PREDICTIVE CAPABILITIES OF FIRE DYNAMICS SIMULATOR OF FLAME SPREAD ON TIMBER IN ENGINEERING APPLICATIONS: AN EVALUATION

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ABSTRACT: Predicting ignition and fire growth of engineered timber products holds significant relevance in the fire safety community, given the extensive application of these materials as structural and façade elements in buildings. Furthermore, understanding the charring process of wooden materials is crucial for predicting their structural performance when exposed to a fire hazard. This article presents an effort to evaluate the engineering code Fire Dynamics Simulator (FDS) in terms of predicting heat impact, fire spread and charring on intermediate-scale wooden panels. Experimental tests were carried out on combustible (spruce wood) panels, representing fire spread on wooden surfaces. The samples were exposed to a propane burner with a power ranging from 30 to 100 kW in three distinct configurations. Good qualitative prediction of the incident heat flux on the panel were achieved for the simple configurations, whereas the model limitations become more evident in more complex configurations. A coupled engineering pyrolysis model was then used to characterize the flame spread, in terms of charring depth and heat release contribution of the combustible surface.

KEYWORDS: Timber; Fire spread; Numerical simulation; Fire Dynamics Simulator; Wood charring.

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1 – INTRODUCTION

The use of engineered timber in building structure and design is rising in popularity driven by its appealing aesthetic appearance and environmentally friendly features. However, fire incidents involving these combustible elements pose severe risks of flame spread, increase in the heat release of the fire and loss of structural integrity. Predicting this phenomenon of flame spread over timber is critical for designing effective fire safety measures and developing strategies to mitigate potential hazards.

In the domain of fire modeling, Fire Dynamics Simulator (FDS) is a widely adopted computational tool by the fire safety engineering community for predicting fire dynamics in diverse scenarios. FDS, originally developed at NIST [1,2], has been subjected to extensive validation over the past decade, and demonstrated to be a reliable tool for predicting overall flow and temperature fields in diverse engineering applications [3]. However, prediction of flame spread over combustible surfaces requires accurate prediction of the complex, coupled phenomena of thermal impact near the flame region and the material thermal response (pyrolysis).

As reported by the code developer, the uncertainty for heat flux predictions in the current guide is of approximately 50 %. Because of this difficulty, a limited number of studies have explored the modeling of flame spread on combustible surfaces using feasible engineering approaches, despite their extensive use by the engineering community. In a single burning item (SBI) test, the accuracy of FDS in predicting the flame surface heat flux was evaluated by Zhang et al. [4]. FDS was found to significantly underpredict the surface heat flux in regions of higher heat release rates (HRR). Experimentally, the heat flux was mapped on both inert and combustible walls by Zeinali et al. [5,6]. An average total heat flux near the burner was approximately 44 and 60 kW/m². Using FireFOAM [7], the impact of the mass density distribution of MDF panels on the flame spread was also numerically studied by Zeinali et al. [8]. This quantity was shown to have a significant impact on the prediction of flame height, HRR and pyrolysis propagation rates. A numerical model for large-scale flame spread of MDF panels was conducted by Baolati et al. [9]. A comparative analysis between two fire modeling tools, FDS and FireFOAM, was conducted. Similarities were observed in total heat fluxes and lateral flame spread distances predicted by both codes. However, it was noted that both models significantly underpredicted the peak HRR from the combustible panels.

The second major modeling component in the prediction of flame spread over timber is pyrolysis. An engineering pyrolysis model named S-Pyro has been recently implemented in FDS. The robustness of this approach in predicting the material mass loss rate outcome as a function of the incident heat flux has been evaluated using bench-

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scale data for 149 different materials, from 6 distinct public datasets [10]. It consists on a mathematical scaling of the burning rate over time based on a single reference heat flux of cone calorimetry data. Recently, our research team has provided a physical interpretation for this formulation, relating the burning rate to the timber charring rate and char layer depth [12]. This correlation allows the prediction of timber structural behavior, which is possible by predicting the material charring upon heat exposure.

