
# Travelling Fires in OpenSees

## OpenSees Workshop, SiF2022, Hong Kong

Dr Xu Dai, 29th November 2022

# Motivation

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**Uncertainties of fire hazard in large spaces in modern architecture and implications for structural engineering?**

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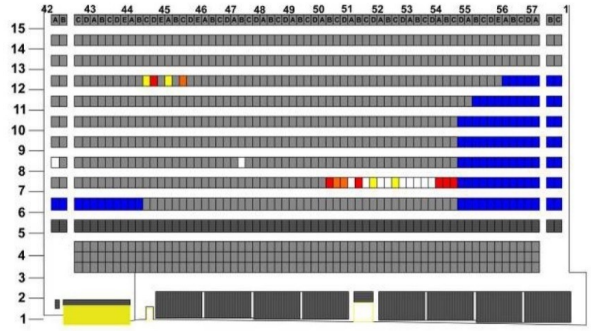
**World Trade Center Tower 1 in New York City in 2001**

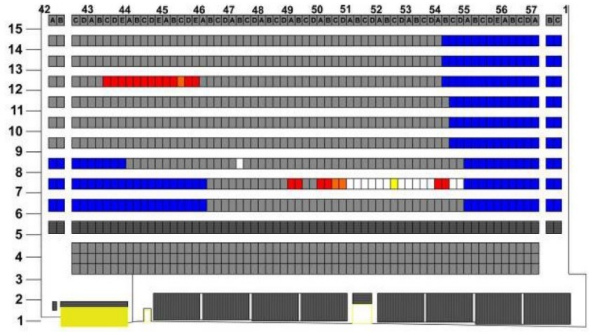
(source: https://www.metabunk.org/)

# WTC 7

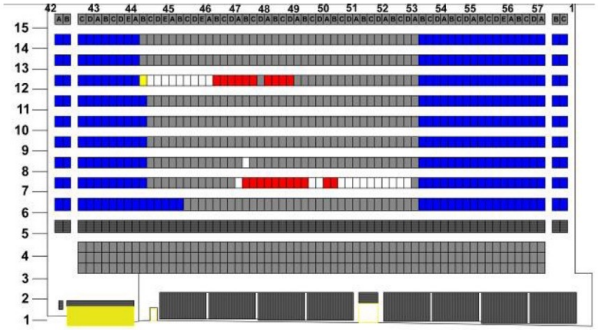
Window glass intact  Window open  Fire visible inside  Not visible



2:57 p.m.



3:05 p.m.



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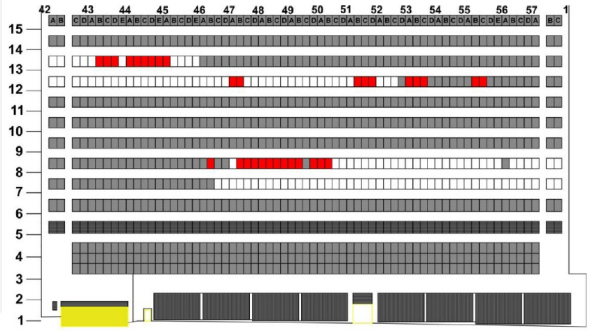

3:44 p.m.

**Facade map summarizing observations of fire spread and window breakage on the north face of WTC 7**

(source: NIST NCSTAR 1-9, Structural Fire Response and Probable Collapse Sequence of World Trade Centre Building 7, 2008)

# Travelling fires

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## What is a travelling fire?

It is a way of approximating fire impact on structures in large open-plan spaces for structural design.

Large compartment fires may burn locally and tend to move across floor plates over a period of time.

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# Travelling fires

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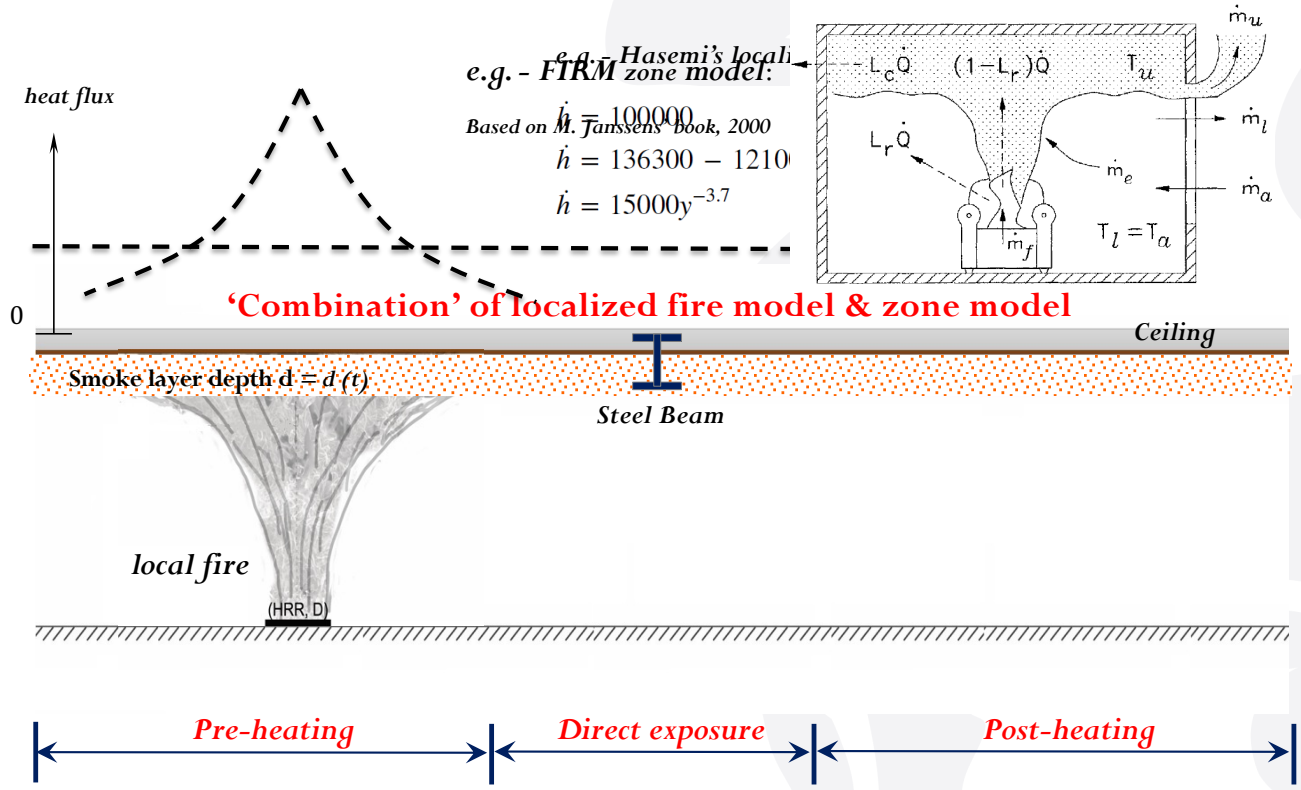
## Extended Travelling Fire Method (ETFM) framework

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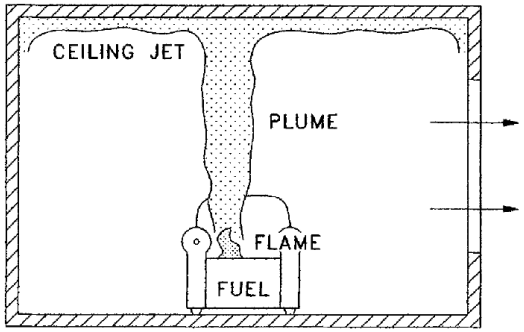
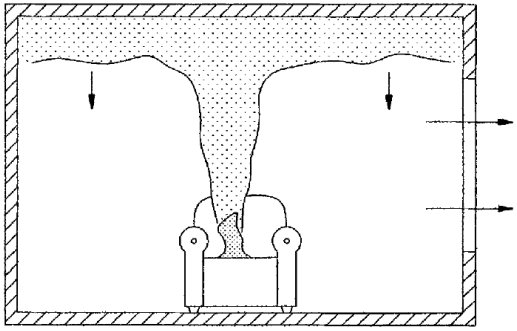
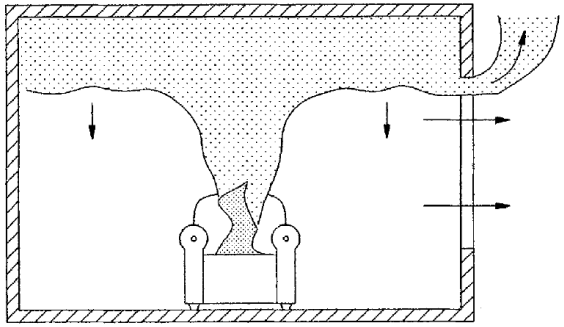
# Extended Travelling Fire Method (ETFM) framework



