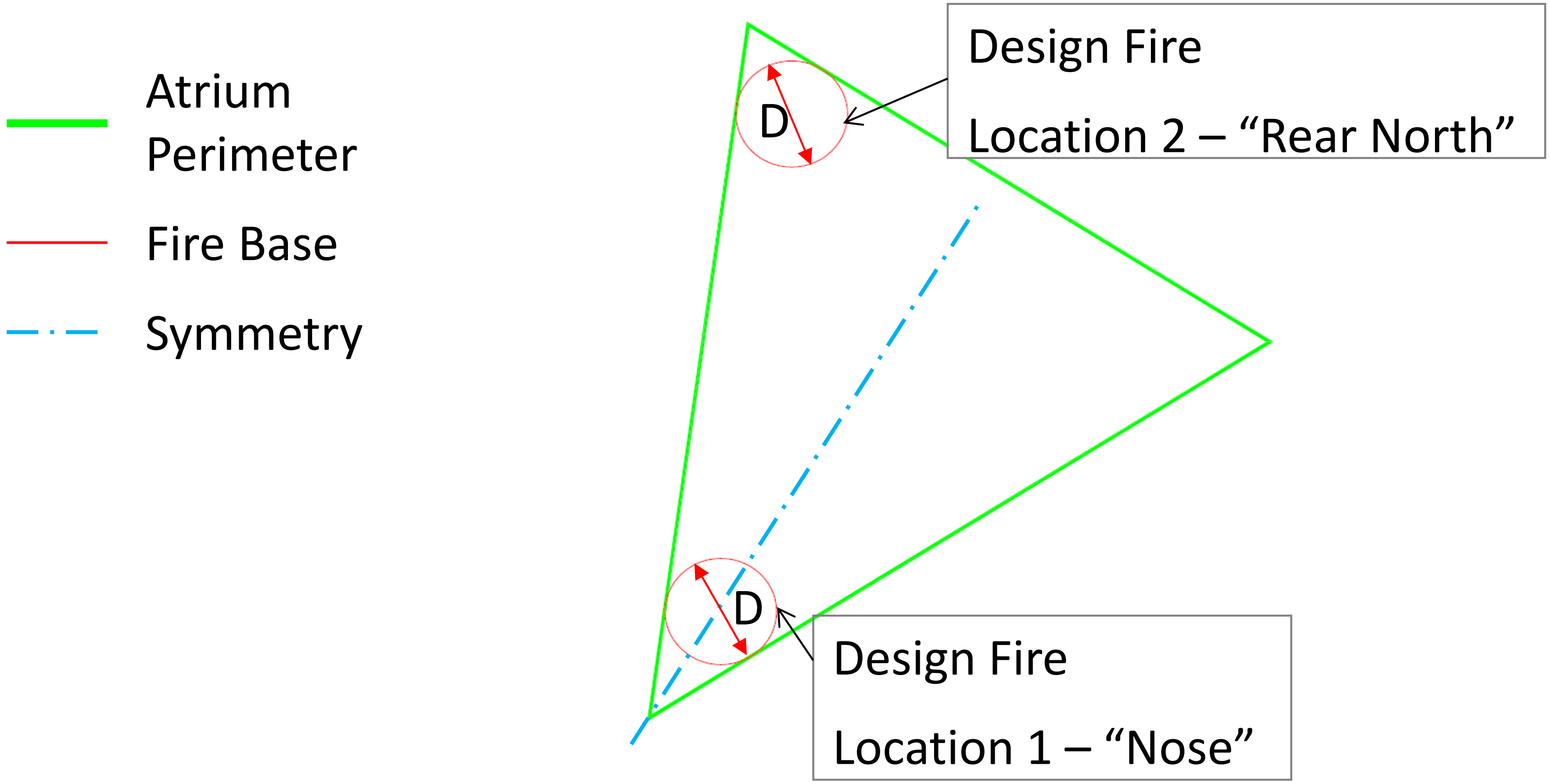




Design Fire Scenarios

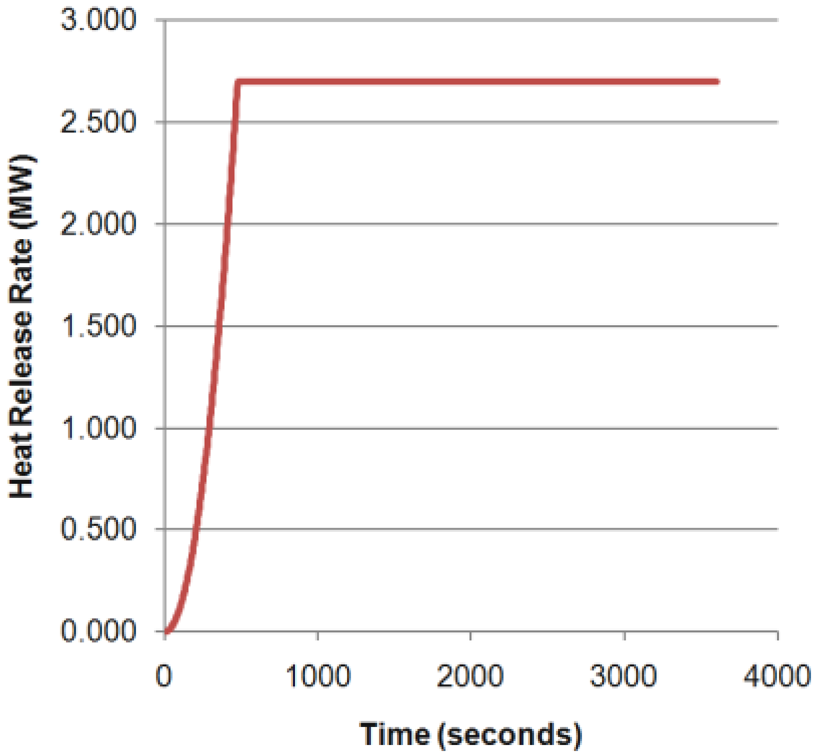
Risk assessment result: Unsprinklered fire at the atrium base