In this work, FDS, predominantly in its default sub-models and parameters, is employed for predicting flame spread on timber. Panels of spruce wood in three distinct configurations are exposed to a propane burner with a power ranging from 30 to 100 kW. The total surface heat flux is calculated and compared with experimental measurements. This analysis aims to provide a deeper insight into the modeling of this quantity near the flame region. The heat release contribution of the combustible panel and the char layer depth of the carbonized sample at the end of the test, which characterize the flame spread, are then evaluated. The strengths and weaknesses of numerical models in the prediction of these challenging phenomena will be evidenced. Acknowledging and addressing these limitations are important steps toward enhancing the reliability and precision of simulations for diverse engineering applications used nowadays.

2 – EXPERIMENTAL METHODOLOGY

The sample material, experimental setups and methods are described in this section.

The material considered in this work is spruce wood in the form of cross laminated timber (CLT). The samples were cut in 1400 mm x 1400 mm panels, with a thickness of 100 mm. The thickness of the samples were chosen so that the material could be considered as a semi-infinite slab. The moisture content of the sample before the test was measured in 20 different panel locations. A mean value of approximately 11 % was determined. The spruce wood density is assumed constant with a value of $\rho = 450\,\mathrm{kg\,m^{-3}}$. The material thermal properties are estimated by following the guidelines of Eurocode 5 [13].

Three distinct intermediate-scale well-ventilated configurations were selected to study the fire behavior of the timber panels, illustrated in Figure 1:

1. Configuration 1 : wide open single vertical panel. A burner is placed centered at its base, 100 mm from the panel;
2. Configuration 2: two vertical panels perpendicularly arranged, with a burner placed 100 mm from the corner;
3. Configuration 3: two vertical panels perpendicularly arranged, similarly as configuration 2, with a third horizontal panel placed at the top (corner + ceiling).

The fire scenarios are studied using a 200 mm square propane, sandstone type burner. After the burner is ignited, it quickly reaches a power of approximately 30 kW, which represents a corner fire source at the base of the panels. After 20 minutes the burner power is increased up to 100 kW for configurations 1 and 2 and 60 kW for configuration 3, lasting 10 minutes. The burner is then extinguished, 30 minutes after the test start. The tests were also carried out under a calorimetric hood, extracting the gases at an averahe flow rate of 0.6 N m3/s (normal cubic meter per second at 298 K), in order to measure the heat release rate (HRR).

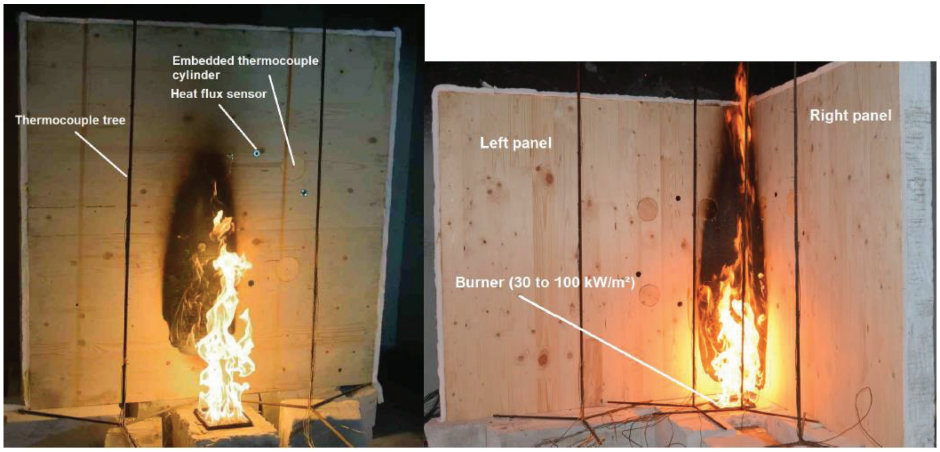


Figure 1. Pictures of the experimental setups, showing the thermocouple trees, embedded cylinders and heat flux gauges for configuration 1 (left) and 2 (right).

Two physical quantities were evaluated during the tests, namely, the heat flux perceived by the wall and the depth of the char layer. Figure 2 shows the instrumentation scheme of the three configurations, concerning the placements of the heat flux sensors. The fluxmeters used are Blet type, water-cooled. All the sensors are connected to two HIOKI type acquisition units.