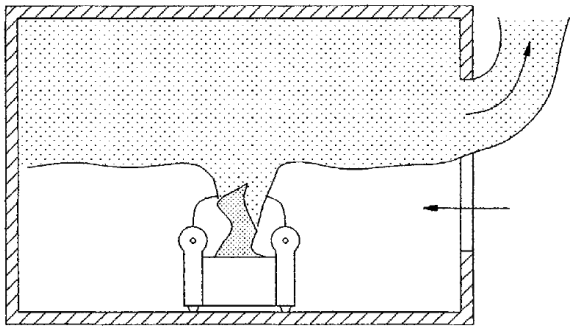

Stage 1



Stage 2



Stage 3

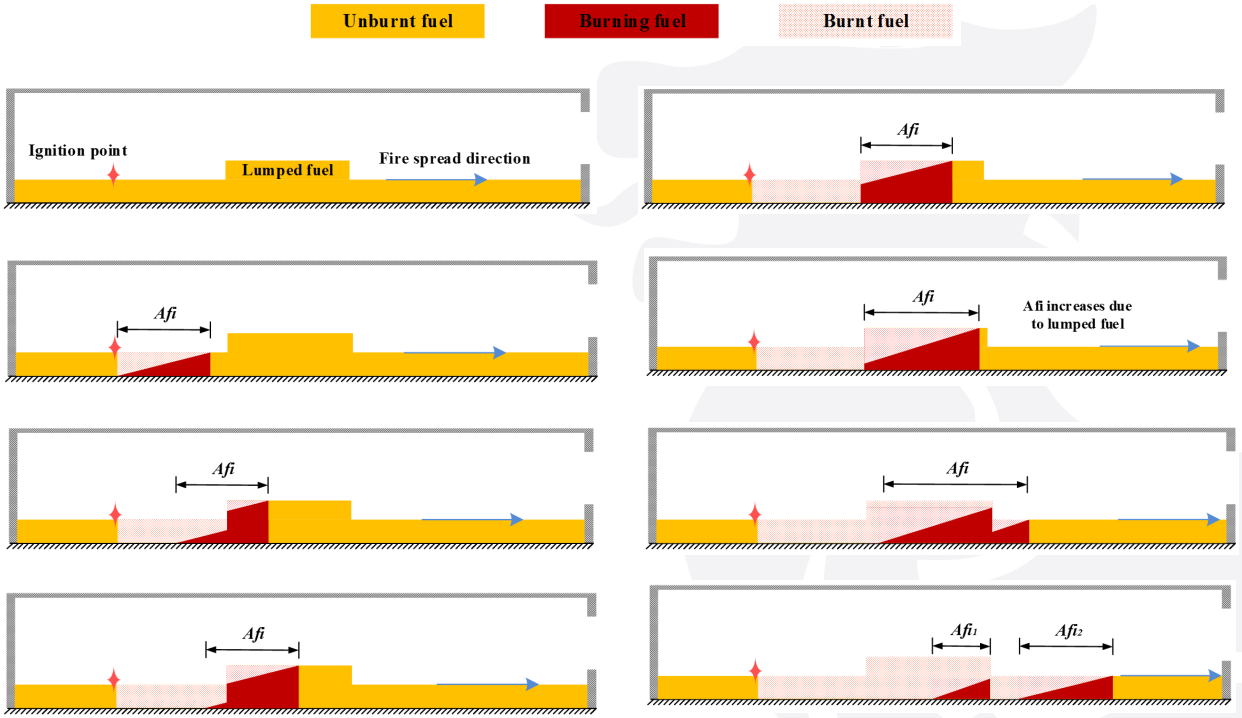


Stage 4

**Stages of the hot smoke layer formation in OpenSees**

**(source: M. Janssens' book, 2000)**

# Extended Travelling Fire Method (ETFM) framework




**Determination of burning area of fuel $A_{fi}$ with lumped fuel In OpenSees**

# Extended Travelling Fire Method (ETFM) framework

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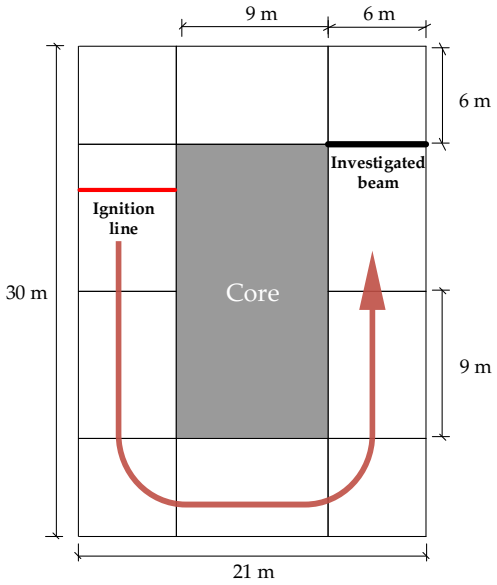
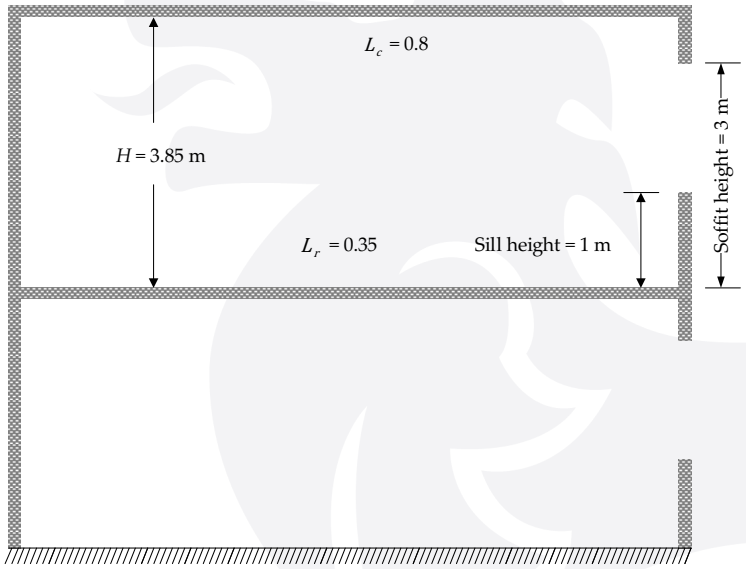
## An idealised steel composite building with a core




Large compartment dimensions:

Building dimensions:

x direction: 6m – 9m – 6m

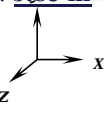
y direction: 5m – 24 m

z direction: 6m – 9m – 6m

Net floor area: 468 m² floor height: 3.85 m

Total vertical width: 28 m Sill height: 1 m

Soffit height: 3 m

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# Extended Travelling Fire Method (ETFM) framework

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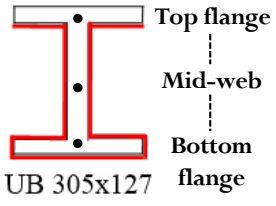


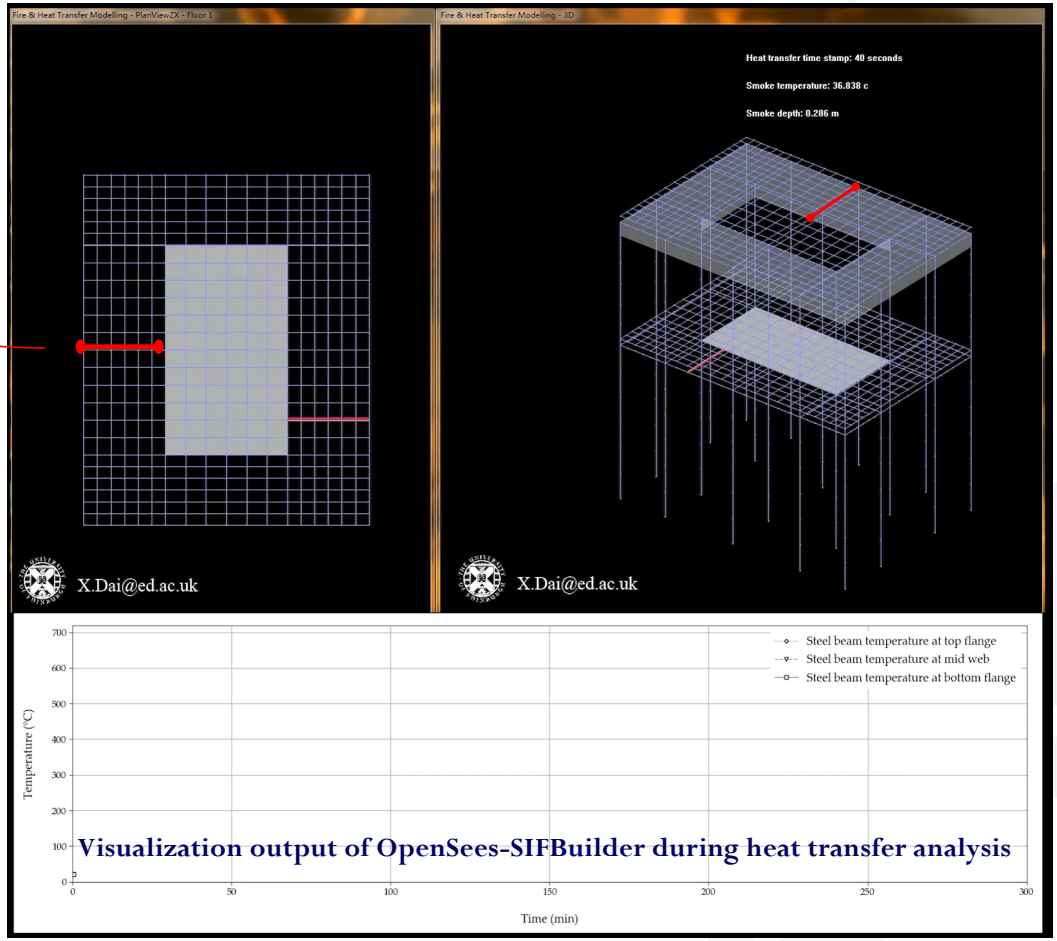


Visualization output of OpenSees-SIFBuilder during heat transfer analysis

Fire scenario:

Fire starts on:
**the first floor**

Fire spread rate:
**5 mm/s**

HRR per area:
**300 kW/m²**

Fuel load density:
**570 MJ/m²**

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# Extended Travelling Fire Method (ETFM) framework

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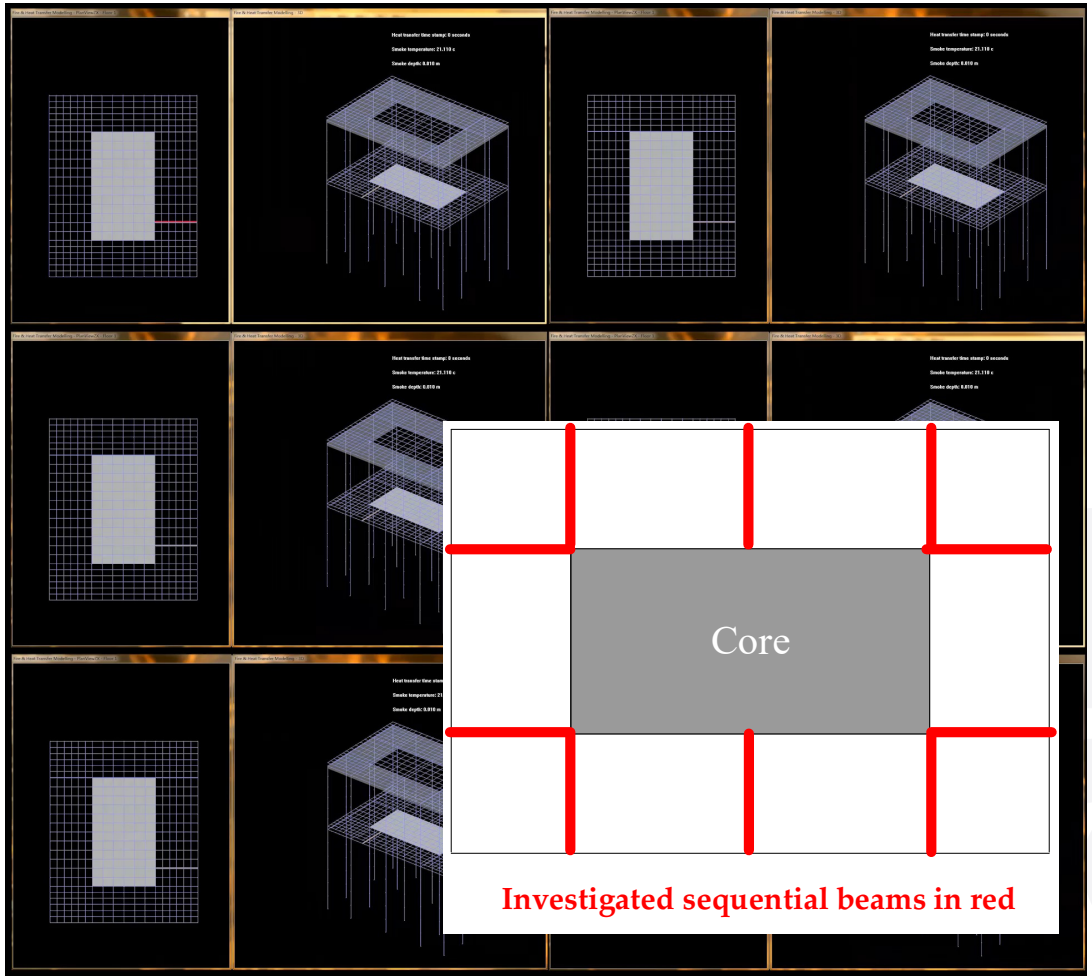
100 MJ/m$^2$

230 MJ/m$^2$

300 MJ/m$^2$




420 MJ/m$^2$

600 MJ/m$^2$

780 MJ/m$^2$

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# Extended Travelling Fire Method (ETFM) framework

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**Structure:** Uniformly distributed loads on all beams: **2 kN/m**

All beams: **UB 305x127x42**

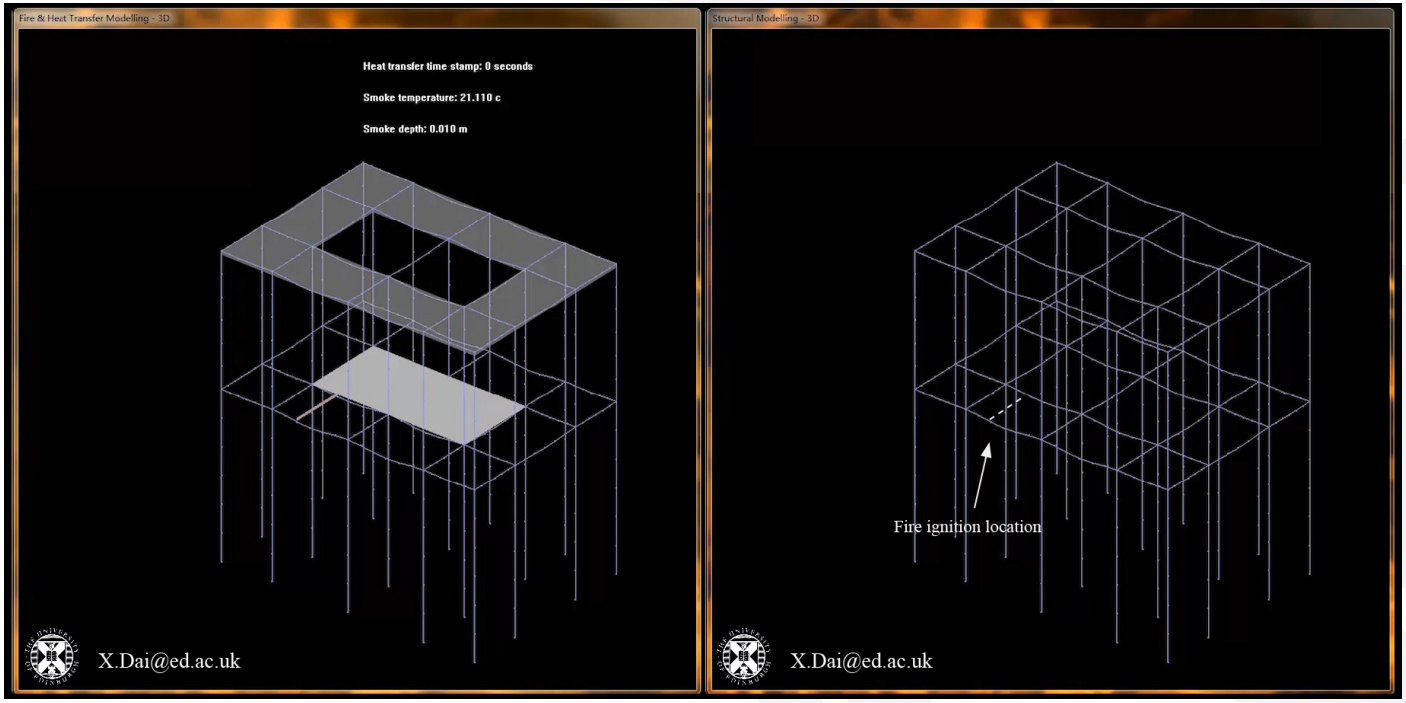
All columns: **UC 356x406x235**

**Fire scenario:** Fire starts on: **the first floor**

Fire spread rate: **5 mm/s**

HRR per area: **300 kW/m²**

Fuel load density: **570 MJ/m²**




Fire & heat transfer analysis in SIFBuilder

Structural analysis in SIFBuilder

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## Extended Travelling Fire Method (ETFM) framework

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# SO WHAT?

**What is a good travelling fire model?**

**More fire science? Upper bound for structural fire design? Easy to use?**

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# ETFM vs. TRAFIR-Ulster Travelling Fire Test 1

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**Experimental building and fuel bed layout of the TRAFIR-Ulster Travelling Fire Test 1**

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| | | |
|---|---|---|
| 9:30-9:45 | LARGE SCALE FIRE TEST: TRAVELLING FIRE WITH FLASHOVER UNDER VENTILATION CONDITIONS AND ITS INFLUENCE ON THE SURROUNDING STEEL STRUCTURE [No.155]<br>***Ali Nadjai**, Naveed Alam, Marion Charlier, Olivier Vassart, Jean-Marc Franssen, Stephen Welch, Johan Sjostrom* | **[Z211]** |
| 9:45-10:00 | "SCALING-UP" FIRE SPREAD ON WOOD CRIBS TO PREDICT A LARGESCALE TRAVELLING FIRE TEST USING CFD [No.194]<br>***Xu Dai**, Naveed Alam, Chang Liu, Ali Nadjai, David Rush, Stephen Welch* | |
| 10:00-10:15 | THE SIGNIFICANCE OF SLAB FOR STRUCTURAL RESPONSE UNDER TRAVELLING FIRES [No. 195]<br>***Zhuojun Nan**, Xu Dai, Stephen Welch, Asif Usmani* | |

# ETFM vs. TRAFIR-Ulster Travelling Fire Test 1

**Key setup parameters in the ETFM for prediction:**

- **Fire spread rate**: **3.46 mm/s**, test observation, calculation: 13.5 m / 65 min = 3.46 mm/s
- **Fuel load density at fuel bed**: **400 MJ/m²**, calculation: $36.5\,kg/m^2 \times 10.84\,MJ/kg = 400\ \mathrm{MJ/m^2}$

  mass of timber per unit fuel bed area

  effective heat of combustion (tested at Edinburgh fire lab)