2 fire locations have been assessed

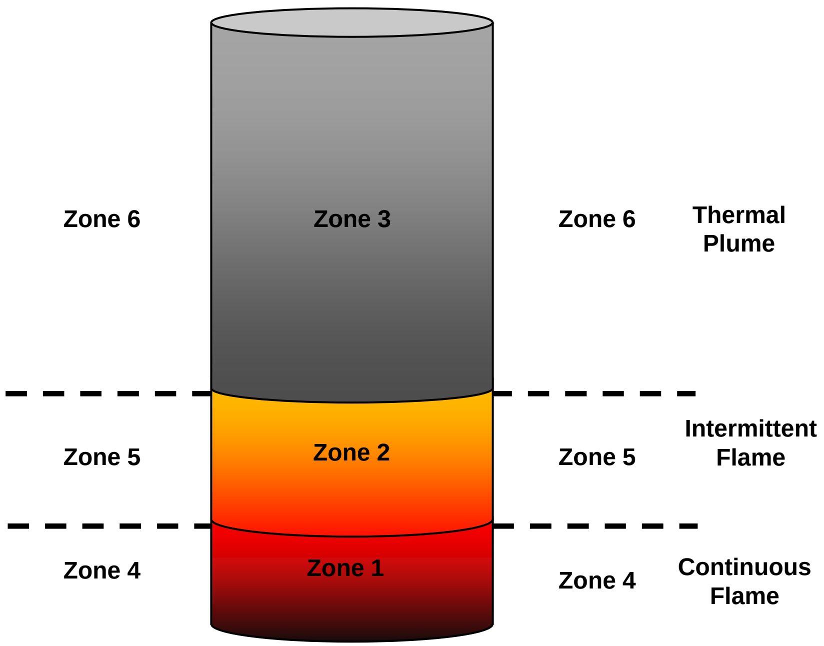


Thermal Analysis – Fire model

Design fire – Localised



Cylinder Model for heat transfer

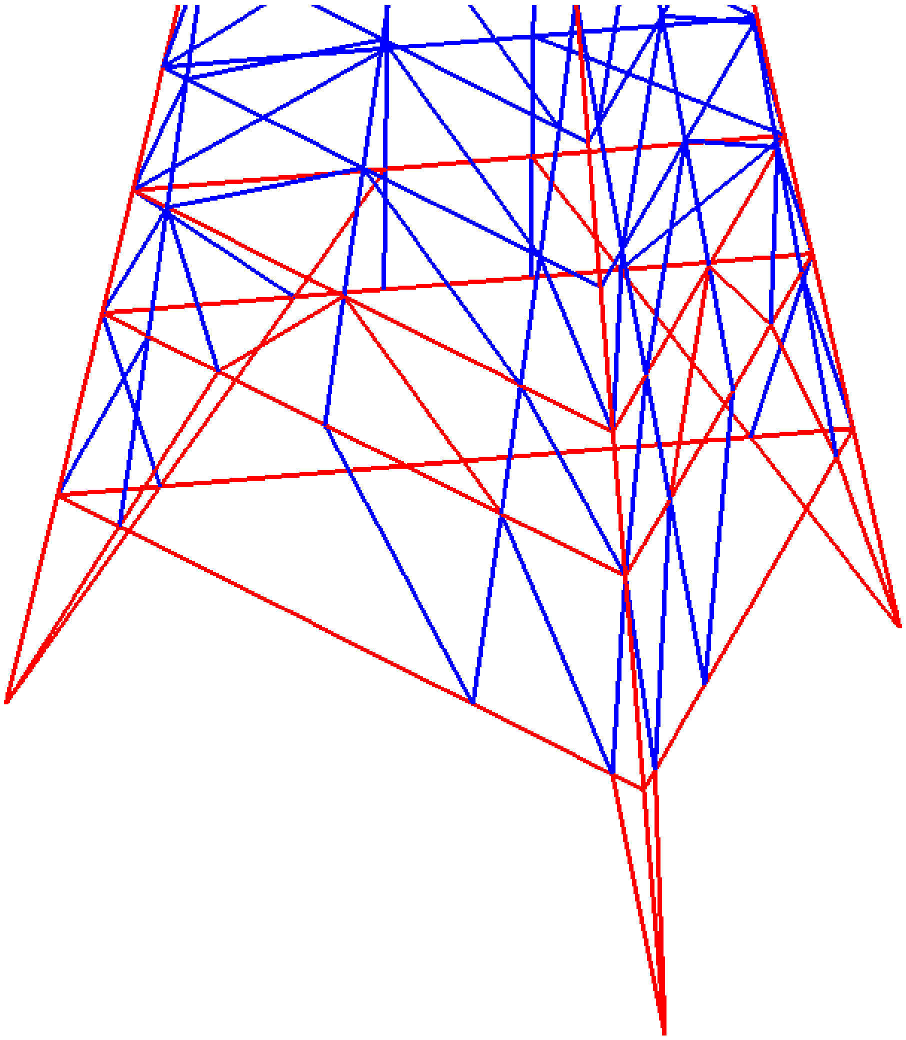


Incident heat flux calculated based on 3D location of steel members in relations to fire for about 980 members.

