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Implementation of a New Design Travelling Fire Model for Global Structural Analysis

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ABSTRACT

This paper presents a new conceptual framework for travelling fires in large compartments with fire resistant islands in order to ensure that the structure so designed is able to resist more realistic fire exposures expected in such compartments, commonly found in modern office buildings. In addition, this paper also presents the implementation of this new travelling fire model in the SIFBuilder framework [1], which is an OpenSees based integrated computational tool for performing automated thermo-mechanical analyses for large structures subjected to a broad range of idealised design fires.

INTRODUCTION

Many studies of large compartments in fire carried out over the past two decades show that fires in such compartments have a great deal of non-uniformity, unlike the homogeneous compartment temperature assumption commonly made in the current fire safety engineering practice. In general, large compartment fires burn locally and tend to move across entire floor plates over a period of time. This kind of fire scenario is beginning to be idealized as travelling fires. Two representations of travelling fires can be found in literature, hereinafter referred to as: Clifton's model [2]; and Rein's model [3]. However, both models neglect important aspects of fire dynamics. For instance the accumulation of a hot smoke layer is ignored in both models, while in Clifton's model, all elements in one 'firecell' (one compartment) share the same time fire exposure history. In Rein's model, Alpert's correlation is adopted to calculate far field temperature and a uniform temperature ($800^oC-1200^oC$) is assumed for the near field, which seems overly prescriptive. Furthermore, due to the reasons of computational complexity, neither of the travelling fire models have been coupled to the global structural response.

In 2009, OpenSees [4] 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

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‘Thermal’ version of OpenSees [5]. Temperature dependent formulations have been incorporated for basic element types, primarily beam-column elements and shell elements to account for the thermal effects [6]. Material library of the original framework has also been updated by adding new temperature dependent material models for steel and concrete based on Eurocodes [7].

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 [8], which aims to perform automated thermo-mechanical analyses for large structures under a wide range of idealised fires, some of which mimic realistic fire exposures (such as localized and so-called travelling fires). The special features of SIFBuilder includes: large model generation with minimal input; rapid heat transfer analysis for a range of idealized-uniform and idealized-nonuniform fires; automatic coupling of the heat transfer output with the structural model to perform thermo-mechanical analyses.

This paper introduces a new travelling fire model, which mobilises Hasemi’s localized fire model [9] and hence create a new kind of travelling fire, and combines it with a simple smoke layer calculation for the areas of the compartment not involved in burning. The heat fluxes received by each structural member in a large compartment using this approach should provide greater fidelity with realistic conditions than any other model currently proposed. Furthermore, this new travelling fire model is programmed into SIFBuilder based on previous work [1] and [8], and would enable rapid testing of multiple travelling fire scenarios. Therefore we believe that this approach also offers a great deal of flexibility for designing structural fire resistance in large compartments and, if properly used, should ensure that worse case scenarios are discovered.

NEW TRAVELLING FIRE MODEL

The proposed design fire is idealized as a localized fire plume with characteristics that include: a predetermined plume propagation trajectory along which it travels; variable fuel load distribution along the trajectory; and consideration of smoke accumulation in the ceiling cavity.