At the end of each test, the panel samples were dried in ambient air until their final mass stabilized. They were then scraped and cut into several parts, in order to measure the charred wood depth.

3 – NUMERICAL METHODOLOGY

The simulations are performed using Fire Dynamics Simulator (FDS) version 6.8.0 as the fire modelling package in this study [1, 2]. FDS is a large eddy simulation (LES) based computational fluid dynamics software which solves unsteady low Mach number combustion equations on a rectilinear grid. In its default configuration, FDS solves the conservation of mass, momentum, energy and species. In FDS combustion is modeled with a mixture fraction concept, and the thermal radiation is computed using a finite volume technique on the same grid as the flow solver. It employs the finite-difference method, with second-order explicit predictor-corrector time discretization and second-order central difference space discretization. The time-step is determined dynamically during calculations based on the local control volume size and velocity to ensure computational convergence. A complete description of FDS technical details can be found in refs. [1,2]. The sub-models and details used in FDS are summarized in Table 1. Unless explicitly mentioned otherwise, all FDS sub-models applied in this work are used in their default settings. The heat of combustion of propane was set to 46.45 MJ/kg [14].

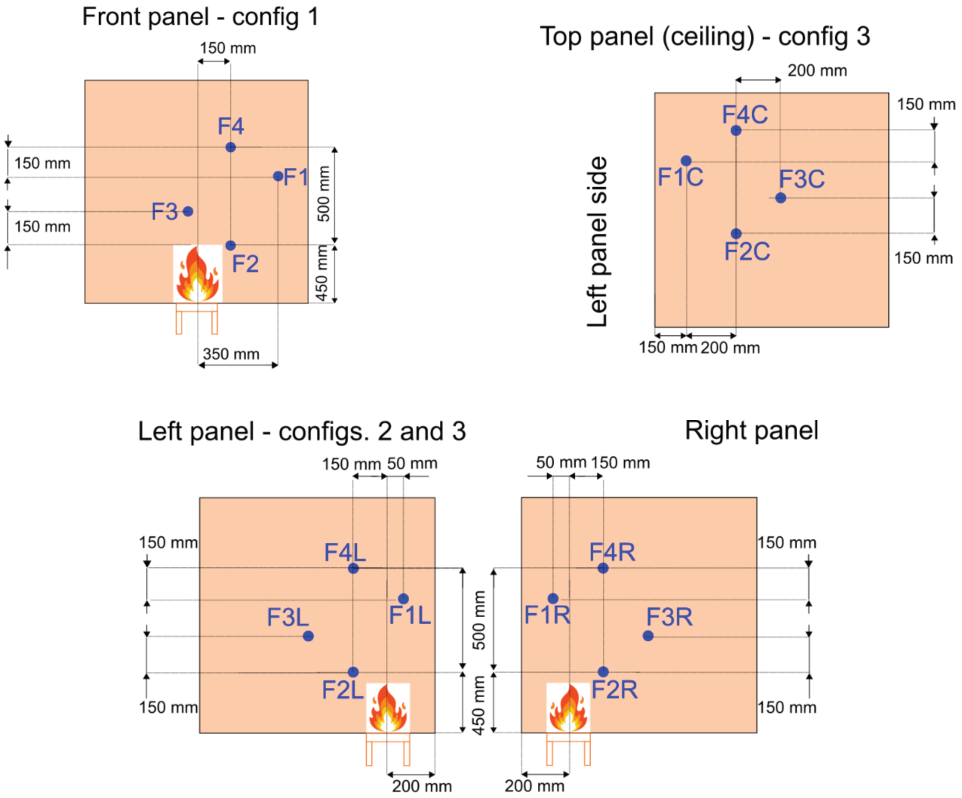


Figure 2 : Diagram of the experimental setups, showing the positions of the embedded thermocouple cylinders and flux meters in the frontal panel of configuration 1 (top), left and right panels of configurations 2 and 3 (middle) and ceiling panel of configuration 3 (bottom).

