A COMPARATIVE ANALYSIS AND EXPERIMENTAL VALIDATION OF MODELING STRATEGIES FOR STRUCTURES SUBJECT TO LOCALIZED FIRES

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ABSTRACT

Evaluation of temperature distributions in structures subjected to localized fires is an important step in the structural fire assessment, which cannot be completed using traditional time-temperature curve boundary conditions from compartment fire models. This paper discusses several modeling approaches including three simple models (Heskestad, Hasemi, and LOCAFI), and two interfacing methods between computational fluid dynamics (CFD) and finite element models. Three case studies are presented on steel structural elements under localized fires and the modeling approaches are benchmarked against test measurements. Results show that interfacing the CFD models with finite element analysis through the adiabatic surface temperatures is an accurate method for the investigated cases. The use of an automatic transfer file containing the gas temperature and radiant intensities in a readable format by finite element software is an efficient alternative when the member is far away from the fire and does not significantly influence the fire development. The simple models can conservatively be adopted within their intended range of validity. Finally, a decision chart is proposed to select the suitable modeling strategy for evaluating the temperatures in structures subjected to localized fires as a function of the problem configuration.

Keywords: localized fire; numerical modeling; FDS; steel structures; structural fire design

1 INTRODUCTION

Structural fire design has traditionally focused on the resistance to compartment fire, which assumes uniform temperature in the compartment due to a fully developed (i.e., post-flashover) fire. However, when a full compartment fire cannot develop, or in the early stage of a fire, such as open car park fires, localized fire models should be used. Among them, simple models, notably the Heskestad model and Hasemi model in Eurocode EN1991-1–2 [1], and the LOCAFI model described by Tondini et al. [2] are computationally efficient, but they have limited fields of application as a result of the simplifying assumptions. To simulate the fire development more accurately, advanced modeling approaches involving computational fluid dynamics (CFD), especially the Fire Dynamics Simulator (FDS) software developed by the National Institute of Standards and Technology (NIST) [3], can be used. To transfer the thermal boundary conditions from CFD models to finite element analysis, the concept of adiabatic surface temperature (AST) has been proposed [4]. Another method, exporting gas temperature and radiant intensities in the domain of interest from the FDS models in a readable format by finite element software, has also been recently developed [5].

Performance-based fire design requires accurate prediction of transient temperature distributions in structural members under fire exposure [6]. The abovementioned simple fire models and advanced modeling approaches provide thermal boundary conditions to evaluate member temperature under localized

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fires. However, there lacks validation studies that compare the models and validate them against experimental data. Such comparative study is needed to investigate the accuracy and suitable field of application of each model. To fill this gap, this study focuses on the available numerical modeling approaches to evaluate temperatures in structures subjected to localized fires with the objective to identify the range of applicability and performance of each approach. First, a summary is made of three simple models and two advanced approaches interfacing the FDS models with finite element analysis. Then, three experiments on structures subjected to localized fires are simulated with the simple models and FDS-based approaches. The predicted member temperatures are compared with the test data. A detailed discussion on the automatic method interfacing FDS with FEM is provided. By assessing the validity and accuracy of each model, a modeling strategy for structures subjected to localized fires is proposed, which provides recommendation regarding the selection of the different models as a function of the problem configuration.

2 LOCALIZED FIRE MODELS

2.1 CFD models

The Fire Dynamics Simulator (FDS), developed by NIST, is a Large Eddy Simulation (LES) based CFD code for fire simulation. It solves the Navier-Stokes equations numerically for low-speed thermally driven fluid flow. Thermal radiation is modeled through the radiation transport equation for gray gas, which is solved by the Finite Volume Method (FVM). To transfer the thermal information from FDS models to finite element analysis, two methods through the use of adiabatic surface temperature (AST) and a dedicated FDS-FEM interface are generally adopted.

(1) FDS-FEM AST

The adiabatic surface temperature (AST), firstly proposed by Wickstrom [4], represents the surface temperature of a perfectly insulated surface exposed to the same conditions as the real surface. It contains both the radiative and convective heat flux information through a single value, calculated by:

$$\dot{q}_{net} = \varepsilon_{AST}\left(\dot{q}_{inc,rad} - \sigma(T_{AST} + 273)^4\right) + h_{c,AST}\left(T_g - T_{AST}\right) = 0 \quad (1)$$

where ε_{AST} and $h_{c,AST}$ are the surface emissivity and convection coefficient, $\dot{q}_{inc,rad}$ is the incident radiative heat flux, T_g is the gas temperature near the surface. With T_{AST} calculated, the net heat flux to a real surface with the same emissivity and convection coefficient can be calculated as:

$$\dot{q}_{net} = \varepsilon_S\, \sigma\, \left((T_{AST} + 273)^4 - (T_s + 273)^4\right) + h_c(T_{AST} - T_s) \quad (2)$$

where T_s is the member surface temperature. By placing AST thermocouples along the structural member in FDS, the thermal gradient can be captured.

