

## AN INTEGRATED TOOL FOR PERFORMANCE BASED ENGINEERING OF STRUCTURES IN FIRE

Liming Jiang<sup>1</sup>, Praveen Kamath<sup>1</sup>, Xu Dai<sup>1</sup>, Jiayu Hu<sup>1</sup>, Suwen Chen<sup>2</sup> and Asif Usmani<sup>1</sup>

<sup>1</sup>Institute for Infrastructure and Environment, School of Engineering,  
The University of Edinburgh, Edinburgh, EH9 3JF, United Kingdom. Email: [asif.usmani@ed.ac.uk](mailto:asif.usmani@ed.ac.uk)  
<sup>2</sup>State Key Laboratory for Disaster Mitigation in Civil Engineering, College of Civil Engineering,  
Tongji University, Siping Road, Shanghai, China.

### ABSTRACT

Performance based engineering (PBE) is increasingly recognised as the gold standard for ensuring structural safety under extreme loading conditions such as a post-flashover fire. While no universally agreed methodology exists for implementing PBE for various kinds of extreme loadings in general, there are three clearly defined stages for doing so in order to design or assess structural resistance under fire loading. The fire loading is characterised in the first stage, which may range from simple prescribed time-temperature relationships if standard fires are adopted, which is against the spirit of PBE, to an expensive computational fluid dynamics simulation, which in most cases would constitute overkill. A number of options are available and gradually being developed that lie between these two extremes. A realistic characterisation of the load should in general allow the possibility of non-uniform heat fluxes to structural surfaces, which makes the second stage of determining structural temperatures very tedious. Furthermore, the computational models used in the third stage of determining nonlinear structural response are usually very different from the models used in the second stage thereby requiring significant manual intervention by the analyst. In the author's view this, bar the need for further research on realistic fire scenarios, is the greatest obstacle in carrying out PBE for structural fire resistance design. This paper presents a simulation tool developed within the open source software framework OpenSees with the aim of integrating all the stages of the analysis discussed earlier in order to make PBE feasible even for design offices with modest resources in terms of trained analysts and computing hardware.

### KEYWORDS

Integrate software tool, performance based engineering, structures in fire, OpenSees, realistic fire loading.

### INTRODUCTION

In modern day design of structures, durability of structures under natural and man-made hazards has been given more prominence to ensure their longevity. There has been a trend in the structural design industry to adopt performance-based design due to numerous advantages over conventional prescriptive approach. Performance based design methodology is now being extended to enhance the fire performance of structures. To achieve this, structural engineers are required to have better understanding of the global behaviour of structures under common fire scenarios, such as standard and parametric fires, or localised travelling fires for buildings with large compartments. One way to make this happen is by performing automated sequential thermo-mechanical analyses using a single numerical tool. The need for such tool was recommended in the proceedings of a workshop held at NIST (National Institute of Standards and Technology), suggesting to establish a framework (or more likely a patchwork) of models to couple the fire exposure, heat transfer to the structure and structural response in order to support performance-based design (Grosshandler 2002).

In general, there are two types of computer programs for simulating structural behaviours in fire: research-oriented and for commercial use. The former such as SAFIR, VULCAN, and ADAPTIC address specific modelling problems, because of a limited number of users and a vanishingly small team of developers. Therefore these frameworks have natural limitations in their capabilities. The development of such software is academic-research driven and highly prone to the risk of losing valuable development work when team members leave the research group. Commercial software packages such as ABAQUS, ANSYS and DIANA are used by researchers and industry across the world. However limited access to source codes; lack of transparency of the computational framework; and the high cost of purchase and maintenance are major limitations.