Table 1 : Summary of sub-models applied in FDS

Sub-model	FDS version 6.8.0 [1,2]
Pyrolysis	Integrated empirical model [10]
Combustion	Eddy dissipation concept model (EDC) [11] Infinitely fast chemical reaction Global combustion reaction of propane [14]
Radiation	Finite volume method with 100 discrete angles [15]
Turbulence	Deardorff model [16]

The timber pyrolysis is treated by using an integrated FDS sub-model which empirically correlates and scales the mass loss rate outcome to the incident heat flux on a combustible surface based on cone calorimetry data. This pyrolysis modeling approach has recently been integrated into FDS. The robustness of this method, called S-Pyro [10], has been evaluated using experimental data at the laboratory scale for 149 different materials, derived from six distinct public datasets. A mathematical model is proposed, which involves scaling the combustion rate, allowing the extrapolation of the evolution of the heat release rate over time from a single reference thermal flux.

A study conducted by our team complements this mathematical model by providing an innovative physical interpretation of this formulation, linking the combustion rate behavior to the depth of the char layer [12]. The main advantage of this approach lies in its offering a generalized expression, requiring minimal material property data, and enabling the prediction of wood combustion over time for any heat flux, with accuracy consistent with engineering requirements.

The FDS models are shown in Figure 3. Configuration 1 measures 1 m in length, 1.6 m in width, and 1.6 m in height. Configurations 2 and 3 are 1.6 m in length, width, and height. To maintain an engineering-feasible approach, a grid resolution of 50 mm was used. Reducing the grid size to 25 mm resulted in an average discrepancy of 7% in heat flux predictions. Further refining it to 12.5 mm reduced the discrepancy to less than 2%. However, it should be noted that such a fine grid is impractical for engineering applications when the computational domain spans tens of meters. The simulations were carried out using the Open Multi-Processing (OpenMP) technique for parallel computing.

5 – RESULTS

Configuration 1

Figure 4 illustrates the temporal evolution of the gauge heat fluxes recorded for the single wooden panel in configuration 1. To reduce signal noise, the total heat flux curves were filtered (smoothed). When the burner heat release remains constant, the measured heat fluxes exhibit a generally stable behavior, except for a few noticeable spikes. These spikes are particularly evident in fluxmeter F3 at around 5 minutes and in fluxmeter F2 at approximately 20 minutes. These fluctuations are attributed to localized flame development and wood cracking during combustion.