- **HRRPUA at fuel bed**: **554 kW/m²**, calculation: $\frac{3.46\ \mathrm{mm/s}}{2500\ \mathrm{mm}} \times 400\,MJ/\mathrm{m^2} = 554\ \mathrm{kW/m^2}$

  fire spread rate

  flame thickness

  fuel load density

# ETFM vs. TRAFIR-Ulster Travelling Fire Test 1

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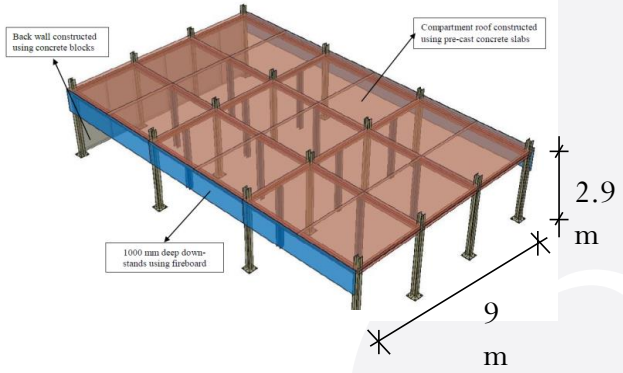
**Key setup parameters in the ETFM for prediction:**

- **Opening height**: **2.9 m**
- **Opening width**: **9 m**




**Note: due to current limitation of zone model in ETFM, only one opening is considered. Hence higher smoke layer temperature can be expected due to mass balance**

- **Radiative heat loss fraction**: **0.35**, (Janssens, 2000)
- **Heat loss fraction through compartment boundaries**: **0.25 – 0.45**,

(Maluk, 2017; and 10% moisture content at ceiling consideration, and larger ceiling area compared to RISE travelling fire test)

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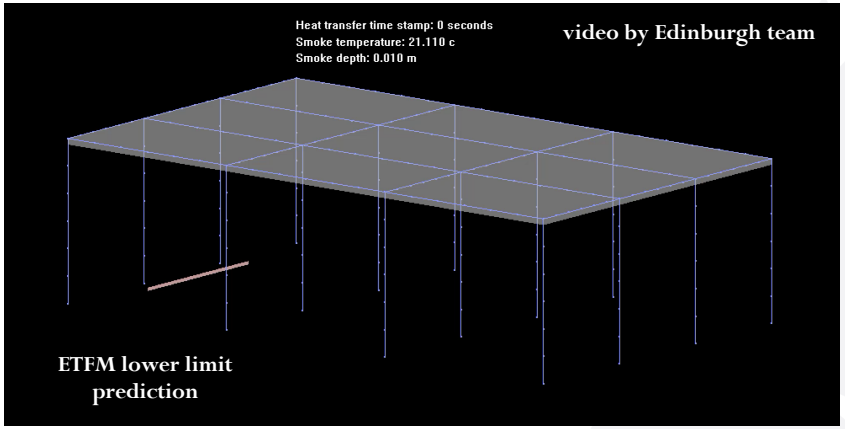
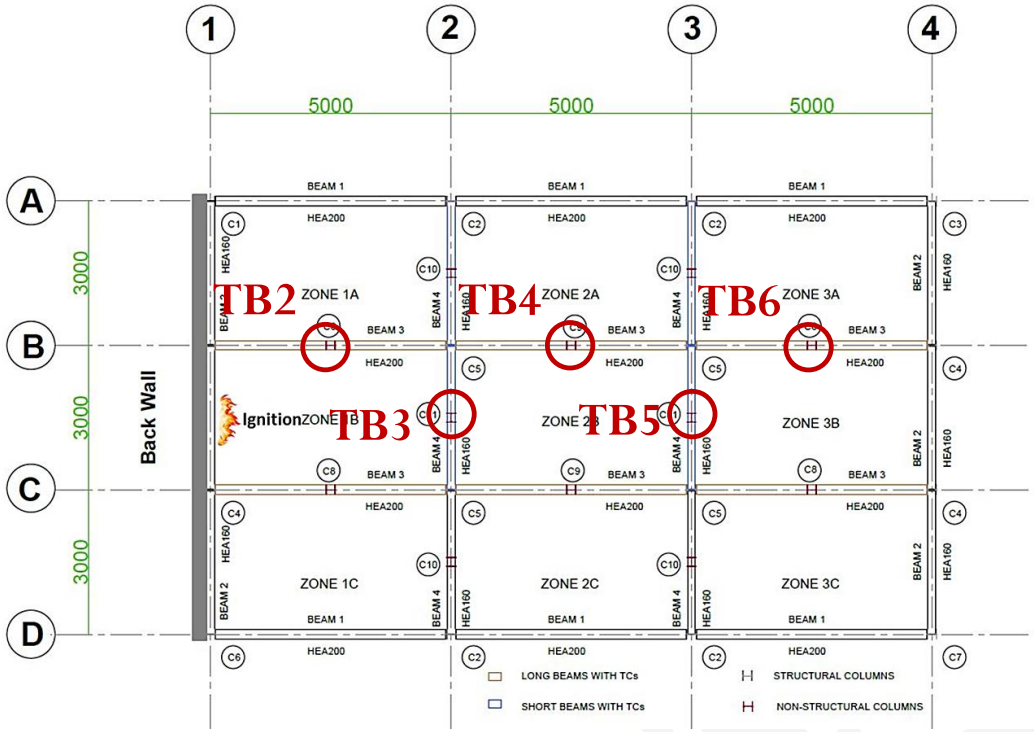
# ETFM vs. TRAFIR-Ulster Travelling Fire Test 1




# ETFM vs. TRAFIR-Ulster Travelling Fire Test 1



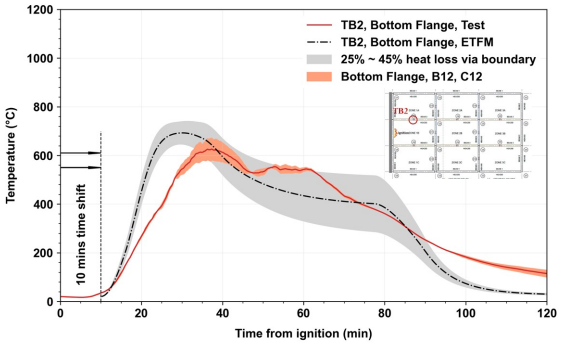

**Investigated steel temperature measurement locations, TB2 – TB6;**
**for the comparison between the ETFM framework and Ulster Travelling Fire Test.**

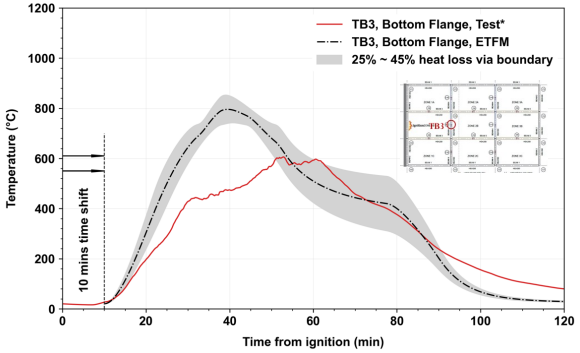
**(source: figure originally from Ulster-TRAFIR-WP3 report )**

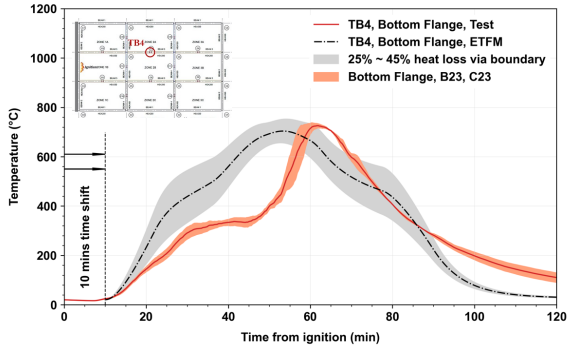
# ETFM vs. TRAFIR-Ulster Travelling Fire Test 1

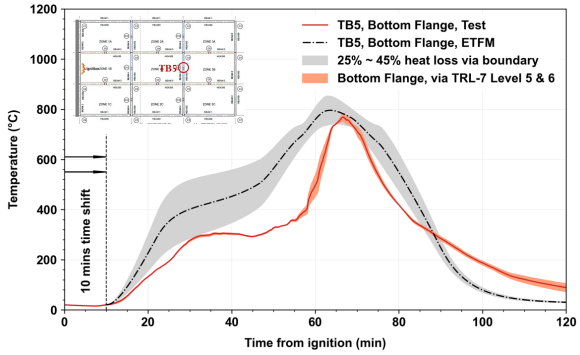
**Remarks:**

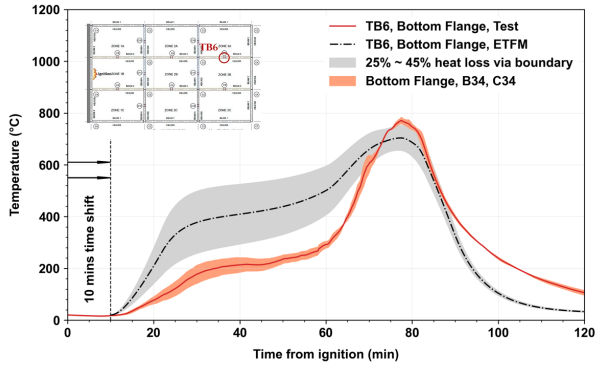
- The ETFM framework prediction on far-field is probably too conservative, an upgrade on zone model considering multiple openings could be added in the future;
- The ETFM framework prediction on near-field is conservative, the superposition of heat fluxes from Hasemi & zone model seems an appropriate assumption;
- The constant fire spread rate STILL looks like an appropriate assumption for this validation case;




Error bar for ETFM:
considering 20% variance of the heat loss fraction of the total energy

Error bar for Ulster test (TB2, 4, 6):
using symmetry of the TC trees at Level 6, along the fire path;

Error bar for Ulster test (TB3, 5):
using the TCs at the same tree of Level 5 and Level 6.