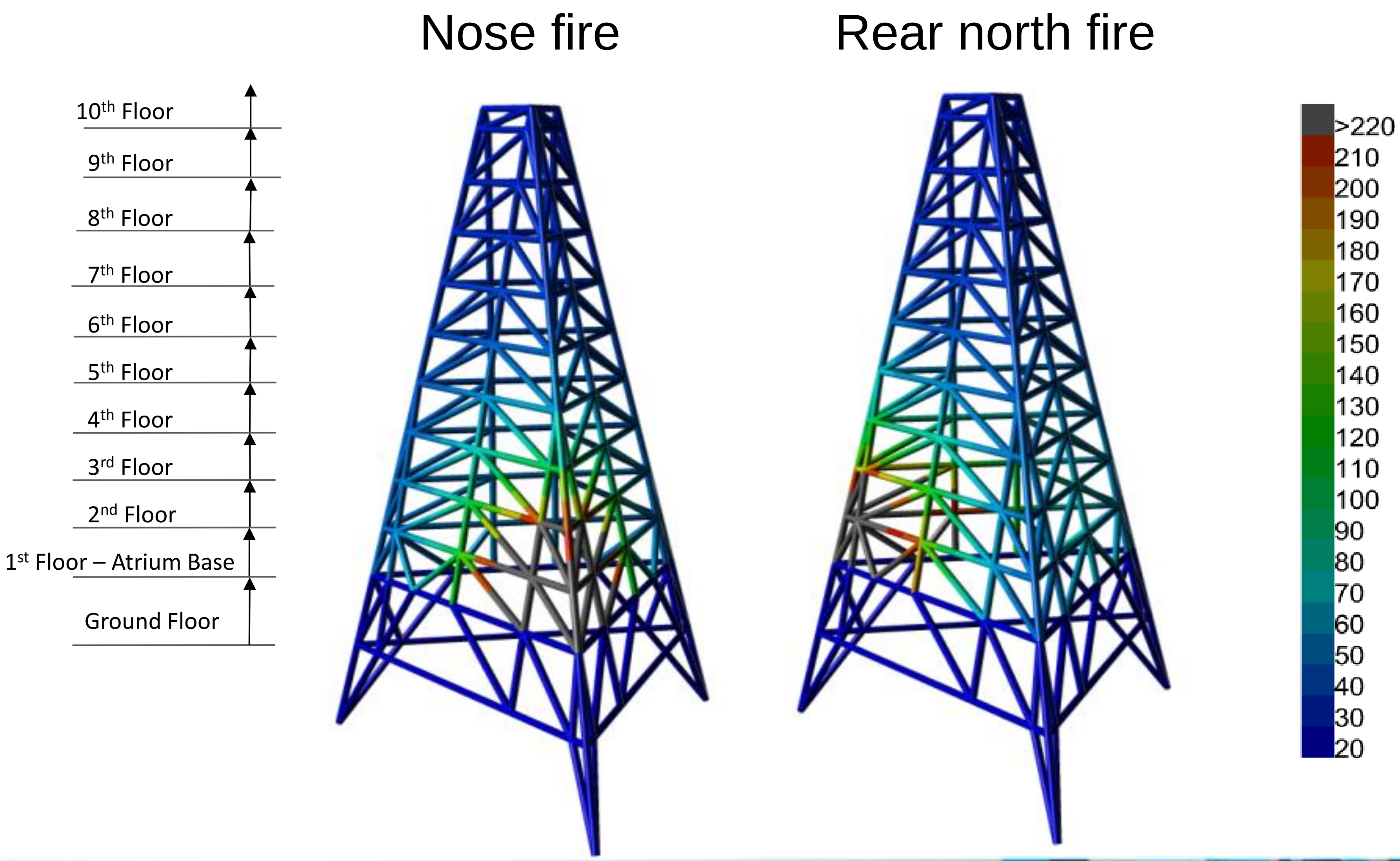
Thermal Analysis – Fire protection

Preliminary protection

- Between G floor level to 1st floor level – 120 mins
- Between 1st floor level to 2nd floor level – 60 mins
- Rest of columns running to top floor – 60 mins
- Rest of atrium steelworks unprotected