In 1997, an open source software framework, Open System for Earthquake Engineering Systems (OpenSees) was developed at the University of California, Berkeley (McKenna 1997). It was initially designed to simulate non-linear response of structural frames under seismic excitations. OpenSees has an object-oriented architecture and is written in C++. Object-oriented capabilities enable structural engineers to focus on modelling objects that also have their own attributes and functions rather than just data. Major attributes such as elements, materials, analysis procedures, and solution algorithms are designed as individual objects and they can be added into the framework freely by anyone anywhere (Usmani *et al.* 2012). An active group of OpenSees experts moderate the framework using a version control system, Subversion. This attracts the researchers from across the globe to contribute their piece of code to the original framework and help make it more robust and bug-free.

In 2009, OpenSees was adopted at the University of Edinburgh to further develop it to perform structural fire analysis. Significant contributions in terms of heat transfer and fire modules have been made to the framework in developing the 'Thermal' version of OpenSees (Jiang Y. Q. 2013). Temperature dependent formulations have been incorporated for basic element types, beam element and shell elements to account for the thermal effects (Jiang J. 2013). Material library of the original framework has also been updated by adding new temperature dependant material models for steel and concrete based on Eurocodes (Zhang 2014).

Development of OpenSees Thermal is an ongoing project and is presently limited to only a few elements, material models and fire scenarios. This cannot fully exploit the great potential of the OpenSees framework. Furthermore, a single software to carry out the full set of analyses which includes relatively realistic fire load modelling (e.g. localised and travelling fires); heat transfer to structural components (by radiation, convection, conduction); and the entire structural response, is still unavailable. In order to move towards a more comprehensive solution for a unified analysis, development of an OpenSees based research tool named SIFBuilder was started in 2014 (Jiang *et al.* 2014), which aims to perform automated structural fire analyses for large structures under realistic fires. It is a comprehensive computational tool, which could enable structural engineers to obtain the structural response automatically with the application of the fire load on the structure in the same manner as any other form of load and so provide a performance-based structural fire engineering tool.

## **THE SIFBUILDER SIMULATION TOOL**

Unlike commercial packages, neither OpenSees nor SIFBuilder has a graphical user interface (GUI). However, it has a script based user input capability. Similar to other commonly used FEM software, SIFBuilder requires the user to input basic structural information for generating the structural model. Procedural scripts are written to specify geometry, materials, loads, heat transfer parameters, fire type, analysis procedures, solution algorithm and output requirements using Tool Command Language / Tool Kit (Tcl/Tk). A typical user input script for model generation includes: model type definition for identifying the dimension of analysis (2D or 3D), geometry of the structure (bay length in each directions in a Cartesian coordinate system), material type and cross section type for the structure members, and boundary conditions for the structural model.

Following model generation, the user defines the structural loading and thereafter the fire loading information. SIFBuilder is programmed to hold the thermal loading information throughout the structural analysis. Subsequently, the heat transfer analysis module launches and the nodal temperature histories are automatically mapped to the fibres of the structural mesh. Following the heat transfer analysis, structural analysis is performed on the building, accounting for the degraded material properties. Hence, the output generated will be the result of a thermo-mechanical analysis in response to realistic fire scenarios. Figure 1(a) shows the flow chart of different operations in the project SIFBuilder.

### ***Model-Generation***

As mentioned in the previous section, the OpenSees framework lacks a pre-processor, and the procedures for model generation are written in Tcl. A series of higher level Tcl commands are created for generating relatively complex structural models easily and quickly, by just providing the geometry information of the structure. Currently, SIFBuilder is capable of generating a regular 3D framed-structure including the floor slab as shown in Figure 1(b).

The basic structural frame model available in SIF builder has also been extended to generate reduced models such as the X-Z grillage model (see Figure 1(c)) with slabs and skewed angles, beneficial in representing asymmetric geometry or bridge models. Similarly 2D frames and even single beams and columns can be generated.

**Material Libraries**

OpenSees has a rich source of material libraries for both steel and concrete. Moreover, its open source development makes it easy to include user defined materials. The thermal version of OpenSees consists of Eurocode and non-Eurocode based temperature dependent material models. A good choice of material models is essential in performing thermo-mechanical analysis.