**Comparison between the ETFM framework and the Ulster Travelling Fire Test 1, (* TRL5-L5 used instead of TRL5-L6 since it was broken).**

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# An example script

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# An example script in OpenSees/SIFBuilder

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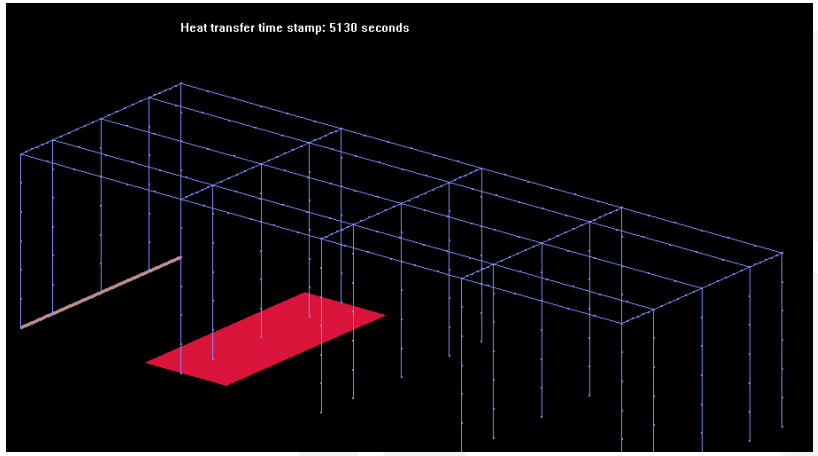
**TCL language-based user input file, structural definition:**

```
1   ##########################################################################################
2   #####                                                                                #####
3   #####                              TRAFIR Model Example Script                       #####
4   #####                                                                                #####
5   ##########################################################################################
6
7   # This Tcl model works in SVN commit version 87
8
9   # For testing TRAFIR model with heat transfer module under SIFBuilder
10  # Written by: Xu Dai (x.dai@ed.ac.uk; xudai1987@gmail.com), Dec. 2020, University of
    Edinburgh
11  # SI unit i.e. meter, newton, second
12
13  wipe;
14  set dataDir TRAFIR_Example;
15  file mkdir $dataDir;
16
17  # Define STRUCTURAL MODEL
18  SIFBuilder -type Frame -ndm 3;
19  SIFXBay 8.0 7.0 7.0 8.0;
20  SIFZBay 2.0 3.0 3.0 2.0;
21  SIFStorey 3.0;
```




**Each bay length is defined, unit in m.**

**For example:**
**X Bay: 8m, 7m, 7m, 8m. 4 bays in total**

# An example script in OpenSees/SIFBuilder

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**Steel material definition following EC3, cross-section dimension (unit in m), and assigning the cross-section dimensions to the relevant beam/column series:**

```
22
23  # ASSIGN SECTION
24  AddMaterial steel 1 -type EC3 2.35e8  2.1e11;
25  AddSection ISection 1 1 0.4026 0.1777 0.0077 0.0109;     # $d $bf $tw $tf, UB 406x178x54
26  AddSection ISection 2 1 0.4000 0.3000 0.0135 0.02405;    # $d $bf $tw $tf, HE400B
27  AssignSection XBeams 1;
28  AssignSection ZBeams 1;
29  AssignSection columns 2;
```

**All the column bases are fixed, and all beams are applied with uniformly distributed load (unit: N/m):**

```
30
31  # Set BOUNDARY CONDITION
32  SetBC fixedJoint -Locy 0;
33
34  # Define LOADING
35  #AddLoad -SIFJoint 2_2_2 -load 0 600000 0;
36  AddLoad -SIFMember allBeams -load 0 -15856 0;
37
```

# An example script in OpenSees/SIFBuilder

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**TRAFIR model is triggered here via keyword "TRAFIR", with defining the fire at floor number 0, ignition line source and fire travel direction prescribed; opening size is also defined with total opening width, sill height, and soffit height (unit in m):**

```
38  # FIRE DEFINITION
39  AddFire -floor 0 -type TRAFIR -IgnitionLine point1 0 0 0 point2 0 0 10.0
    -fireTravelDirection AntiClockWise;
40
41  # MORE FIRE INFO
42  AddFirePars -floor 0 -type TRAFIR -ventWidth 25 -sillHeight 0.5 -soffitHeight 2.5;
```

**Uniform fuel load is assigned with fuel base height 0.3m, fire spread rate 2mm/s, fuel load density 511MJ/m2, and HRRPUA 250kW/m2:**

```
44  # FUEL LOAD DISTRIBUTION DEFINITION
45  AddFuel -RMFD 1 -floor 0 -fuelBaseHeight 0.3 -SpreadRate 2.0 -FuelLoadDensity 511
    -HRRperArea 250;
```

# An example script in OpenSees/SIFBuilder

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**Structural FEM model mesh control is setup here. Six elements per beam/column. Linear geometry transformation is considered, P-Delta effect could also be used via changing the keyword to "P-Delta":**

```
46
47   # BUILD MODEL
48   BuildModel -MeshCtrl 6 6 6 -geomTransf Linear;
```

**Four display windows setup, users might change the setup by their preference, but default is recommended.**

```
--
50   # Define DISPLAY FOR ONE SCREEN
51   DisplaySIFModel PlanViewZX FloorNumber 0 WindowLoc 15 15 WindowSize 250 750 ViewScale 20;
52   DisplaySIFModel 3D WindowLoc 275 15 WindowSize 1200 550 ViewScale 20;
53   DisplaySIFModel ElevationViewZY WindowLoc 15 765 WindowSize 650 280 ViewScale 20;
54   DisplaySIFModel ElevationViewXY WindowLoc 275 565 WindowSize 1200 200 ViewScale 20;
```

# An example script in OpenSees/SIFBuilder

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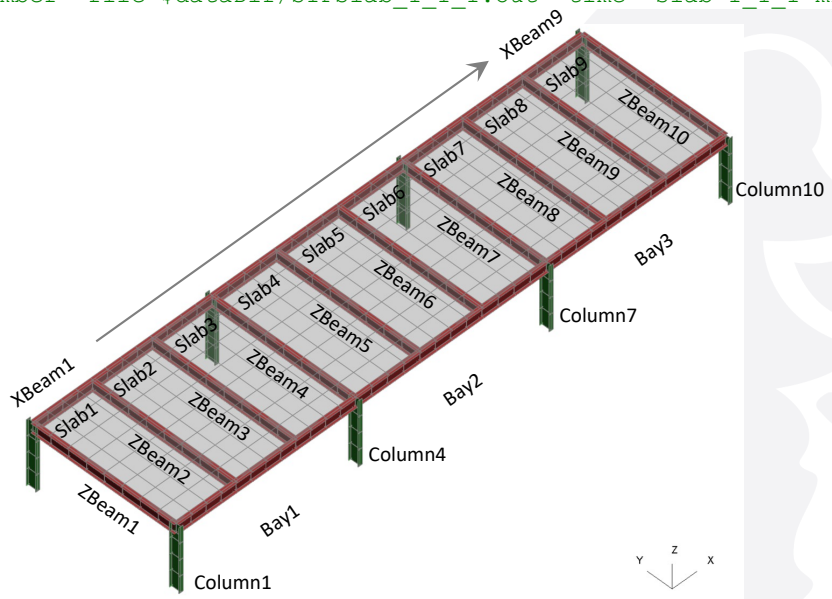
**Structural response is setup by the user's request, tag system is below:**

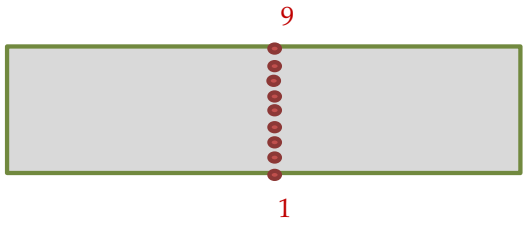
```
55
56   # Define OUTPUT RESULTS
57   SIFRecorder SIFJoint -file $dataDir/SIFJoint_1_1_1_Disp.out -time -joint 1_1_1 disp;
58   #SIFRecorder SIFJoint -file $dataDir/SIFJoint_10_1_1_Disp.out -time -joint 10_1_1 disp;
     #to debug
59   #SIFRecorder SIFMember -file $dataDir/SIFXBeam_5_1_1_Mid_Deflect.out -time -xBeam 5_1_1
     mid-deflect;
60   #SIFRecorder SIFMember -file $dataDir/SIFZBeam_3_1_1_Mid_Deflect.out -time -zBeam 3_1_1
     mid-deflect;
61   #SIFRecorder SIFMember -file $dataDir/SIFColumn_5_2_1_Mid_Deflect.out -time -column
     5_2_1 mid-disp;
62   #SIFRecorder SIFMember -file $dataDir/SIFSlab_1_1_1.out -time -slab 1_1_1 mid-deflect;
```