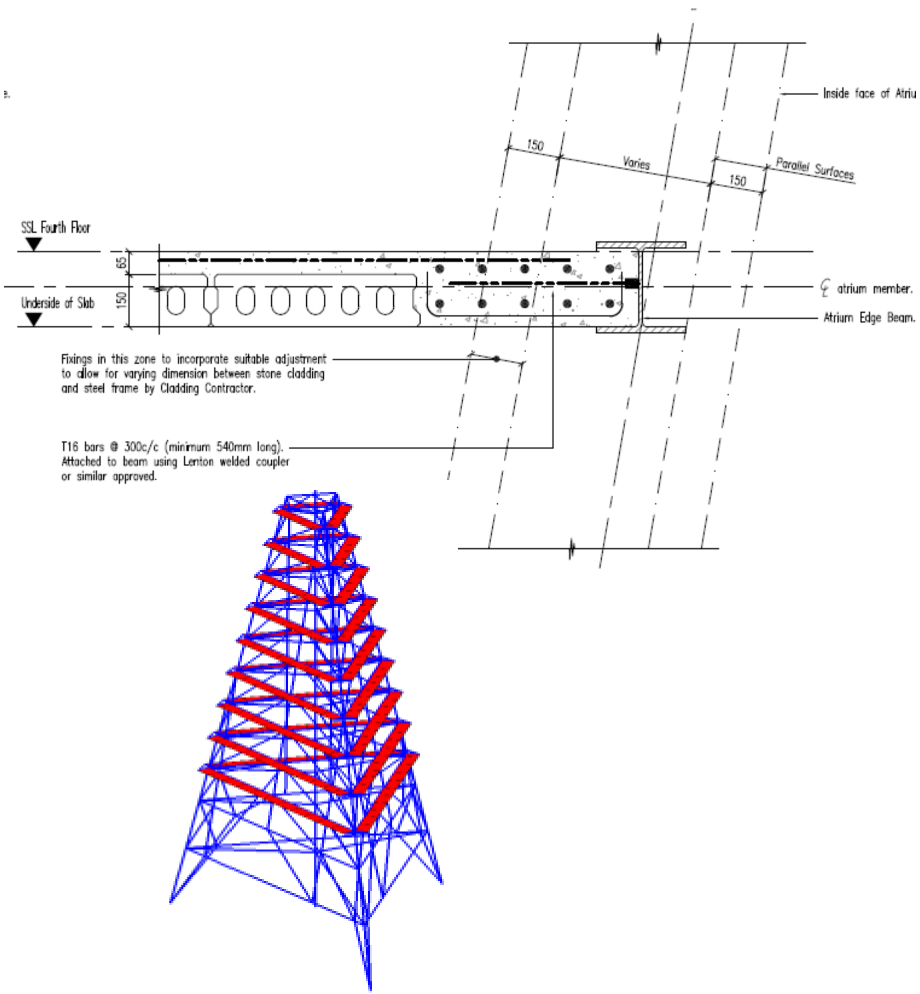


Thermal Analysis - Results

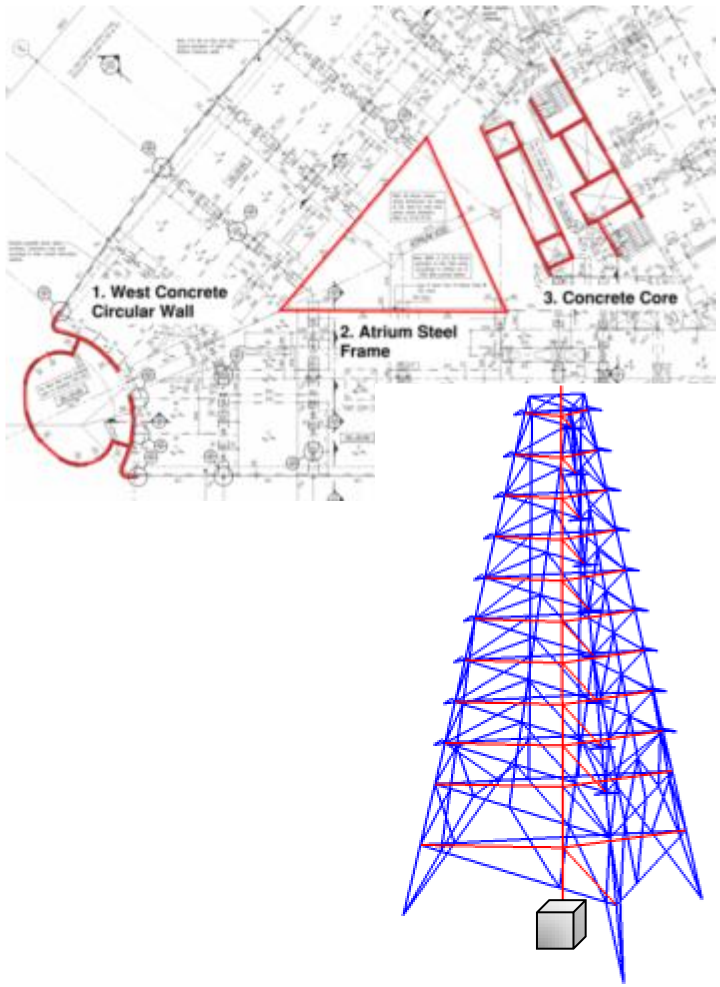


Structural Analysis using Vulcan - Restraints