(2) FDS-FEM interface

Another method to transfer the thermal boundary conditions, referred as FDS-FEM interface method, has been proposed to facilitate the computation of large and complex models (which would require a very large number of AST thermocouples). The FDS-FEM interface method allows exporting the gas temperature and radiant intensities at various directions in the domain of interest from FDS in a readable format by finite element software. The method has been incorporated in the FEM software SAFIR [7], but it can used with other software as well. The incident radiative heat flux $\dot{q}_{inc,rad}$ at the surface of structural member is computed in FEM software by integrating the radiant intensities. A trilinear interpolation is performed between the points of the grid in FDS model and position in the compartment where the information is needed. Once the incident heat flux is obtained, the net heat flux can be calculated as:

$$\dot{q}_{net} = \varepsilon_S\left(\dot{q}_{inc,rad} - \sigma(T_s + 273)^4\right) + h_c\left(T_g - T_s\right) \quad (3)$$

This method allows an automatic transfer of thermal boundary information from FDS simulation to FEM analysis with very fine discretization. It is also efficient in capturing the influence of the shadow effect and view factors without the need to model the structure in the FDS model.

2.2 Simple models

As CFD simulations are time-consuming, simple models have been proposed by researchers and adopted in standards and codes to capture the localized fire exposure on structures. Among them, the Heskestad model and Hasemi model in Eurocode EN1991-1–2 [1], and the LOCAFI model described by Tondini et al. [2] are the most used. These models are valid within the limits in terms of fire diameter $D \leq 10\ m$ and heat release rate $HRR \leq 50\ MW$.

(1) Heskestad model

The Hesketad model [8] is applicable to predict the temperature along the vertical centerline in the fire plume when the flame is not impacting the ceiling:

$$T_f(z) = \min\left(900\ °\mathrm{C};\ 20 + 0.25\ Q_c^{\frac{2}{3}}(z - z_0)^{-\frac{5}{3}}\right) \tag{4}$$

where z_0 is the virtual fire origin, Q_c is the convective part of heat release rate.

(2) Hasemi model

When the flame is impinging the ceiling, the Hasemi model [9] can be used to calculate the heat flux received by a unit surface area of the member at the ceiling level:

$$\dot{q} = \begin{cases} 100000 & if\ y \leq 0.3 \\ 136300 - 121000\ y & if\ 0.3 < y < 1.0 \\ 15000\ y^{-3.7} & if\ y \geq 1.0 \end{cases} \tag{5}$$

$$y = \frac{d + H + z'}{L_h + H + z'} \tag{6}$$

where y is a non-dimensional ratio, d is the horizontal distance between the centerline of the fire plume and the section of interest along the ceiling where the flux is calculated, H is the ceiling height, and z' is the vertical position of the virtual heat source, L_h is the horizontal flame length.

(3) LOCAFI model

The LOCAFI model [2] evaluates the radiative heat flux from a localized fire to a member that is not engulfed in the flame. Since the member is outside the fire area, the temperature of the surrounding gas is close to ambient, and the convective heat flux can be neglected. This model assumes that the flame is of virtual solid shape, either conical or cylindrical. Radiative heat fluxes are emitted from the surface of the solid flame which is discretized into different vertical cylinders. It assumes that each cylinder is of uniform temperature taken as that of the centerline, calculated by Eq. (4). Once the solid flame model is defined, the incident heat flux to the structural surface can be calculated considering the view factors:

$$\dot{q}_{inc,flame\ to\ B} = \sum_{i=1}^{n} \Phi_{i\ to\ B}\ \varepsilon_i\ \sigma\ (T_i + 273)^4 \tag{7}$$

where $\Phi_{i\ to\ B}$ is the configuration factor from radiating surface i to surface B, T_i is the temperature of fire surface i, calculated by Eq. (4), n is the number of discretized cylinders.

3 CASE STUDY 1: STEEL BEAM UNDER LOCALIZED FIRE

3.1 Experiment description

The first validation study is based on the test by NIST [10], in which a simply supported W16 ×26 beam was heated by a 1 m square gas burner, as shown in Figure 1. The beam was 6.17 m long and placed 1.1 m above the gas burner. The gas burner was 0.5 m above the floor. In the transient-state Test 8, the beam was firstly loaded to 67% of its ambient temperature capacity, and then heated with a HRR following a t-squared function while the load was maintained constant. The heating continued until failure of the beam.

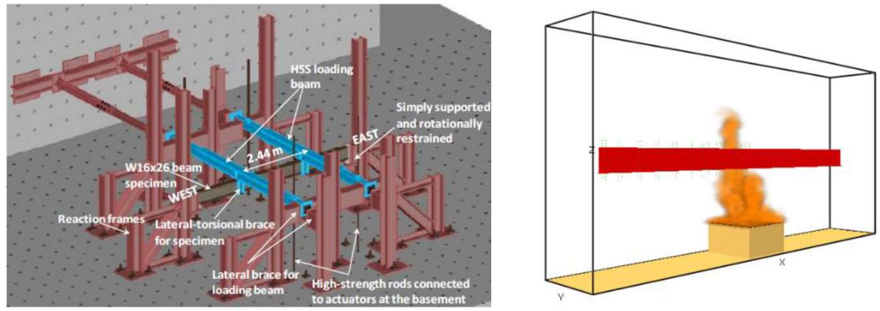


Figure 1 Experimental setup and FDS modeling of steel beam Test 8.