# An example script in OpenSees/SIFBuilder

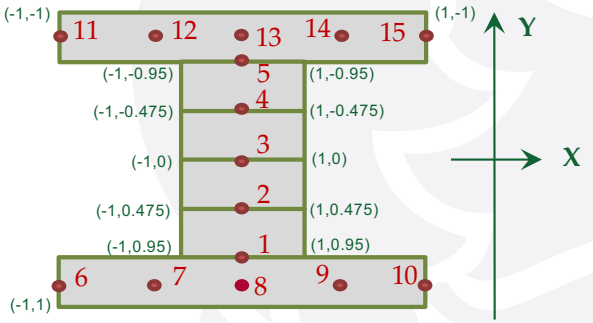
**In this case only fire load is analysed. Examples of combination of fire load & mechanical load are commented below. 9 Data point for data transfer from 1D for slab, or 2D for beams/columns heat transfer to structural model.**

```
63
64   # Apply LOADS & Define ANALYSIS & Define HT OUTPUT
65   SIFAnalyze Fire -dt 10 -output $dataDir -datapoints 9;
66   #SIFAnalyze selfWeight -dt 0.2 Fire -dt 20 -output $dataDir -datapoints 9;
67   #SIFAnalyze selfWeight -dt 0.2 Load -dt 0.1 Fire -dt 20 -output $dataDir -datapoints 9;
68   #SIFAnalyze Load -dt 0.1 Fire -dt 30 -duration 960 -output $dataDir;
69   #SIFAnalyze Load -dt 0.1;
70
71   # Print KEY INFO
72   print $dataDir/domain.out
73
74   wipe;
75   #wipeSIFBuilder;
```




Shell element

1D heat transfer




Beam-column element

2D heat transfer

# An example script in OpenSees/SIFBuilder

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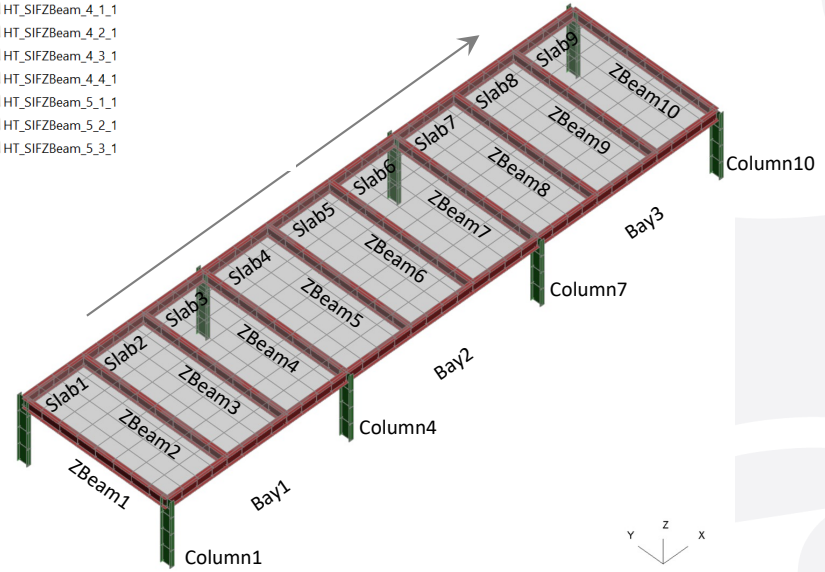
**Heat transfer data files are .out files can be opened by any text editor:**

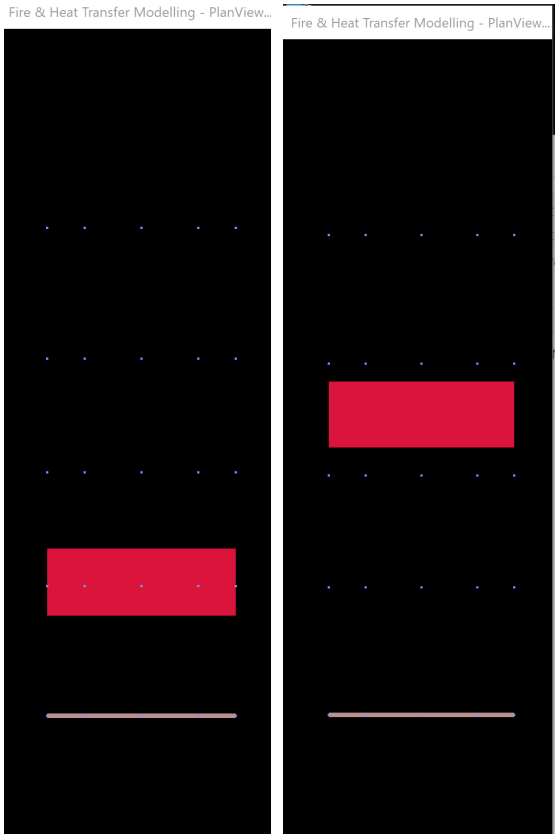
| | | | | |
|---|---|---|---|---|
| HT_SIFColumn_1_1_1 | HT_SIFColumn_4_2_1 | HT_SIFXBeam_2_3_1 | HT_SIFZBeam_1_4_1 | HT_SIFZBeam_5_4_1 |
| HT_SIFColumn_1_2_1 | HT_SIFColumn_4_3_1 | HT_SIFXBeam_2_4_1 | HT_SIFZBeam_2_1_1 | |
| HT_SIFColumn_1_3_1 | HT_SIFColumn_4_4_1 | HT_SIFXBeam_2_5_1 | HT_SIFZBeam_2_2_1 | |
| HT_SIFColumn_1_4_1 | HT_SIFColumn_4_5_1 | HT_SIFXBeam_3_1_1 | HT_SIFZBeam_2_3_1 | |
| HT_SIFColumn_1_5_1 | HT_SIFColumn_5_1_1 | HT_SIFXBeam_3_2_1 | HT_SIFZBeam_2_4_1 | |
| HT_SIFColumn_2_1_1 | HT_SIFColumn_5_2_1 | HT_SIFXBeam_3_3_1 | HT_SIFZBeam_3_1_1 | |
| HT_SIFColumn_2_2_1 | HT_SIFColumn_5_3_1 | HT_SIFXBeam_3_4_1 | HT_SIFZBeam_3_2_1 | |
| HT_SIFColumn_2_3_1 | HT_SIFColumn_5_4_1 | HT_SIFXBeam_3_5_1 | HT_SIFZBeam_3_3_1 | |
| HT_SIFColumn_2_4_1 | HT_SIFColumn_5_5_1 | HT_SIFXBeam_4_1_1 | HT_SIFZBeam_3_4_1 | |
| HT_SIFColumn_2_5_1 | HT_SIFXBeam_1_1_1 | HT_SIFXBeam_4_2_1 | HT_SIFZBeam_4_1_1 | |
| HT_SIFColumn_3_1_1 | HT_SIFXBeam_1_2_1 | HT_SIFXBeam_4_3_1 | HT_SIFZBeam_4_2_1 | |
| HT_SIFColumn_3_2_1 | HT_SIFXBeam_1_3_1 | HT_SIFXBeam_4_4_1 | HT_SIFZBeam_4_3_1 | |
| HT_SIFColumn_3_3_1 | HT_SIFXBeam_1_4_1 | HT_SIFXBeam_4_5_1 | HT_SIFZBeam_4_4_1 | |
| HT_SIFColumn_3_4_1 | HT_SIFXBeam_1_5_1 | HT_SIFZBeam_1_1_1 | HT_SIFZBeam_5_1_1 | |
| HT_SIFColumn_3_5_1 | HT_SIFXBeam_2_1_1 | HT_SIFZBeam_1_2_1 | HT_SIFZBeam_5_2_1 | |
| HT_SIFColumn_4_1_1 | HT_SIFXBeam_2_2_1 | HT_SIFZBeam_1_3_1 | HT_SIFZBeam_5_3_1 | |

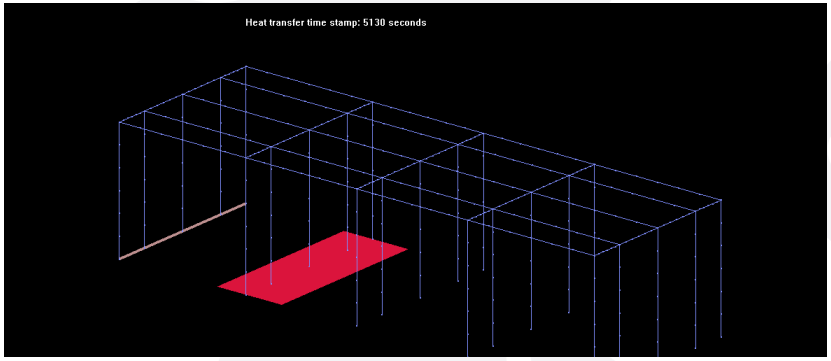


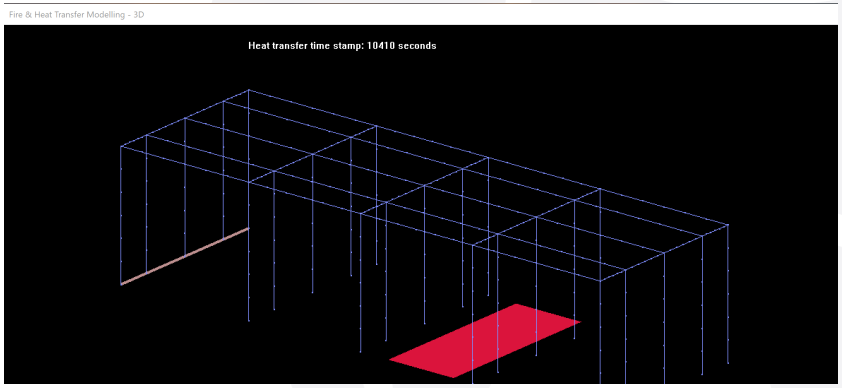
# An example script in OpenSees/SIFBuilder