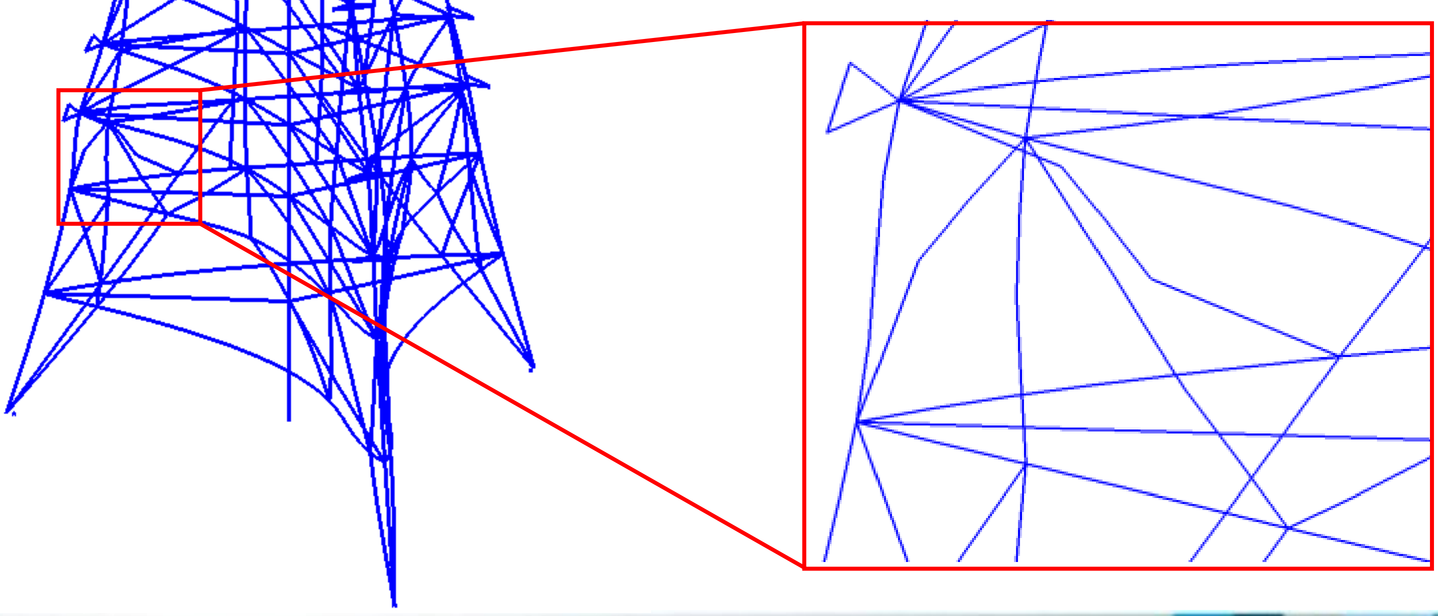
Thermal restraints from slab

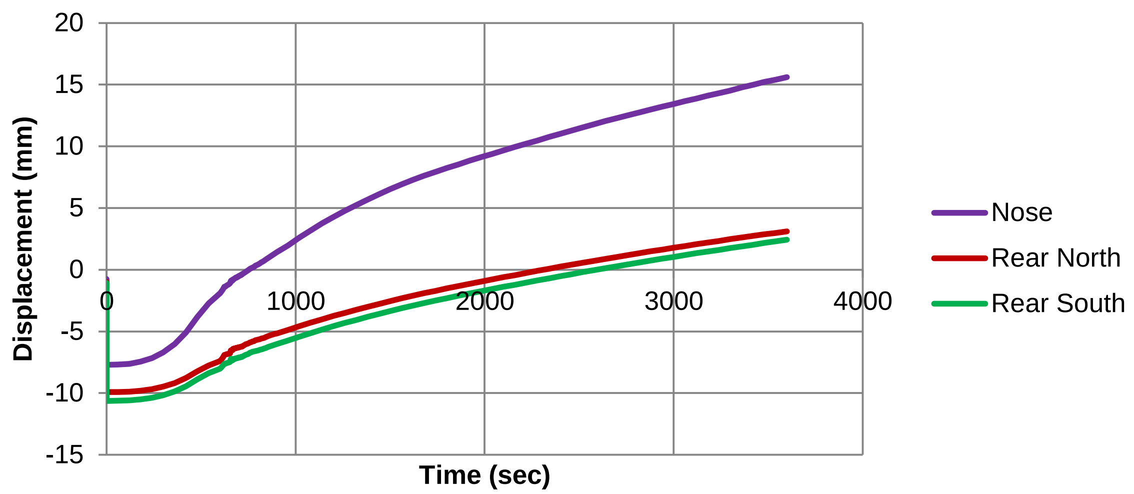


Stiff cantilever representing concrete cores