3.2 Heskestad/LOCAFI model

The steel beam temperature at the center section was first evaluated by simple models. As the HRR followed a t-squared function, the fire grew during the test. During the first 392s, the flame length was smaller than the distance between the burner and the beam, meaning the beam was outside the fire. During that time, the LOCAFI model was used. After 392s, the center section of the beam became engulfed in the fire. The simple model was shifted to Heskestad model. The member was surrounded by hot gas, the temperature of which was calculated by Eq. (4). Both incident radiative heat flux and convective heat flux were considered.

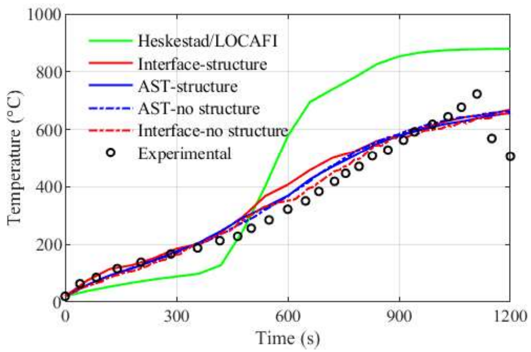
Temperatures are plotted in Figure 2. The LOCAFI model (over the first 392s) yielded lower predictions than the test. The underestimation of steel temperature during the initial phase may be due to the fact that LOCAFI neglects the convective heat flux. As the tested beam is right above the gas burner and is heated by the hot gas rising by buoyancy, the convective heat flux is not negligible. The flame temperature reached the limiting temperature 900 °C at 618 s beyond which a more gradual temperature increasing trend of member temperature to 900 °C was observed. Compared with the test data, the Heskestad model gives conservative predictions of the member temperature, which is consistent with the observation by others that Heskestad model overestimates the plume temperature along the centerline [11].

3.3 FDS-FEM model

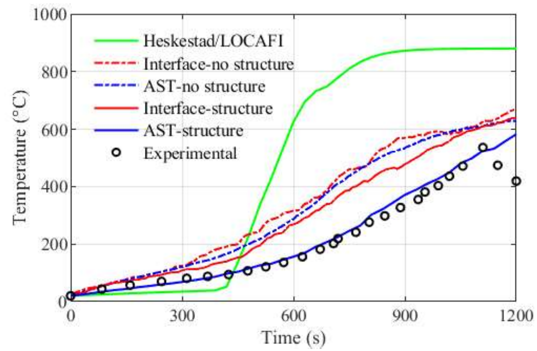
The steel beam test was modeled in FDS with a computational domain of $7.2 \times 1.2 \times 3.6\ m\ (X \times Y \times Z)$. The mesh size was 0.04 m in Y and Z direction, and 0.12 m in X direction. The steel beam was modeled with zero thickness and thermal properties specified in EC3 [12]. The beam convection coefficient was taken as 9 $W/m^2\,K$ for localized fires [13], and the emissivity as 0.9 [10]. 14 DEVICEs were placed along the length of the flange and web of the cross section to record AST data, which were then applied to FE thermal analysis in SAFIR. For the interface method, gas temperature and radiant intensities were written in a readable transfer file which was then applied as the thermal boundaries in SAFIR.

The member temperatures predicted by FDS-FEM AST ('AST-structure) and interface method ('Interface-structure') at the center section are plotted in Figure 2. The steel temperatures from the FDS-FEM AST method agree well with the test measurements, while the interface method yields higher prediction at the mid web and upper flange. This may be because the gas temperature and radiant intensities are output at the center of the grid in FDS, while the structure is modeled on nodal points. Thus, a 3D Cartesian interpolation in space is needed to obtain the information at the beam surface nodes in the thermal analysis, which leads to erroneous results if the values at the FDS nodes used for interpolation significantly differ.

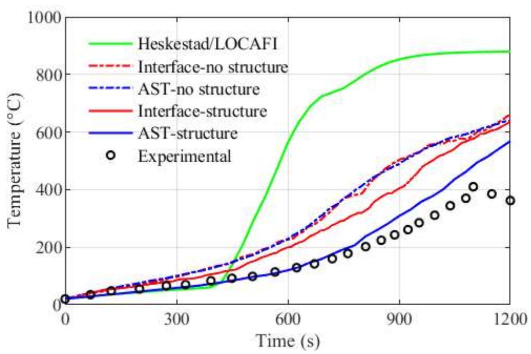
The FDS simulation was repeated using the same computational domain but omitting the beam in the model. Thermal boundary conditions were once again obtained using both AST and Interface at the location where the beam would be present, then applied to the surfaces of the beam in the FE model. The member temperatures predicted by these cases are referred as 'AST-no structure' and 'Interface-no structure' in Figure 2. The two methods yield very similar results when the structure is not modeled in FDS. This verifies the correct implementation of the two approaches. However, the overestimation of the member temperature at the web and upper flange is observed with these two cases. This is because they incorrectly neglect the influence of structure member on the fire development, which in this test is significant as the beam deflects the flames and hot gas.