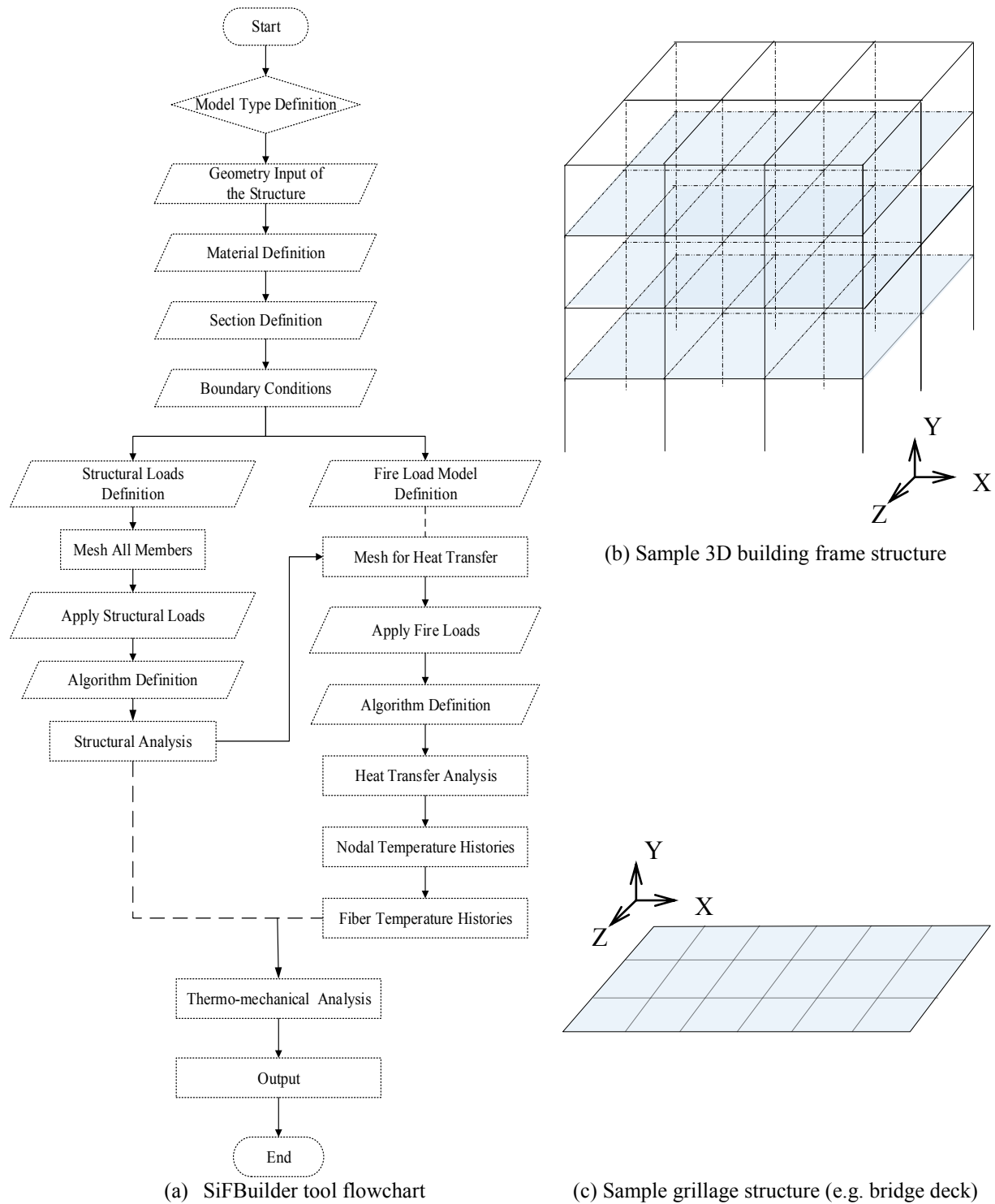


Figure 1. Features of the SiFBuilder simulation tool

### Structural Material

To perform structural analysis at high temperature, Eurocode [ENV 1992-1-2 (Eurocode 2 2004); ENV 1993-1-2 (Eurocode 3 2004)] stipulates uniaxial and multi-axial steel and concrete material models. Some of the material models that have been incorporated in OpenSees material libraries are shown in Table 1. Details of these materials can be found in the research group's web portal (OpenSees Edinburgh 2010).