BIRMINGHAM CITY University

During the fire analysis, the fire modelling status is rendered to the screen using OpenGL:



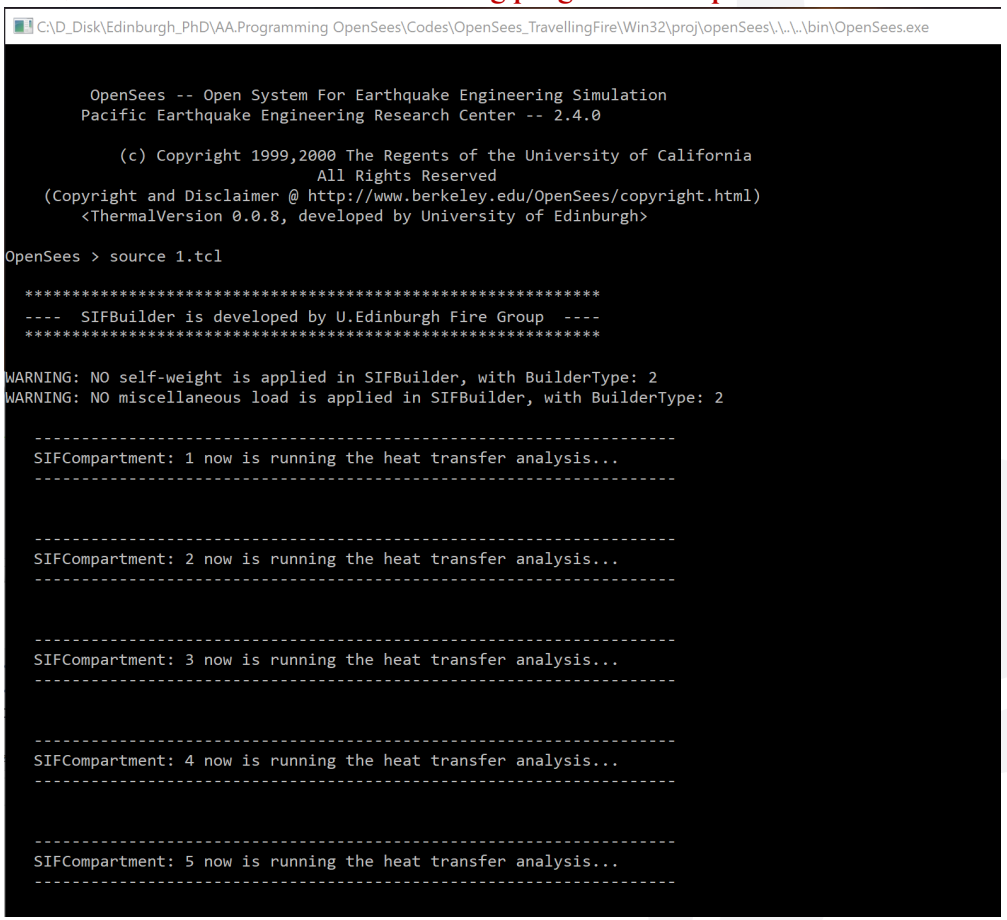



# An example script in OpenSees/SIFBuilder

BIRMINGHAM CITY University

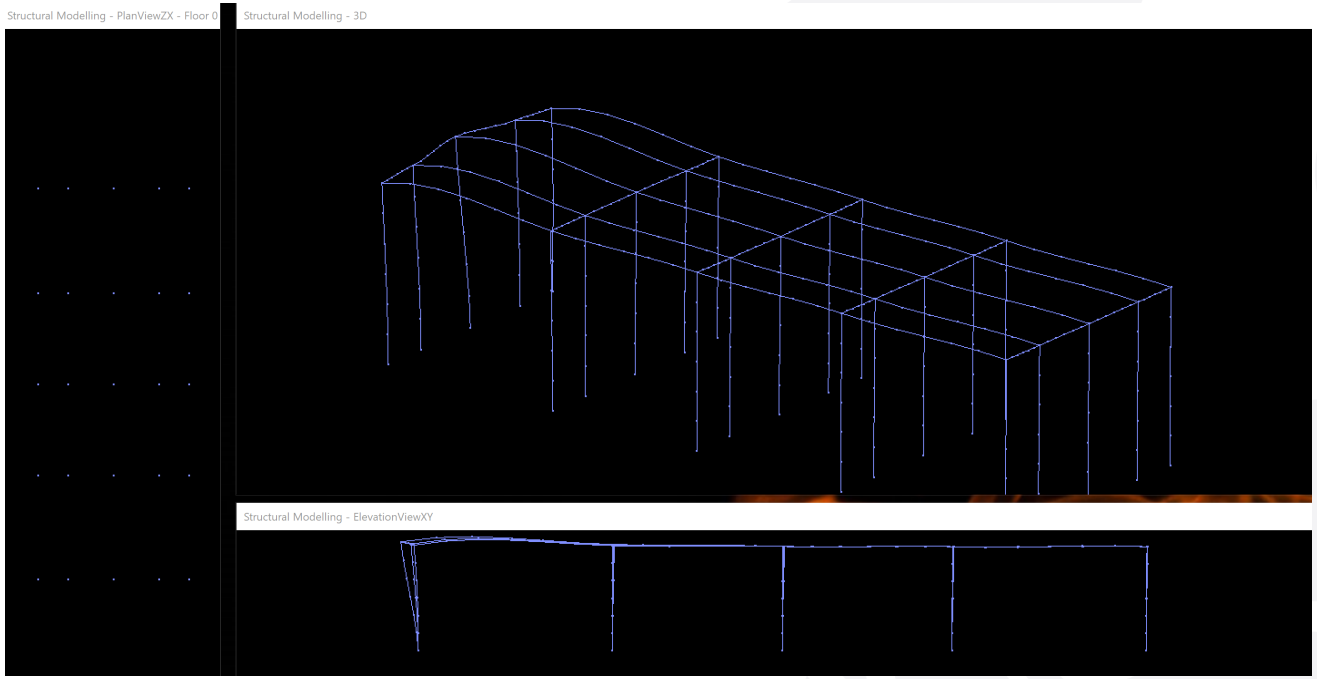
**At OpenSees terminal, the fire & heat transfer modelling progress is also printed:**