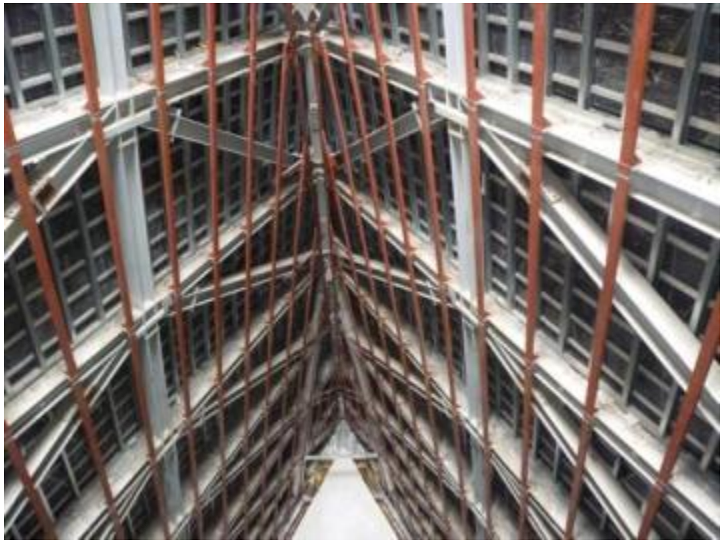


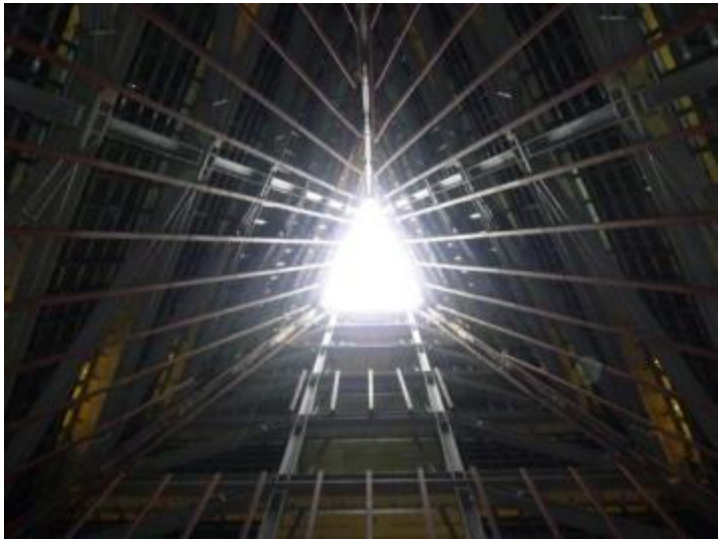
Structural Analysis – Results at Rear North