(1) Lower flange



(2) Mid web



(3) Upper flange

Figure 2 Temperatures in the center section of the steel beam from case study 1.

4 CASE STUDY 2: STEEL COLUMN ADJACENT TO A LOCALIZED FIRE

4.1 Experiment description

A $0.1 \times 0.1 \times 1.6\ m$, $3.2\ mm$ thick steel column was heated by a $0.3\ m$ propane burner right next to the column [14]. The burner was $0.25\ m$ from the ground. The heat release rate in the test was $52.5\ kW$ and the heating process continued for $60\ min$.

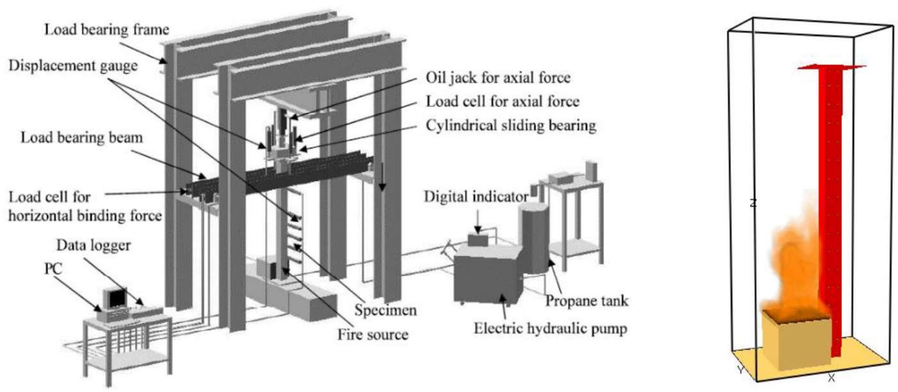
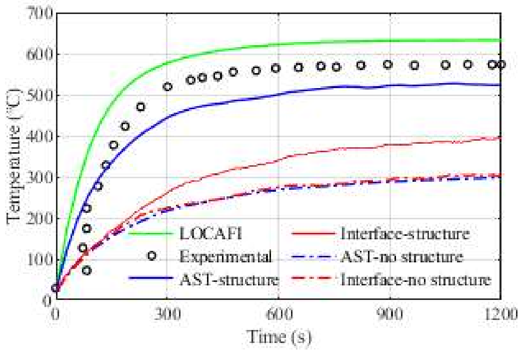


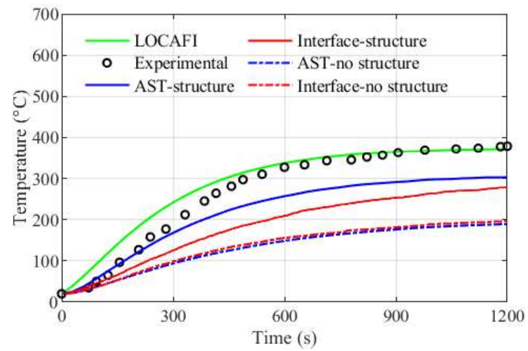
Figure 3 Experimental setup and FDS modeling of steel column test.

4.2 LOCAFI model

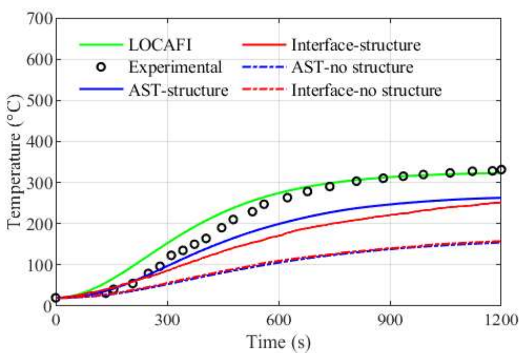
Since the column is outside the fire area, the LOCAFI model can be used to evaluate the member temperature. Steel temperatures are plotted in Figure 4. The temperatures predicted by the LOCAFI model on the side and back surface are in good agreement with the test data, while the predicted temperatures on the front surface are slightly higher than the test measurements.



(1) Front surface (z=0.4 m)



(2) Side surface (z=0.6 m)



(3) Back surface (z=0.6 m)

Figure 4 Temperatures in the steel column from case study 2.