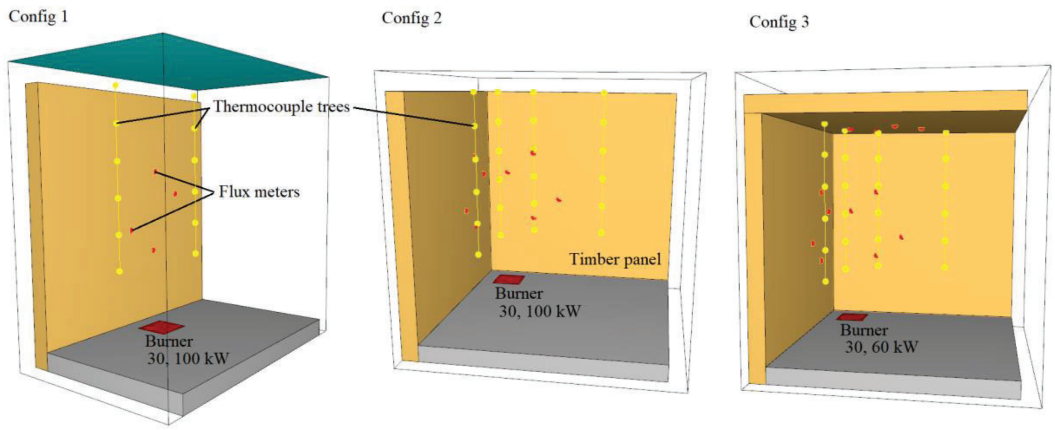


Figure 3 : Schematic view of the computational model used in FDS simulations

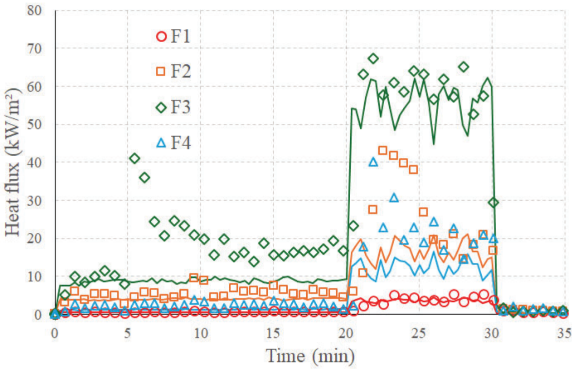
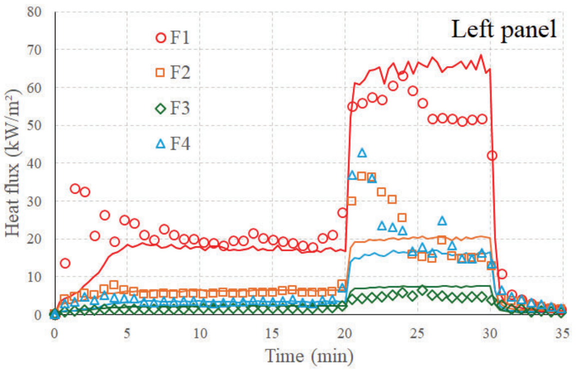


Figure 4 : Comparisons of the FDS model predictions and measurements of gauge heat flux of configuration 1

The FDS model predictions, represented by solid lines in Figure 4, demonstrate overall qualitative and quantitative agreement with the measured gauge heat fluxes. However, the model does not capture the sudden spikes in heat flux, as its predictions tend to exhibit steady fluctuations under constant burner power. This discrepancy arises because the model oversimplifies the combustion process and does not accurately account for the localized burning of pyrolysis gases.

Configuration 2

Figure 5 shows the temporal evolution of the gauge heat fluxes calculated for the double wooden panels in configuration 2. The FDS model effectively captures the overall trends in surface heat flux for both the left and right panels of configuration 2, within the bounds of engineering accuracy. As observed in configuration 1, the model struggles to predict the transient behavior of heat flux spikes, highlighting its difficulty in capturing such fluctuations.



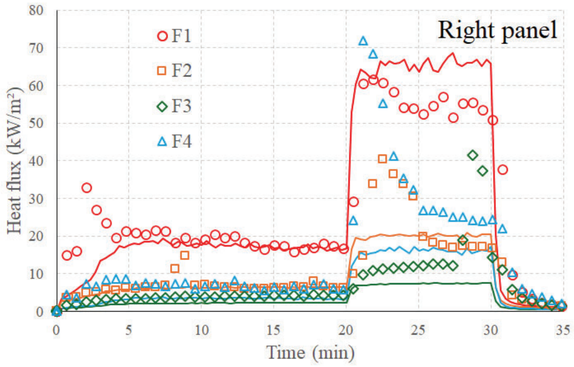
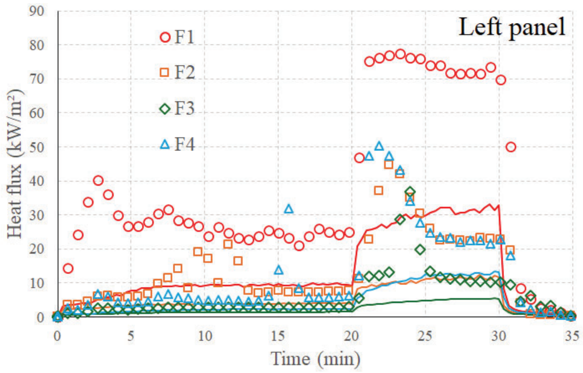


Figure 5 : Comparisons of the FDS model predictions and measurements of gauge heat flux of configuration 2

Configuration 3

The evolution of the surface heat fluxes for configuration 3 is shown in Figure 6. The FDS model significantly under-predicted the surface heat flux across all three panels. In certain regions with the highest heat flux intensity, this underprediction is as much as 10 times lower than the measured values. The presence of local flames has a more pronounced impact in this configuration, with the flame heat flux directly affecting the top panel. Additionally, the radiative heat feedback between panels led to an increased measured heat flux, which the oversimplified model failed to capture. Previous studies have shown that the inaccuracy of FDS sub-models of convective and radiative transport to a solid surface near the flame region, and their compensating errors, can also lead to large divergencies of results when considering different scales and geometries [17].