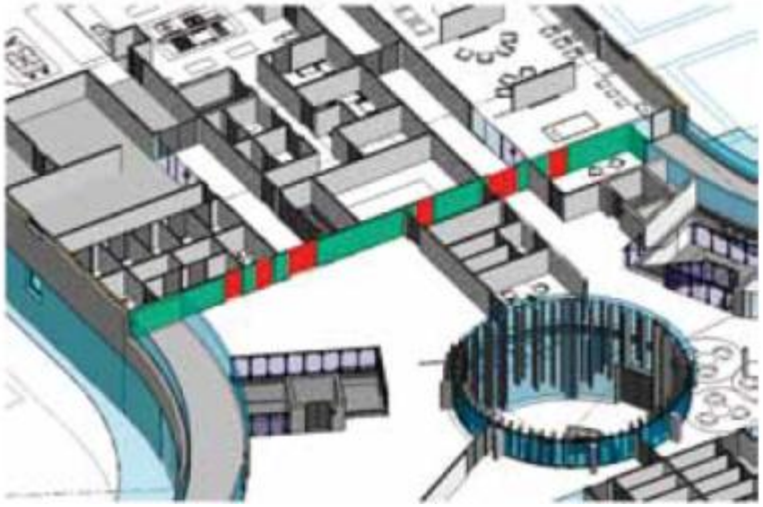
Site images

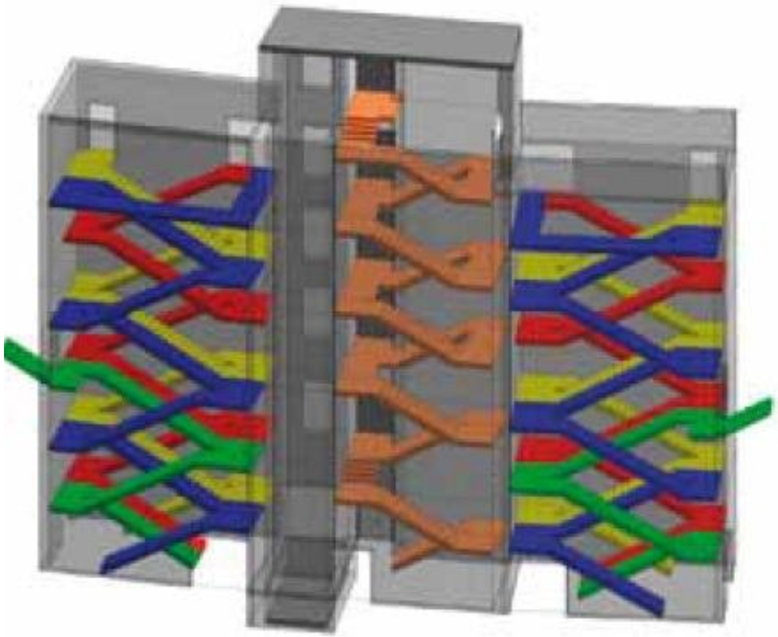




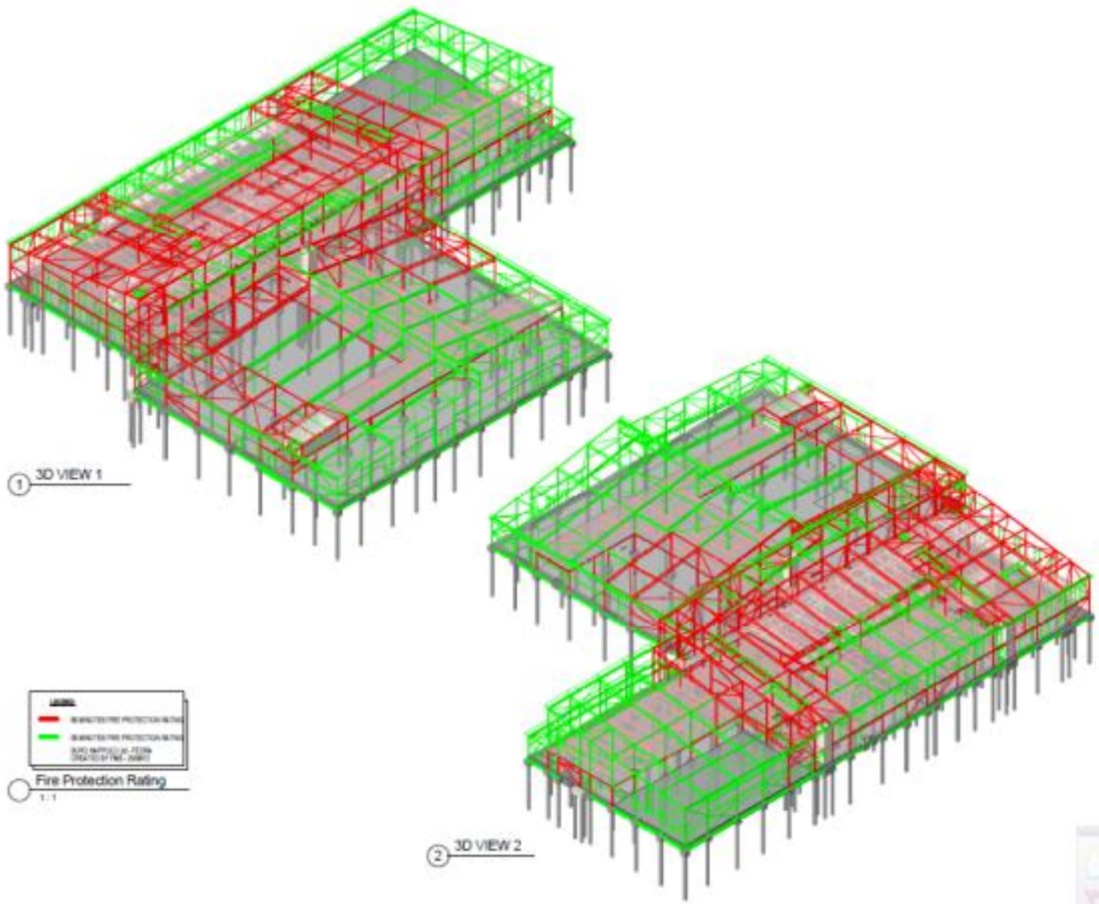
BIM – Building Information Modelling

- Communicating the design solutions is essential to the work we do.
- Use of 3D visualisation becomes new standard.





Revit



Conclusion

- Performance based design is sometimes the only way to demonstrate the safety of a building.
- Buy-in from all stakeholders required.
- Sensitivity studies are essential.
- Communication of solutions to contractors and site is very important.
- If carefully conducted performance based design can generate significant value for a project.
- Great engineering discipline!