Table 1. Structural Material Types

ElasticThermal	Steel01Thermal
SteelECThermal	Steel02Thermal
ConcreteECThermal	Concrete02Thermal
DruckerPrager3DThermal	DruckerPragerConcreteThermal

For instance, *SteelECThermal* contains different steel types based on Eurocode classification (Table 2).

Table 2. Steel Types of SteelECThermal Model

TypeTag	Steel Type
EC3	EN1993-1-2:2005 Structural Steel
EC2NH	EN1992-1-2:2004, Class N, Hot Rolled
EC2NC	EN1992-1-2:2004, Class N, Cold Worked
EC2X	EN1992-1-2:2004, Class X

### Heat Transfer Material

To perform heat transfer analysis, four types of material are developed: *NWConcreteEC2* for normal weight concrete, *LWConcreteEC4* for lightweight concrete, *CarbonSteelEC3*, and *SteelASCE*, which are based the Eurocode and Lie *et al.* (1992). A user defined material model called *SimpleMaterial* is also provided. All these heat transfer materials hold the information on heat transfer parameters such as thermal conductivity, specific heat, density and enthalpy (Jiang Y. 2013).

### Element Types

OpenSees offers a extensive element library. Due to its efficiency and high accuracy in thermo-mechanical analysis, *dispBeamColumn3dThermal* (displacement-based 3D beam/column element) and *ShellMITC4Thermal* are chosen as primary element types during the SIFBuilder model generation process. However, other options (shown in Table 3) may also for be considered for this purpose.

Table 3. Structural Element Types

dispBeamColumn2dThermal	dispBeamColumn3dThermal
forceBeamColumn2dThermal	ShellMITC4Thermal

For both 2D and 3D heat conduction analysis, the four-noded and eight-noded quadrilateral elements and the eight-noded brick element are used.

## FIRE LOADS IN SIFBUILDER

Fire loads form the salient feature of SIFBuilder tool. A wide variety of well-established fire models are integrated into SIFBuilder, to provide its users the freedom of using different types of fire scenarios (based upon the model types proposed in section 2.1) to assist their design calculations.

### ***Idealised Uniform Fires***

Based on the temperature-time curves presented in Eurocode 1 (EN1991 2002), post-flashover fires such as standard fire (ISO-834), hydro-carbon fire, and empirical parametric fire are all implemented in SIFBuilder. Although these fire models are relatively simple, they are still widely used for both research and design purposes in fire safety engineering. A user defined external fire curve is also included for providing more flexibility. These idealised uniform fire models are all assumed to have the same temperature distribution in the entire compartment at a specific time according to Eurocode.

### ***Idealised-non-uniform-fires***

Compared to uniform fire models, more advanced non-uniform fire models are provided in SIFBuilder. These non-uniform fire models are capable of producing both spatially and temporally non-uniform temperatures in the compartment.

### ***Localised Fire***

SIFBuilder also includes two pre-flashover and localised fire models: Eurocode 1 localised fire model (Hasemi *et al.* 1996) and SFPE localised fire model (Alpert 2002). These two localised fire models are regarded to be very efficient for carrying out simulations such as vehicles burning in an open plan car park building.

### ***Travelling Fire***

Current travelling fire model in Stern-Gottfried and Rein (2012a and 2012b) can be employed in SIFBuilder to simulate the travelling fire and relevant work can be found in (Jiang Y. 2013).