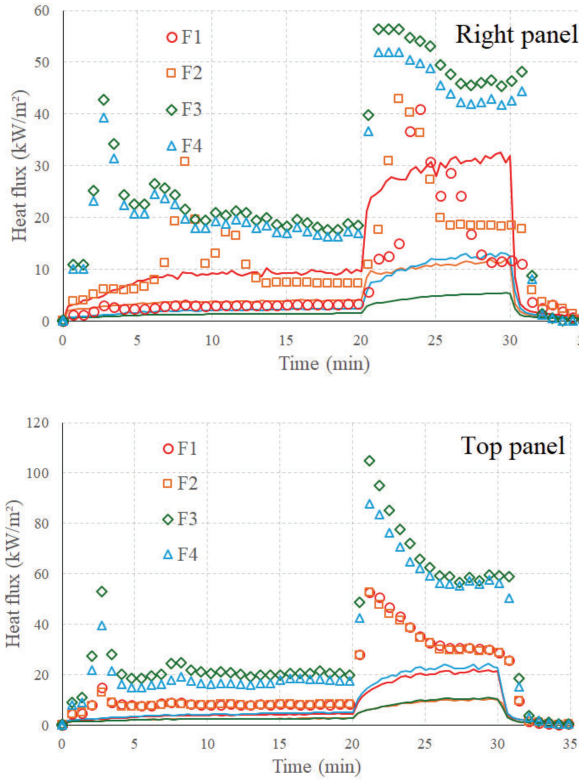


Figure 6 : Comparisons of the FDS model predictions and measurements of gauge heat flux of configuration 3

Heat released by timber

Figure 7 presents a comparison of the heat release rate evolution (from both the burner and the timber panel burning) between the experimental measurements and model predictions, using the integrated engineering pyrolysis sub-model, S-Pyro. The additional heat generated by the wooden sample exhibits a qualitative behavior similar to that observed in wooden and other charring materials during fire tests at smaller scales. Once pyrolysis begins, the HRR increases rapidly, reaching a short peak. Subsequently, a char layer of significant thickness forms, which inhibits further wood degradation by slowing heat and mass transfer between the gaseous and condensed phases, thus protecting the substrate material. Following this, the HRR decreases and stabilizes, tending towards a quasi-steady-state behavior for the remainder of the test [18].

The model's prediction of the overall heat release contribution from the wooden panel is satisfactory for configurations 1 and 2, although it shows a slight under-prediction. This under-prediction is more pronounced in configuration 3, as anticipated from the significantly lower heat fluxes predicted in Figure 6. The mean calculated total heat released was 152 MJ, compared to the measured value of 177 MJ, resulting in a deviation of 14%.

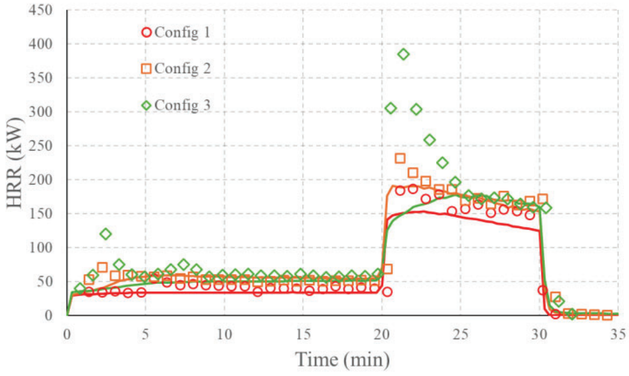


Figure 7 : Total heat released in the system (burner + timber combustion). Symbols denote experimental measurements, solid lines denote numerical predictions

Timber charring prediction

The char layer depth is an important quantity in the description of flame spread over a combustible surface. Accurate prediction of this quantity by a numerical model is particularly useful for the study of structural analysis under heat exposure. It is directly related to a material's rate of release of pyrolysis gases, and, therefore, to its contribution to a fire spread. The local mass loss rate $\dot{m}''$ of the wooden sample was obtained by dividing the HRR by the effective heat of combustion of the spruce wood pyrolysis gas, assumed constant with a value of 14.0 MJ kg^{-1} [19]. The derived char layer thickness e could then be expressed as:

$$\dot{e} = \frac{\dot{m}''}{\rho_0 \cdot (1-\tau_c)}, \tag{1}$$

where ρ_0 is the spruce wood density and τ_c is the char fraction, defined as the char density divided by the initial, virgin wood density and given the value of 0.25.