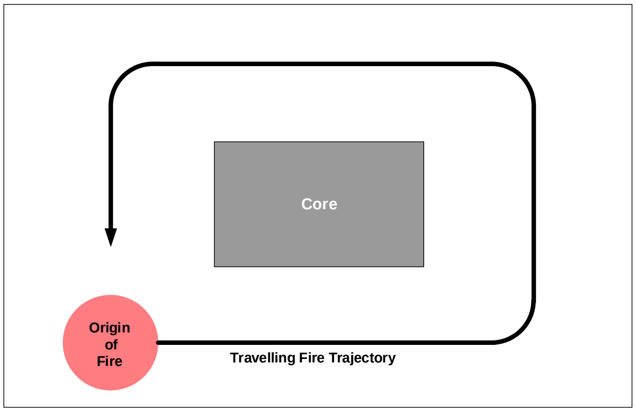

Figure1. New travelling fire model on open plan office floor

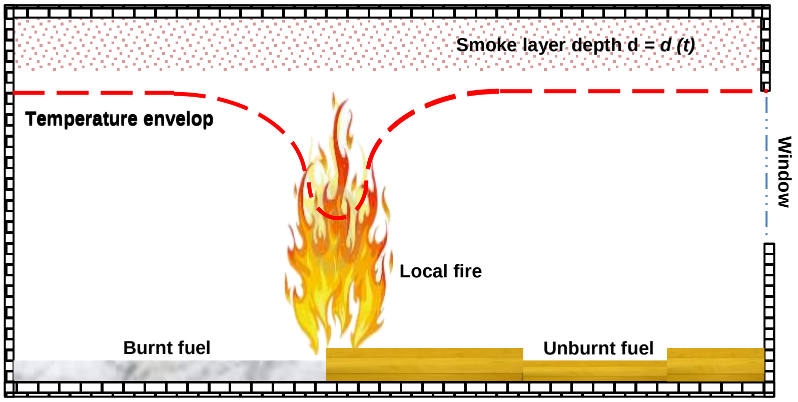

Figure 2. Elevation view - new travelling fire model.

It is proposed here to combine Hasemi's model for determining the temperature evolution in structural members close to the plume location, with a simple smoke layer calculation for predicting the temperatures of structural members away from the burning region. Figures 1 and 2 schematically illustrate the proposed scheme.

Near field: Hasemi localized fire model

For quantifying the local effect of the travelling fire on adjacent structural members, Hasemi's localized fire model is utilized here. When the fire plume is impinging the ceiling, the net heat flux $\dot{h}$ (W/m^2) is given in EC1 as,

$$\dot{h} = 100000 \qquad \text{if } y \leq 0.30 \tag{1a}$$

$$\dot{h} = 136300 - 121000y \qquad \text{if } 0.30 < y \leq 1.0 \tag{1b}$$

$$\dot{h} = 15000y^{-3.7} \qquad \text{if } y \geq 1.0 \tag{1c}$$

The parameter y is obtained by calculating the following equation:

$$y = \frac{r + H + z'}{L_h + H + z'} \tag{2}$$

Where r (m) is the horizontal distance between the vertical axis of the fire and the point along the ceiling where the heat flux is calculated, H (m) is the distance between the fire source and the ceiling, z' (m) is the vertical distance between the virtual fire origin and the fire source, L_h (m) is the horizontal flame length.

Far field: simple smoke layer calculation

The combination of energy conservation and smoke generation is brought into the travelling fire model in an elementary way, considering different fuel distributions along the trajectory. The depth of the smoke layer is assumed to be time dependent and uniform over the whole ceiling. The rate of air entrainment is determined using a number of different models. Meanwhile, smoke will be generated as more and more local lumped fuel is consumed. This feature would reproduce preheating and post heating effects for the structural analysis, which is the hallmark of travelling fires.

Combination of the two models

Since Hasemi's equation is applicable to localized fires in an unconfined space and smoke accumulation is not considered in his model, this may lead to the far field predicted temperature based on Hasemi's localized fire calculation in a confined space lower than the actual temperature. Therefore, it is proposed here to combine Hasemi's model with a hot smoke layer calculation. In other words, the radiant and convective heat fluxes to structural surface can be calculated based on the summation of heat flux from Hasemi's localized fire, and heat flux from the hot layer of the smoke (see Figures 3).

Fire trajectory

As the final objective of this new travelling fire model is for applications in structural analysis, the travelling fire trajectory is assumed to be the worst case of the structural response: under the mid-span of the main beams (see Figures 1).

Ignition Point

The ignition point of the travelling fire could be anywhere in the compartment. However, a fully developed localized fire will be the initial state of this travelling fire model, at which point it becomes mobile. From the structural design point of view, the development phase of the localized fire is not considered important, just as the pre-flashover stage is ignored in compartment fires

Regulatory minimum fuel depth (RMFD)

The concept of a regulatory minimum fuel depth (RMFD) is introduced corresponding to a reference travelling fire velocity in the model. This RMFD is a layer of fuel uniformly distributed over the entire floor plate, and contributes to the total heat fluxes calculation.

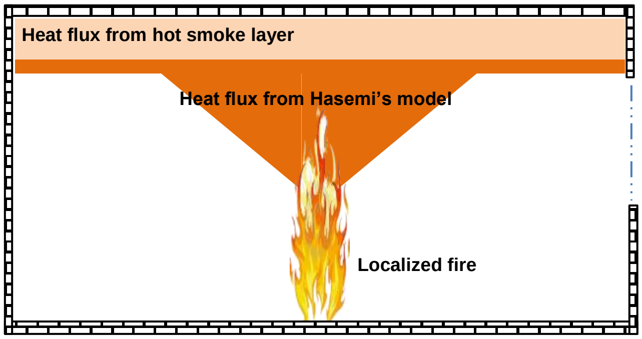

Figure 3. Heat fluxes superposition from two models.