## **HEAT TRANSFER IN SIFBUILDER**

### ***Implementation of Idealised Fires in SiFBuilder***

Fire load calculations are succeeded by the heat transfer analysis. SIFBuilder adopts a smart member identification algorithm, where the heat transfer analysis activates on pre-specified members based on their exposure conditions. Figure 2(a) depicts schematically a localised heat flux distribution adopted in a compartment or building sub-frame.

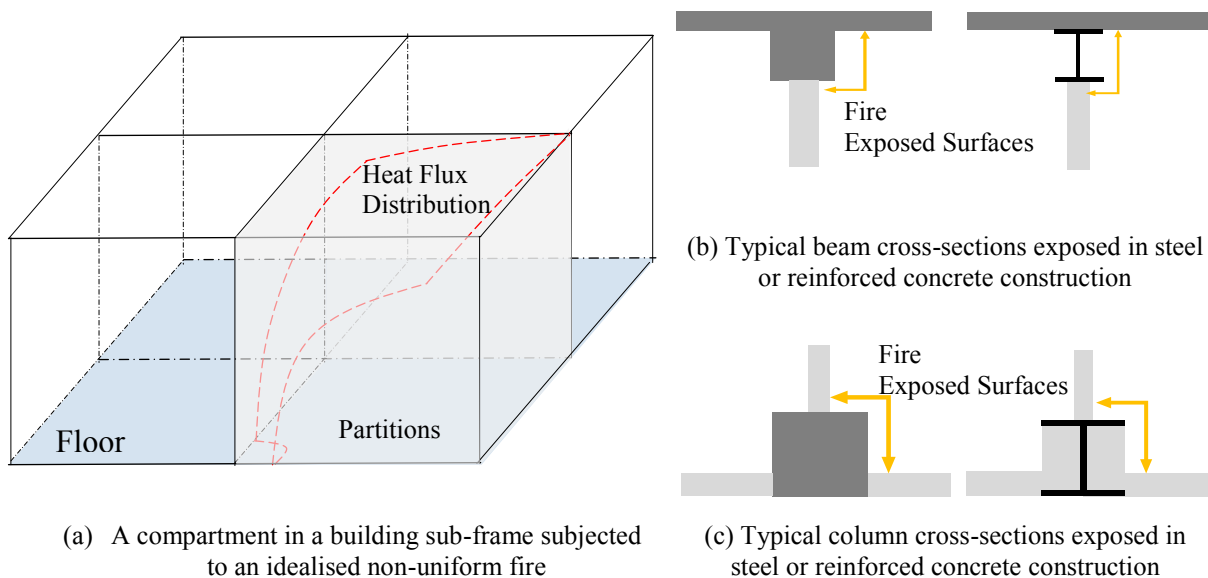


Figure 2. An idealised non-uniform fire in a building sub-frame and associated exposed structural surfaces

Figures 2(b) and (c) shows the exposure conditions in a typical beam and column respectively. These exposure conditions are used by SIFBuilder to obtain time-temperature histories within each structural component. The

key capability of SIFBuilder is enabling consideration of non-uniform heat flux, which is a far more realistic situation for large compartments, where performance-based engineering is usually required.

### **EFFICIENT HEAT TRANSFER**

SIFBuilder is designed for simulating whole-frame structural behaviour in realistic fires. To achieve this, an efficient heat transfer strategy is employed for saving computational resources and offering additional flexibility to the end users.

Repeated tests on the developed module has confirmed that for idealised uniform fires in a compartment, 1D heat transfer for the slab and 2D heat transfer for beam and column cross-sections holds good and hence, this strategy is adopted in SIFBuilder. Since heat flux is spatially invariant over structural component surfaces under idealised uniform fire scenarios this can be regarded as a reasonable approach without significant dispute.