The calculated char layer thickness and its comparison with experimental measurements are presented in Figure 8. The char layer thickness was measured at the positions marked by black dots, and linear interpolation was applied to obtain the char layer depth contour. For brevity, only the left panel for configuration 2 and the top panel for configuration 3 are shown.

Overall, the FDS model provided a qualitative description of the char layer depth. In configuration 1, the maximum char layer depth of 20 mm at the end of the test was accurately calculated. However, due to the under-predicted heat fluxes in configuration 2 and, especially, configuration 3, the char layer depth was under-

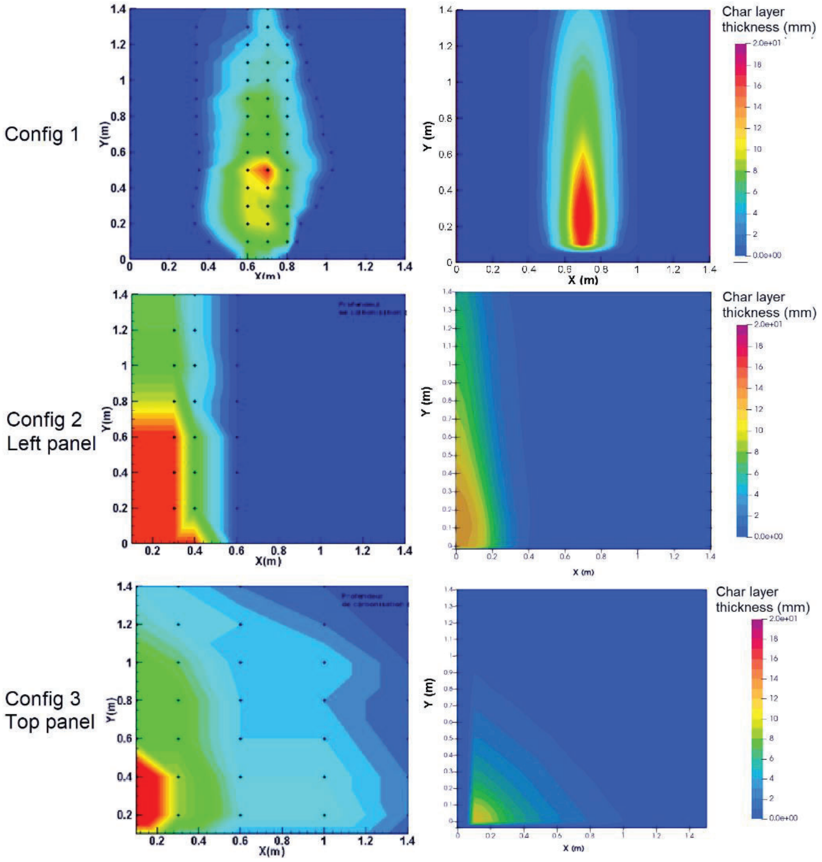


Figure 8 : char depth of the carbonized timber panel at the end of the test. Left : experimental measurements ; right : numerical prediction

predicted. The maximum calculated char layer depth was approximately 12 mm for both configurations 2 and 3, while the measured values were still around 20 mm.

For fire safety engineering applications, this under-prediction of charring could be overcome by majoring the pyrolysis correlation law with respect to the observed standard deviation over the whole experimental setup.