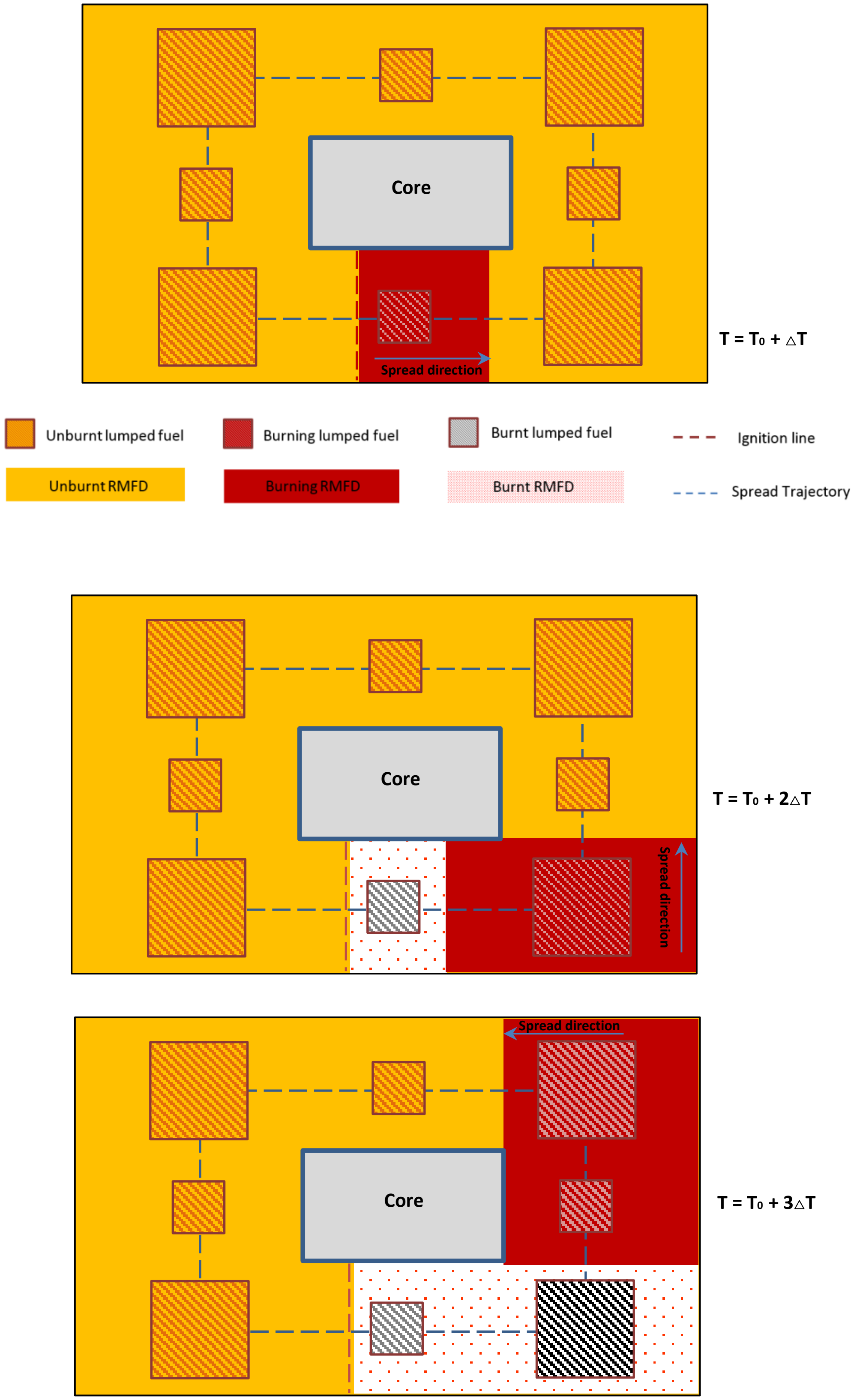

Figure4. Plan view - RMFD concept in 1D Travelling fire with one trajectory.