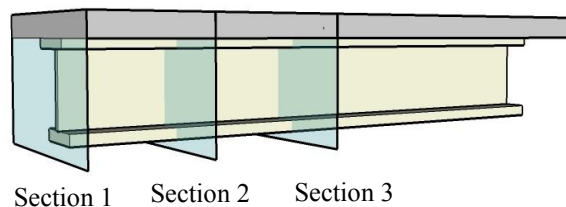


Figure 3. Efficient Heat Transfer for Beam

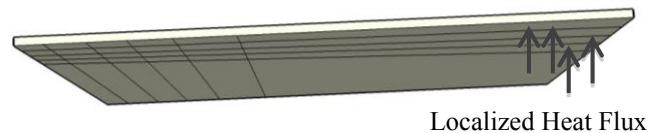


Figure 4. Efficient Heat Transfer for Slab

For compartments under idealised non-uniform fires the incident heat flux on structural members varies with location. The same approach as above here is more questionable, however numerical tests carried out by the authors show that even in this case this approach is highly feasible. Localised 1D heat transfer analysis for the slab and a series of 2D heat transfer for beam and column cross-sections is implemented and temperature-time histories between sections are obtained by interpolation. Schematic representations of this strategy are illustrated in Figures 3 and 4.

### **DATA OUTPUT & TRANSMISSION**

#### ***Data Output***

As discussed above, both the fire loading calculation and the heat transfer analysis are implemented in a realistic, accurate, and efficient way. Moreover, as this convenient computational tool is not a black box, it is easy for users to customise their models and access the intermediate and final analysis information. The temperature history from the heat transfer module can be easily accessed by defining proper Tcl ‘recorder’ commands in the model script. Many other simple tasks such as monitoring the analysis by creating break points, obtaining the desirable node output by specifying parameters, simple debugging of the input scripts are made possible by adapting simple tips and tricks offered by Tcl.

#### ***Data Transmission***

The most prominent feature of SIFBuilder is that it can map the heat transfer temperature results to the structural elements automatically during the analysis. The fire model provides the heat flux exposure evolution in time for all relevant structural surfaces; this information is automatically passed on to the heat transfer module to be used as the boundary condition for the heat transfer calculations, performed efficiently using reduced dimensional

heat transfer at representative cross-sections; this develops a full 3D history of temperature evolution in the structural members for the full fire duration (and through to cooling if desired); finally these temperatures are passed on to the thermo-mechanical response simulation module. The temperature histories are processed to locate and interpolate nine temperature points across the depth of the section, and then further transformed to be applied to the fibers in the structural cross-sections of the exposed structural elements.

## APPLICATION EXAMPLES

An idealised frame building is modelled to demonstrate the usage of SIFBuilder. The building is assumed to be comprised of two bays along each direction corresponding to the global x and z axes, respectively, as illustrated in Figure 5. Storey height is set as 5m for the ground floor, above which a 4m high storey is located.

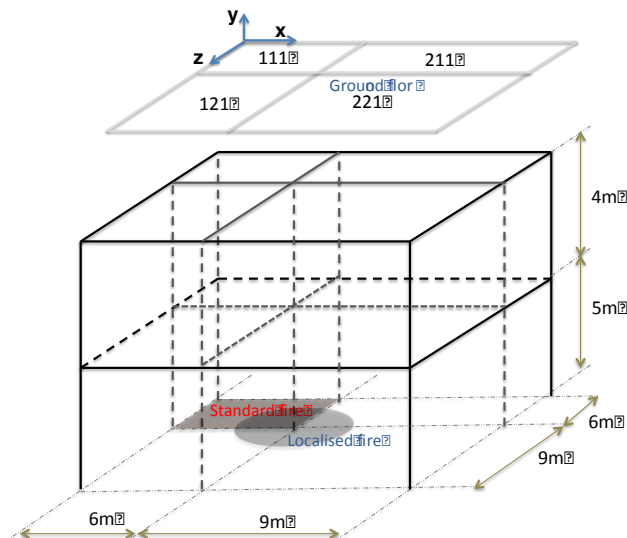


Figure 5. Idealised building configuration

Tcl script for constructing the building model begins with lines written in a simple fashion:

```
SIFXBay 6 9;
SIFZBay 6 9;
SIFStorey 5 4;
```