4.3 FDS-FEM model

The steel column test was modeled in FDS with a computational domain of $0.75 \times 0.5 \times 1.8\ m\ (X \times Y \times Z)$ and a mesh size of 0.025 m, as shown in Figure 3. The emissivity and convection coefficient were taken as 0.9 and 9 $W/m^2\ K$ for localized fires. DEVICEs were placed on the front, side, and back surface of the column to record AST along the column height. Both the FDS-FEM AST method and interface method were used to transfer the thermal boundary conditions. The radiation and convection within the cavity were also taken into account. The predicted temperatures are shown in Figure 4. The AST method yields reasonable predictions of the member temperature. The slight underestimation at the side and back surface may be because the AST method is more suitable to radiation dominant fire scenario, while the heat transfer at the side and back surface is dominated by convection. The interface method yields much lower steel temperature on the front surface. This results from interpolation limitations that will be discussed in details in Section 6.

5 CASE STUDY 3: STEEL BEAM AT CEILING LEVEL SUBJECTED TO LOCALIZED FIRE

5.1 Experiment description

A H-section steel beam at the ceiling level was heated by a 1.0 m square porous propane burner [9], as shown in Figure 5. The dimensions of the steel beam were $3.6 \times 0.075 \times 0.15\ m\ (X \times Y \times Z)$ and the thickness was 5 mm in the web and 6 mm in the flange. The ceiling was made of 0.024 m thick mineral fiber Perlite board. The steel beam was at a height of 1.2 m above the burner. This case study considers the transient-state test with HRR of 900 kW. In the test, the member temperatures were measured after 7 min of fire exposure.

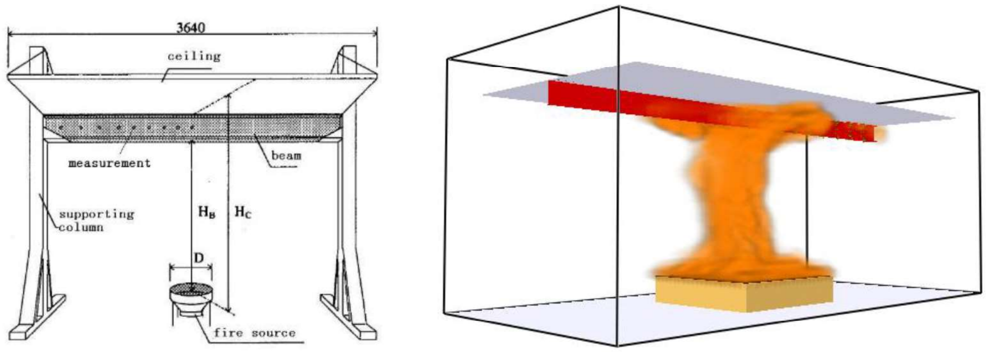
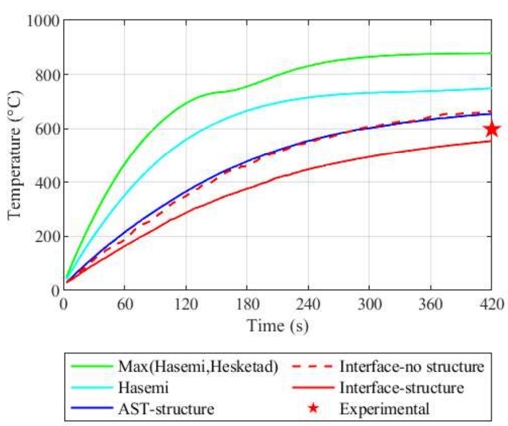


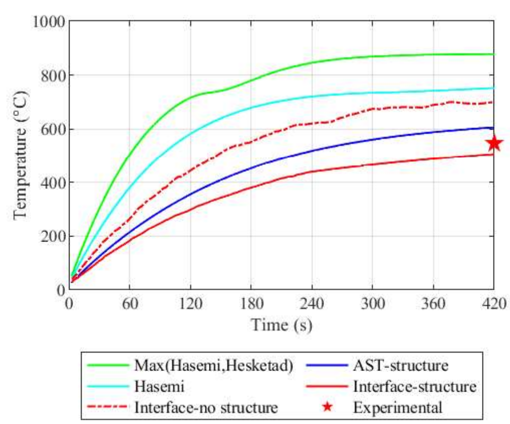
Figure 5 Experimental setup and FDS modeling of steel beam test.

5.2 Hasemi model

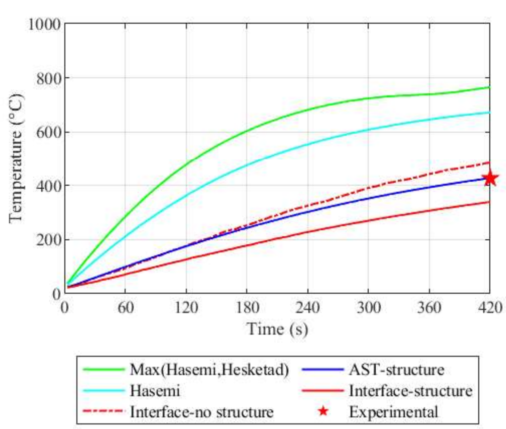
Since the flame is impacting the ceiling, the Hasemi model was used to predict the steel temperature. Computed steel temperatures are plotted in Figure 6. Compared with test data, the Hasemi model yields conservative results. Meanwhile, when using the Hasemi model, all boundary elements on the cross sections receive the same heat flux (calculated at the node line) and no shadow effect can be considered.