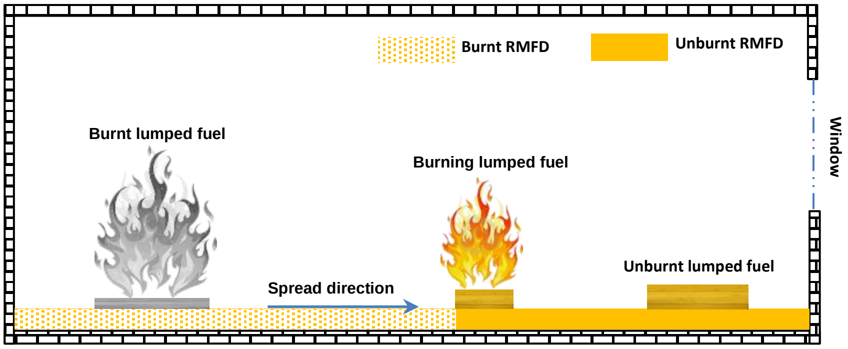

Figure 5. Elevation view - RMFD concept in 1D Travelling fire with one trajectory.

Moreover, an agreed quantity of additional lumped fuel is placed next to the most critical and/or most vulnerable parts of the structure identified in consultation with the structural engineer according to performance-based design principles. Figure 4 & 5 illustrate how the fire travels based on the RMFD concept.

Other key assumptions

The proposed design fire is fuel controlled based on the assumption that sufficient air is available at the beginning and subsequently the glazing adjacent to the fire plume breaks. All fuel is assumed to be consumed over the design fire duration with: non-uniform burning rates of the travelling fire along the trajectory; changing fuel load density; and variable heat release rates.

A flashover scenario arises naturally in this model and the fire transitions from a localized travelling fire to a whole compartment fire when the temperature of the hot smoke layer reaches 500^oC [10].

IMPLEMENTATION IN SIFBUILDER

This new travelling fire model is programmed into SIFBuilder based on previous work [1] and [8], which is mainly about the development of OpenSees for integrating the heat transfer and thermo-mechanical analysis for modelling localized fire in structures. The implementation of this new travelling fire model in SIFBuilder follows the same workflow as the localized fire model. After inputting basic structural information for generating the structural model, the user defines the structural loading and thereafter the fire loading information.

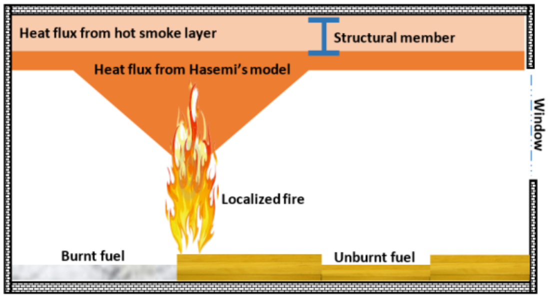

Figure 6. Heat flux at time t_0.

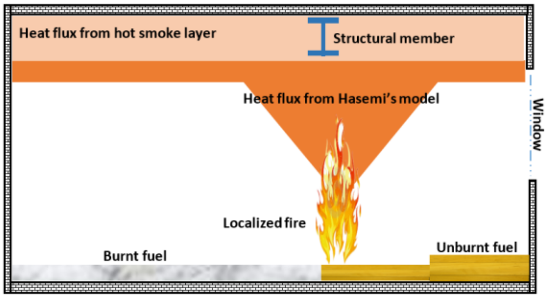

Figure 7. Heat flux at time $t_0 + \Delta t$.