A SIFModel is created based on the above information and governs the building configuration, using which the finite element (FE) models for heat transfer and thermo-mechanical analyses are built up. The FE model requires the section definition in conjunction with a material library. Typical Tcl scripts responsible for material and section definitions are written as follows:

```
AddMaterial steel 1 -type EC3 3e8 2e11;
AddSection ISection 1 1 0.203 0.102 0.0054 0.009;
AssignSection beams 1;
```

The first line of the code above defines a Eurocode 3 carbon steel material, which is associated with an I-section (UB 203x102x23). This section is later assigned to the beams, whereas for the columns another I section is defined as universal column section (UC 203x203x46) and assigned. Concrete slab of 100 mm thickness has also been included in this model. A uniformly distributed load ( $2\text{kN/m}^2$ ) is firstly applied to the slabs, which is then followed by the fire action. The fire may be a conventionally uniform fire and constrained in one compartment, or it may be defined as spatially localised such as the Eurocode 1 localised fire model. For the first scenario, a uniform fire following the standard time-temperature curve is located in compartment 111 (as Figure 11 shows). The script written in Tcl is:

```
Addfire -compartment 111 -type Standard;
```

The second case for localised fire action is given as a fire surrounding the central column and defined as Eurocode 1 localised fire, with the rate of heat release as 4MW, and nominal diameter as 1.0m. The T<sub>cl</sub> definition is as follows:

*Addfire –compartment 111 121 211 221 –type EC1Local –origin 6 0 6 –HRR 4e6 –Dia 1;*

Both of the fires last for half an hour, leading to the totally different responses for this framed structure. Significant deflection of slab can be observed from the compartment where the standard fire was imposed (see Figure 6a). For the localised fire, the slab deflection is not as great but localised to the centre due to the support from the centre column. While the column retains nearly full strength (at temperatures below 400 Celcius) it is forced to bear greater floor load due to its expansion while it loses strength at higher temperatures and may collapse, leading to a progressive collapse of the whole structure (as shown in Figure 6b).

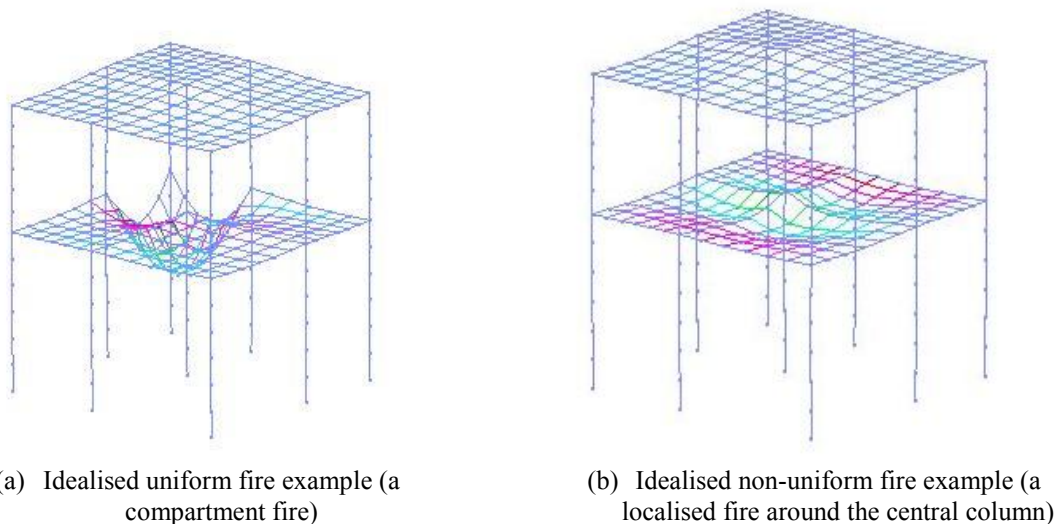


Figure 6: Deflection profiles at the end of the fire for the two example problems