(1) Lower flange



(2) Mid web



(3) Upper flange

Figure 6 Temperatures in the center section of the steel beam from case study 3.

5.3 Maximum heat flux between Hasemi model and Heskestad model

Since the center section is in the fire area and in the smoke ceiling jet, a relatively rapid gas flow in a shallow layer beneath the ceiling surface [15], the heat flux received can be taken as the maximum between that evaluated with the Hasemi model and that of the Hesketad model. The computed member temperatures (labeled as 'Max (Hasemi, Heskestad)') are shown in Figure 6. Compared with the other methods, this method yields the most conservative results.

5.4 FDS-FEM model

The ceiling steel beam test was also modeled in FDS with a computational domain of $4 \times 2 \times 1.8\ m\ (X \times Y \times Z)$. The mesh size was 0.05 m. The thermal properties of the steel were taken as the same as those in Case study 1. Both the FDS-FEM AST method and interface method were used. Results are shown in Figure 6. The results obtained with the AST method agree well with the test data. The interface method yields relatively lower prediction of the member temperature than the AST method as a result of the influence of the beam on the fire development. Results obtained with the interface method without modeling the beam in FDS (but including the ceiling in FDS) are also plotted in Figure 6. It can be seen that 'interface-no structure' yields the same results as the 'AST-structure' model at the lower flange, but higher predictions at the mid web and upper flange. This observation is consistent with the findings from the NIST steel beam test and shows the effect of neglecting the influence of the structural member on the fire development. However, the difference between 'interface-no structure' and the test data in this case study is much less significant than in the NIST beam test, probably due to the presence of the ceiling in the FDS model. This observation suggests that for the member at ceiling level, the interface method can be conservatively used to predict the member temperature provided that the member is not modeled in FDS while the ceiling is.

6 DISCUSSION ON FDS-FEM INTERFACE METHOD

The above case studies have highlighted situations where discrepancies between test data and temperatures predicted with the FDS-FEM interface method result from the spatial interpolation used in the method. To describe this problem, the front surface of the column test (Case study 2) is illustrated in Figure 7. The surface represented by the red line is the exposed surface to the fire, while the surface represented by the blue line is the unexposed side. The dashed lines are the cell boundaries in FDS, while the red and blue solid lines are the element boundaries in FEM. The blue dots 1, 2, 3, and 4 are the grid centers from which the gas temperature and radiative intensities are output in FDS. The interface transfer file is applied onto the external boundary elements, shown by the red line. To obtain the thermal boundary information at the structural nodes, a Cartesian interpolation of the nearby FDS nodes is conducted. For example, for the structural node S-1 shown in Figure 7, interpolation of the FDS cell nodes 1, 2, 3, and 4 is conducted by the FEM software. However, as shown in Figure 8, the gas temperature and radiant intensities at cell nodes 3 and 4 are very low since they are on the unexposed side. Thus, interpolation results in the incorrectly "averaging effect", which leads to underestimating the heat flux received by the boundary elements.

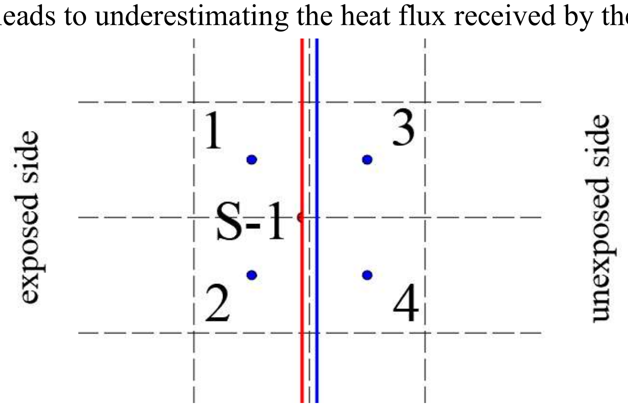
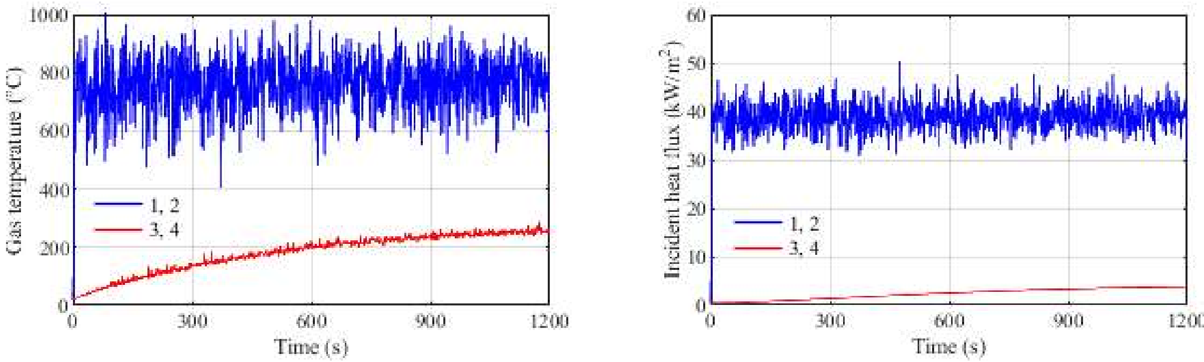