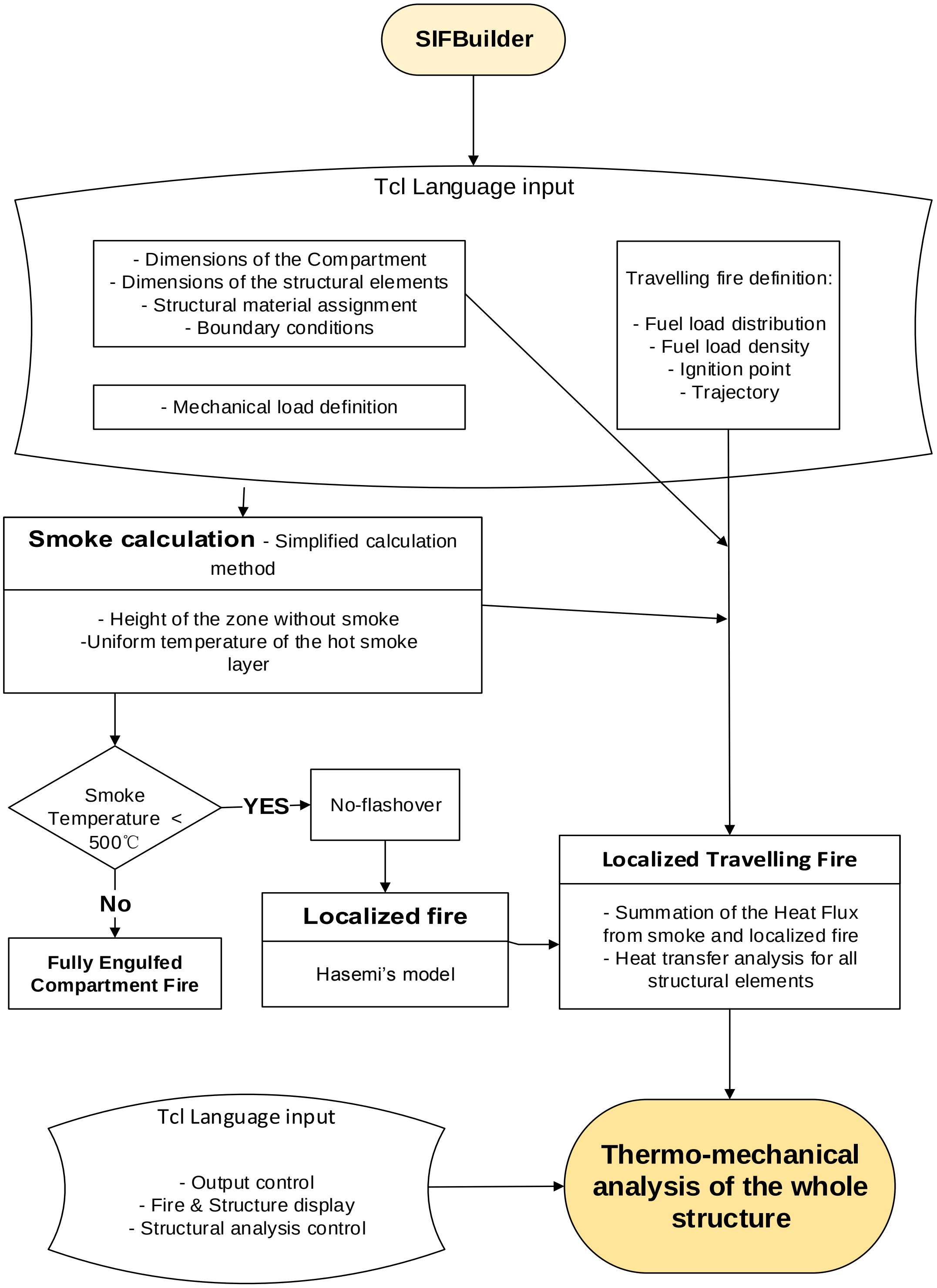

Figure 8. Flow chart of implementing new travelling fire model in SIFBuilder.

The travelling fire module interacts with the heat transfer module through their respective interfaces at each time step in order to determine the transient fire imposed boundary conditions adjacent to the structural surfaces.

Unlike the localized fire model in SIFBuilder, both spatially and temporally non-uniform heat fluxes for different structural elements produced from the summation of the heat flux from the hot smoke layer and Hasemi's model, are updated at each time step according to the travelling fire location in the compartment (see Figures 6 and 7, only one structural element showed for clarity).

Subsequently, the heat transfer analysis module launches and the nodal temperature histories are automatically mapped to the fibers of the structural mesh for each structural member. Following the heat transfer analysis the thermo-mechanical analysis module is invoked to determine the structural response history for the whole frame including all heating phases for each structural member. This may include the effects of preheating, direct heating, post-heating and cooling.

Ultimately, the new tool will provide a flexible approach for examining the impact of fire on structural behavior under realistic design fire scenarios, at greatly reduced cost in the analysis time and user effort than currently possible. Figure 8 shows how the new travelling fire model is implemented in SIFBuilder.

CONCLUSIONS

Although it is still early in the life of this work to make definite conclusions, a good start has been made in developing a conceptual idea of the travelling fire model, a possible programming scheme, and also a set of case studies for the framework verification and validation (which is not illustrated in this paper due to the paper length limitation).

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