## CONCLUSIONS

A comprehensive structures-in-fire analysis tool is presented that can potentially truly revolutionise performance-based structural fire engineering. However at this stage this tool is primarily meant for researchers to explore the structural response to previously unfeasible (in terms of complexity of modelling and user effort) but realistic fire scenarios. For example the large compartment fires in tall buildings, vehicle fires under bridges, large warehouse type fires etc. Furthermore the tool is entirely free to be used and improved by research users and developers. All the source codes, examples, user and developer manuals on project SIFBuilder may be found at the University of Edinburgh - OpenSees wiki site (OpenSees Edinburgh 2010), so any interested researcher or engineer can review, download, and use it for free.

## ACKNOWLEDGMENTS

The authors acknowledge the support of UKEIRI and Royal Academy of Engineering for supporting Praveen Kamath and the China Scholarship Council and the University of Edinburgh for supporting Liming Jiang.

## REFERENCES

- Alpert, R. L. (2002). "Ceiling jet flows", *SFPE handbook of fire protection engineering*, vol. 3, pp. 2-18.
- EN 1991 1-2:2002. Eurocode 1: Actions on structures—Part 1-2: General actions—Actions on structures exposed to fire," *British Standards*.
- Grosshandler, W. L. (2002). *Fire resistance determination and performance prediction research needs workshop: proceedings*: US Department of Commerce, Technology Administration, National Institute of Standards and Technology.
- Hasemi, Y., Yokobashi, Y., Wakamatsu, T. and Pchelintsev, A. (1996)., "Modelling of Heating Mechanism and



- Thermal Response of Structural Components Exposed to Localized Fires: A new application of diffusion flame modelling to fire safety engineering," in *Thirteenth meeting of the UJNR panel on fire research and safety*. Jiang, J. (2013). "Nonlinear thermomechanical analysis of structures using OpenSees", PhD thesis, University of Edinburgh.
- Jiang, J. (2013). "Nonlinear thermomechanical analysis of structures using OpenSees", PhD thesis, University of Edinburgh.
- Jiang, L., Jiang, Y., Jiang, J., Usmani, A. and Chen, S. (2014). "An OpenSees-based integrated tool for modelling structures in realistic design fires", presented at the 8<sup>th</sup> International Conference in Structures in Fire Conference, Shanghai, China.
- Jiang, Y. Q. (2013). "Development and application of a thermal analysis framework in OpenSees for structures in fire", PhD thesis, University of Edinburgh.
- Lie, T. T. (1992). "Structural fire protection", American Society for Civil Engineers, Reston, VA.
- Mckenna, F. T. (1997). "Object-oriented finite element programming: frameworks for analysis, algorithms and parallel computing", PhD thesis, University of California, Berkeley.
- OpenSees Edinburgh. (2010). *OpenSees Edinburgh*. Available at <https://www.wiki.ed.ac.uk/display/opensees/UoE+OpenSees>
- Stern-Gottfried, J. and Rein, G. (2012a). "Travelling fires for structural design–Part I: Literature review," *Fire Safety Journal*, vol. 54, pp. 74-85.
- Stern-Gottfried, J. and Rein, G. (2012b). "Travelling fires for structural design–Part II: Literature review," *Fire Safety Journal*, vol. 54, pp. 96-112.
- Usmani, A., Zhang, J., Jiang, J., Jiang, Y. and May, I. (2012). "Using OpenSees for structures in fire", *Journal of Structural Fire Engineering*, vol. 3, pp. 57-70, 2012
- Zhang, J. (2014). "Developing OpenSees software framework for modelling structures in fire", PhD thesis, University of Edinburgh.