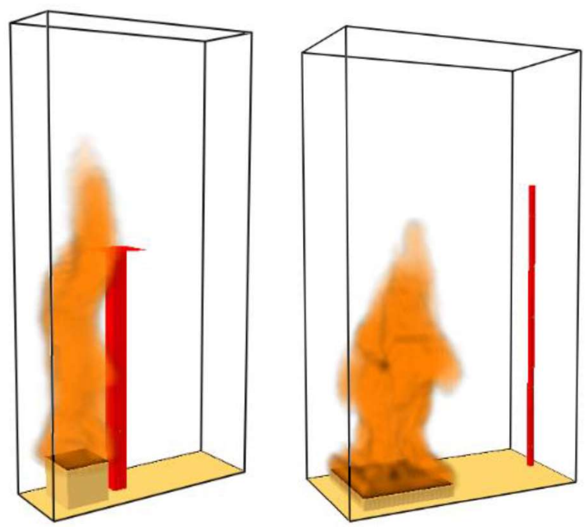
Figure 7 Interpolation in the domain to transfer information from the fire to the thermal model. FDS fire outputs at nodes 1 to 4 are used to evaluate thermal boundary conditions at FE node S-1.



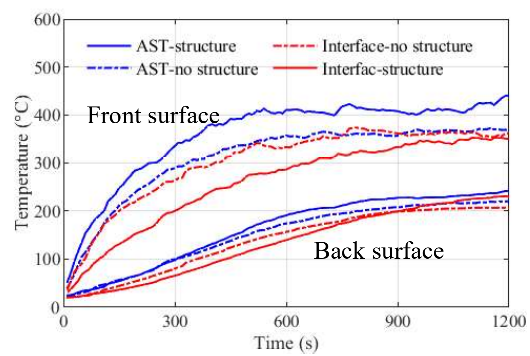
(1) Gas temperature (2) Radiant intensities

Figure 8 Gas temperature and incident heat flux output from FDS cell nodes.

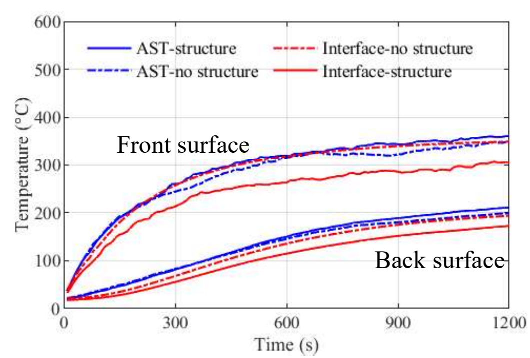
To illustrate the applicability of the interface method, two variations of the column case study are presented here. In the first case, the column is shifted away from the 400 kW fire with a distance of 0.1 m. In the second case, the column is shifted away from the fire with a distance of 2 m, and a 20 MW fire with dimensions of $1.77 \times 1.77\ m$ is used. For both cases, four combinations of advanced modeling approaches were used: either with or without the column modeled in FDS, and either using the AST or interface method.



Case 1 Case 2



(1) Case 1 (z=0.4 m)



(2) Case 2 (z=3 m)

Figure 9 FDS models and computed steel temperatures.

The computed steel temperatures on the front and back surface of the column are plotted in Figure 9. Since the AST method with structure modeled in FDS ('AST-structure') has been validated in the previous case studies, it is used here as benchmark. For Case 1, the interface method yields lower temperatures than the benchmark for the front surface, due to the spatial interpolation. For Case 2, the interface method without the structure modeled in FDS ('Interface-no structure') yields almost the same results as the AST method. This suggests that when the member is far away from the fire, such that it does not noticeably impact the air flow, the interface method can be used. The member should not be present in the FDS model when using the interface method.

Whether the structure impacts the fire development is a case-by-case judgement that requires insights of fire dynamics. The main factors are the dimension of the structure and relative position of the member to the fire. Walls and floors that form the enclosure will influence the fire development, while a column at a 5 m distance from a localized fire has a minor impact. Generally, frame-type members that are outside the flames and do not noticeably affect the ceiling jet have negligible impact on the fire development.

7 PROPOSED MODELING STRATEGY

Based on the underlying theory and results of case studies, a numerical modeling strategy for structural fire design under localized fires is proposed. The flowchart of Figure 10 guides decision toward the suitable fire modeling approach within either simple fire models or advanced FDS fire models.