# An example script in OpenSees/SIFBuilder

BIRMINGHAM CITY University

**OpenSees/SIFBuilder will do the structural response automatically for the user, no data transfer pain!**

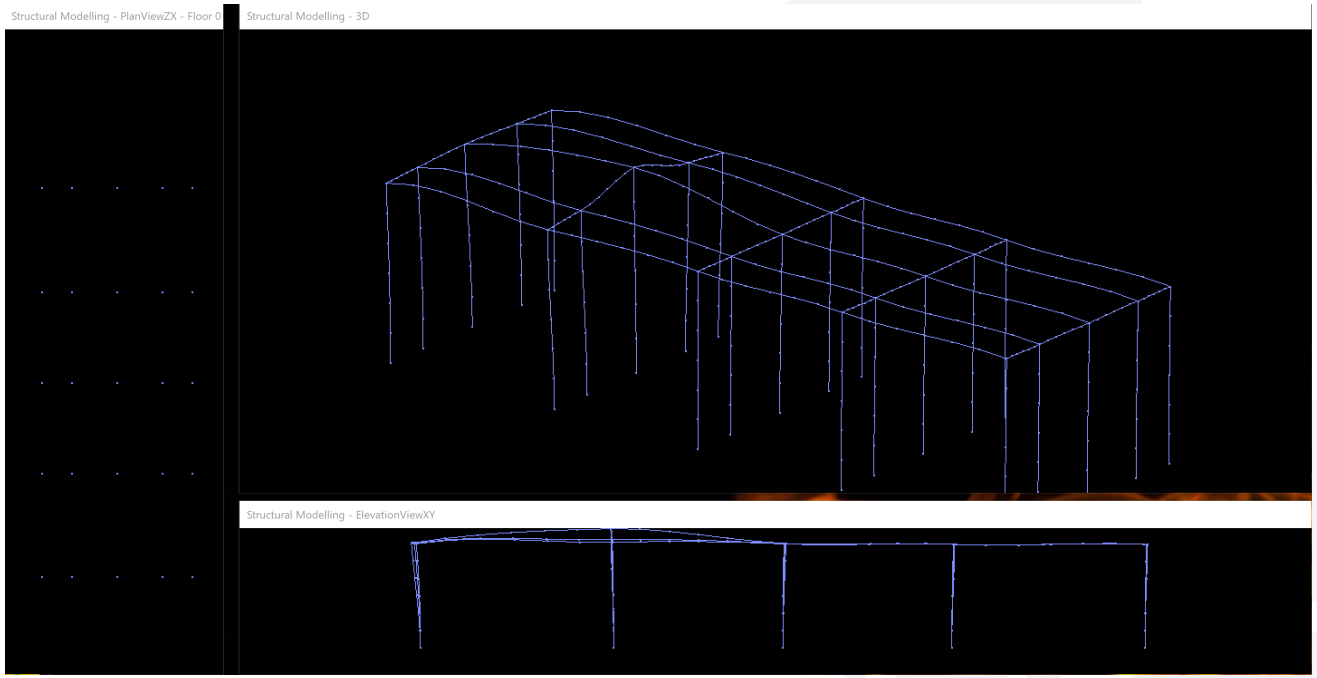



**Fire at Bay 1**

# An example script in OpenSees/SIFBuilder

BIRMINGHAM CITY University

**OpenSees/SIFBuilder will do the structural response automatically for the user, no data transfer pain!**

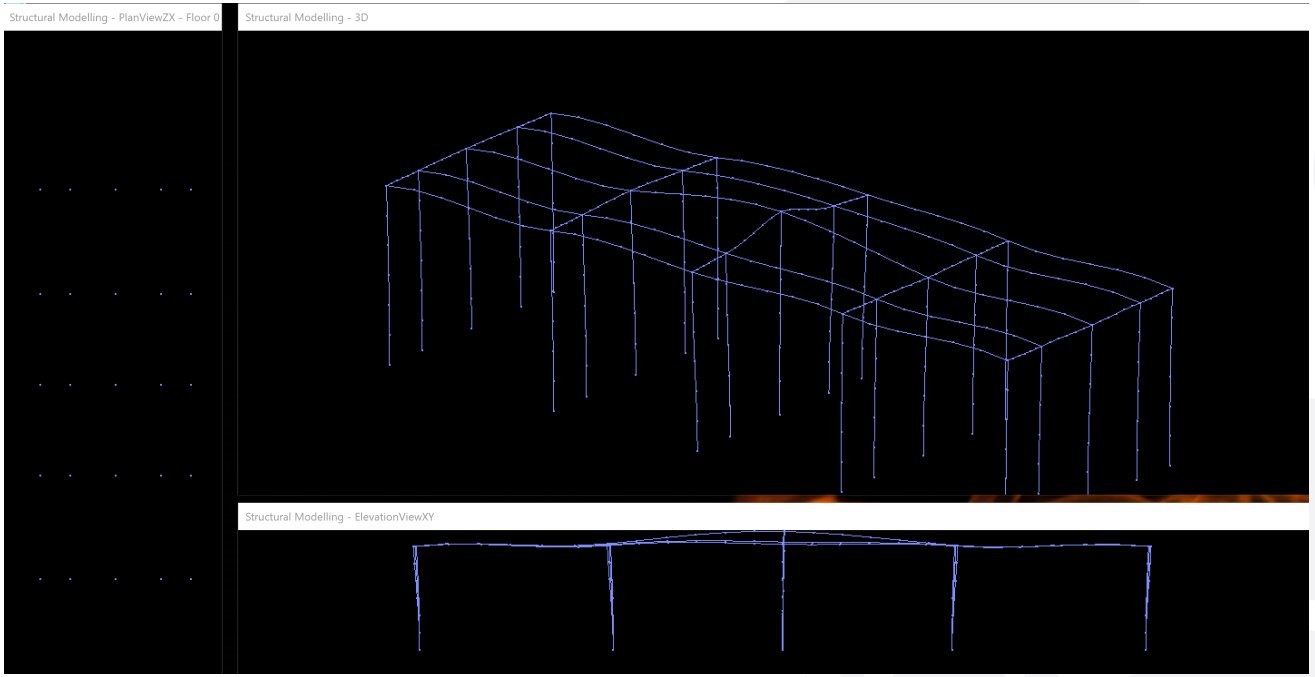



**Fire at Bay 2**

# An example script in OpenSees/SIFBuilder

BIRMINGHAM CITY University

**OpenSees/SIFBuilder will do the structural response automatically for the user, no data transfer pain!**

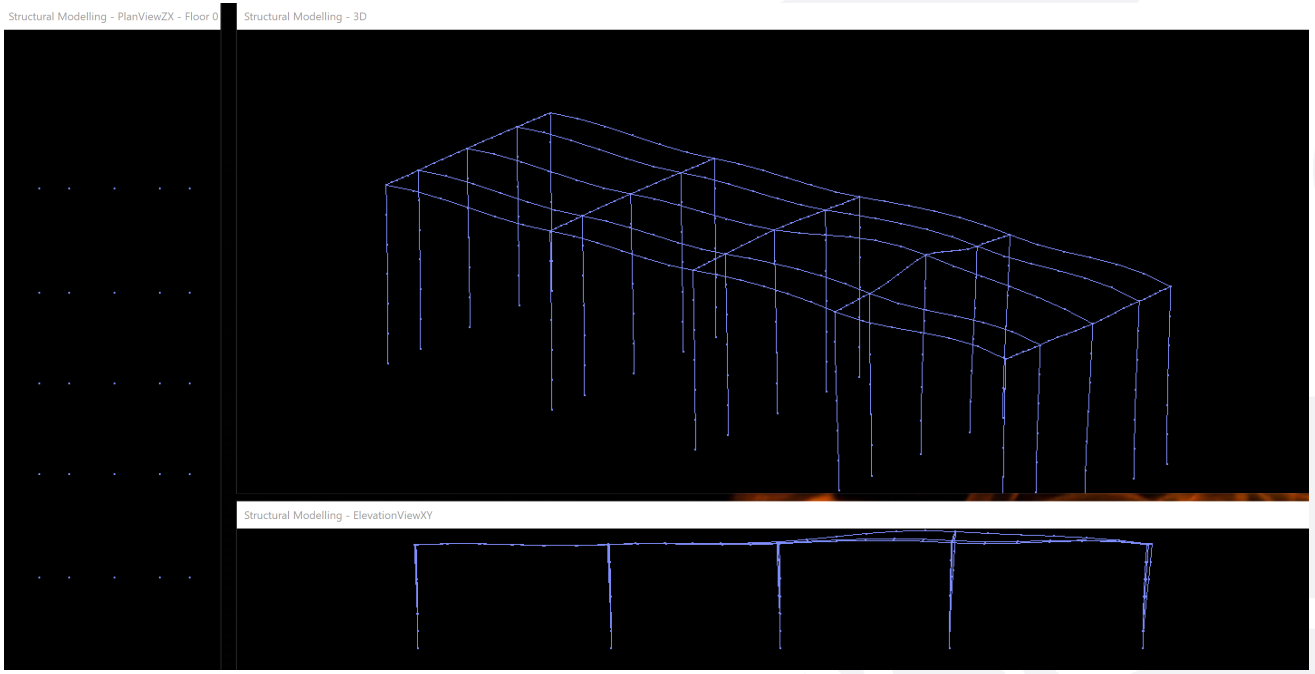



**Fire at Bay 3**

# An example script in OpenSees/SIFBuilder

BIRMINGHAM CITY University

**OpenSees/SIFBuilder will do the structural response automatically for the user, no data transfer pain!**

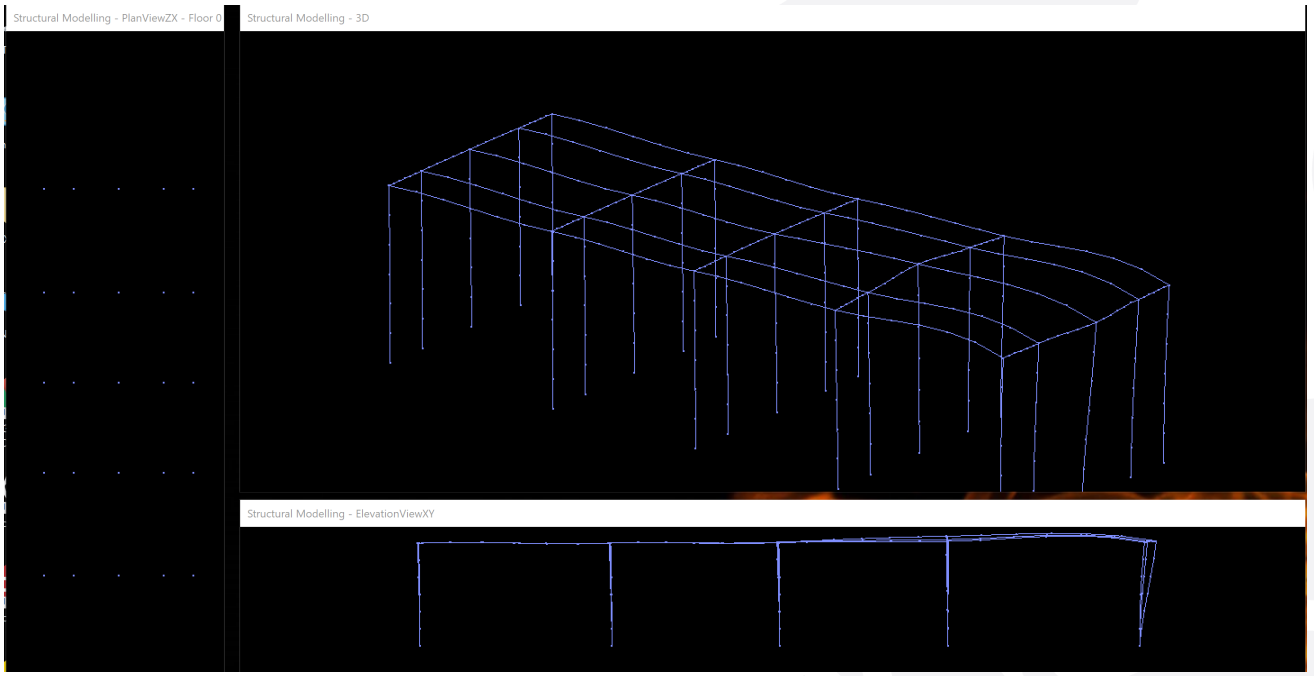



**Fire at Bay 4**

# An example script in OpenSees/SIFBuilder

BIRMINGHAM CITY University

**OpenSees/SIFBuilder will do the structural response automatically for the user, no data transfer pain!**




**Fire at Bay 4 end**

# Travelling Fires in OpenSees

## Q & A?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