The first consideration is whether the member is inside the localized fire area, i.e., the member is engulfed in the localized fire. If it is, the presence of the member will impact the fire. If choosing FDS in this case to model the fire development, the FDS-FEM AST method should be used. The interface method may yield erroneous results due to the spatial interpolation (see Section 6). If choosing simple models for the fire development, the next consideration is whether the section is inside the smoke layer. If it is, the heat flux should be taken as the maximum between that computed from the Hasemi model and the Hesketad model. If the section is outside the smoke layer, the Heskestad model can be used to compute the plume temperature and the member temperature can be evaluated with the heat transfer from the plume.

If the member is outside the fire area and does not impact the fire, both FDS-FEM AST and interface method can be used to evaluate the member temperature. When selecting the interface method, the member should not be included in the FDS model, while with the AST method it can be included or not. If the member still impacts the fire, the AST method should be used, and the member should be modeled in FDS. If selecting a simple method, the distinction is again made based on the position of the member in the smoke layer. If inside the smoke layer, the Hasemi model should be used. If the member is outside the smoke layer, the convective heat flux can be neglected and thus the LOCAFI model can be used.

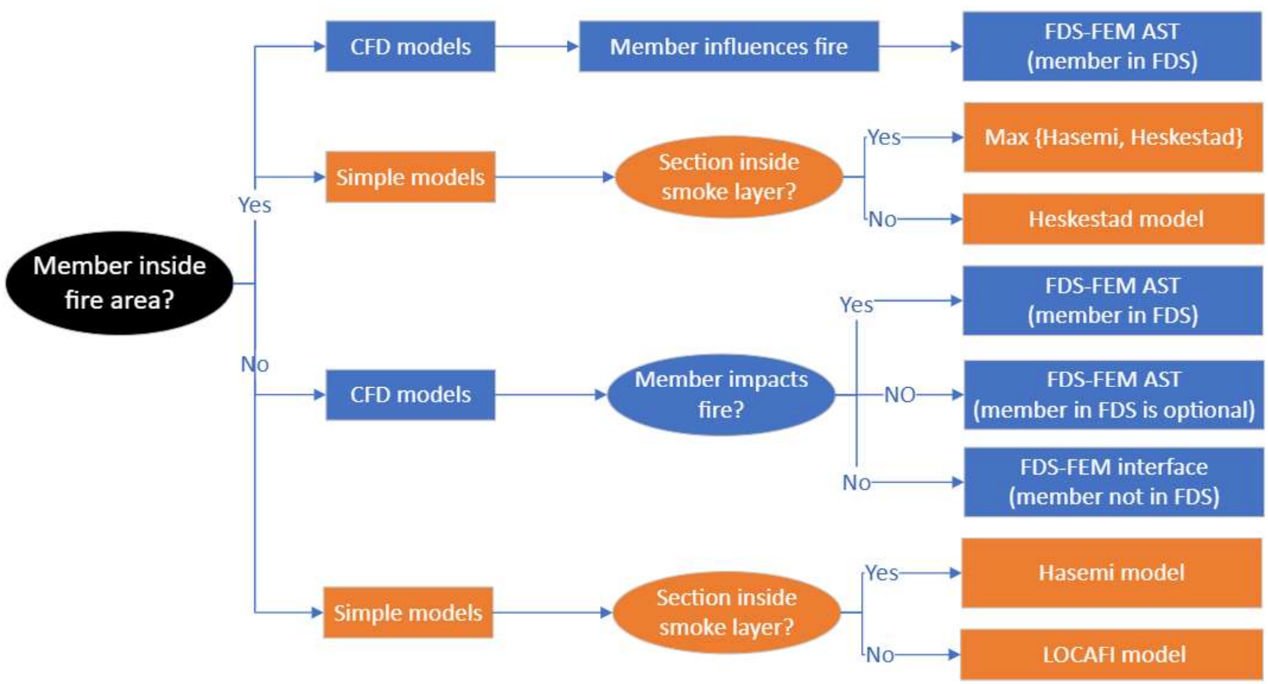


Figure 10 Modeling strategy for structures subject to a localized fire.

8 CONCLUSION

This study investigated the accuracy of different fire-thermal models to evaluate the temperature of structural members subjected to localized fires. Three experiments were modeled using different simple and advanced fire-thermal modeling approaches and steel temperatures were compared.

Results showed that the effects of localized fires on steel structures can accurately be captured by combining FDS fire modeling with FE heat transfer analysis of the steel sections. One possible approach to couple FDS with FE is through the Adiabatic Surface Temperature (AST); this method was validated for the three case studies, provided AST data is recorded at a sufficient number of points along the section surface. An alternative coupling method is through an interface file that records gas temperature and radiant intensities. The interface method is efficient in terms of modeling effort especially for large models and was validated for structural members outside the fire area with negligible influence on the fire development, such as frame members relatively far from the fire source. Structural members which boundary conditions are assigned through the interface method should not be represented in the FDS model.

Results also showed that simple fire models are generally conservative when used within their intended range of validity. Based on the case studies, a modeling strategy is proposed, which provides guidance for structural fire engineers to apply the suitable modeling approaches for fire safe design.

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