4 – CONCLUSIONS AND PERSPECTIVES

This study evaluated the capabilities of Fire Dynamics Simulator (FDS) in predicting flame spread and charring behavior of engineered timber under fire exposure. The results highlighted the model's strengths in qualitatively predicting heat fluxes and providing a general understanding of flame spread dynamics. However, notable discrepancies were observed, particularly in capturing localized fluctuations in heat flux, as well as in the under-prediction of surface heat flux and char layer depth in more complex configurations. The results from the numerical modelling of experiments with spruce wood panels revealed that while FDS offers reliable predictions for heat release and overall flame spread in certain setups, its limitations become apparent when considering more intricate scenarios involving multiple panels and radiative heat feedback.

The modeling of flame spread on timber using engineering approaches continues to be a complex and underexplored topic. While FDS has proven to be a powerful tool for describing flow and temperature fields in fire-related scenarios, certain aspects, such as soot radiation, pyrolysis, convective and radiative heat feedback to surfaces, remain outside its full descriptive capability.

In light of these limitations, it is important for FDS users to exercise caution, particularly when relying on its default sub-models to predict surface heat flux, flame spread and charring near flame regions. Adjustments to these models should be done with care, as compensating errors in the sub-models can introduce inaccuracies.

5 – REFERENCES

1. McGrattan, McDermott et al. Fire Dynamics Simulator User's Guide. NIST Special Publication 1019 Sixth Edition, 2023.
2. McGrattan, Hostika et al. Fire Dynamics Simulator Technical Reference Guide Volume 1: Mathematical Model. NIST Special Publication 1018-1 Sixth Edition, 2023.
3. McGrattan, Hostika et al. Fire Dynamics Simulator Technical Reference Guide Volume 3: Validation. NIST Special Publication 1018-1 Sixth Edition, 2023.
4. Zhang, Jianping, Michael Delichatsios, and Matthieu Colobert. Assessment of fire dynamics simulator for heat flux and flame heights predictions from fires in SBI tests. Fire Technology 46, 291-306, 2010.
5. Zeinali, Davood, et al. Experimental study of corner fires—Part I: Inert panel tests. Combustion and Flame 189, 472-490, 2018.
6. Zeinali, Davood, et al. Experimental study of corner fires—Part II: Flame spread over MDF panels. Combustion and Flame 189, 491-505, 2018.
7. FireFOAM, Version 2.2.x, Available at https://github.com/fireFoam-dev/ fireFoam-2.2.x .
8. Zeinali, Davood, et al. Study of the importance of non-uniform mass density in numerical simulations of fire spread over MDF panels in a corner configuration. Combustion and Flame 200, 303-315, 2019.
9. Baolati, Jiayidaer, et al. Large eddy simulation of room fire spread using a medium scale compartment made of medium density fiberboard (MDF) panels. Building Simulation. Vol. 15. No. 4. Beijing: Tsinghua University Press, 2022.
10. Hodges, Jonathan L., et al. "An engineering model for the pyrolysis of materials." Fire safety journal 141 (2023)
11. Poinsot, Thierry, and Denis Veynante. Theoretical and numerical combustion. RT Edwards, Inc., 2005.
12. Lardet, Paul, et al. "An empirical correlation for burning of spruce wood in cone calorimeter for different heat fluxes." Fire Technology 60.6 (2024)
13. Porteous, Jack, and Abdy Kermani. Structural timber design to Eurocode 5. John Wiley & Sons, 2013.
14. Hurley, Morgan J., et al., eds. SFPE handbook of fire protection engineering. Springer, 2015.
15. Liu, L. H. Finite volume method for radiation heat transfer in graded index medium. Journal of Thermophysics and Heat Transfer 20.1, 59-66, 2006.
16. Nicoud, Franck, and Frédéric Ducros. Subgrid-scale stress modelling based on the square of the velocity gradient tensor. Flow, turbulence and Combustion 62.3, 183-200, 1999.
17. Coimbra, A. et al., "Assessment of the predictive capabilities of fire dynamics simulator for heat flux and flame spread on large-scale wooden fa¸cades," Proceedings of FSF 2024. The 4th International Symposium on Fire Safety of Facades, vol. 32, no. 3, pp. 103–104, 2024.
18. Boonmee, N., and J. G. Quintiere. Glowing and flaming autoignition of wood. Proceedings of the combustion institute 29.1, 289-296, 2002.
19. Martinka, Jozef, et al. Improvement of Heat Release Rate Measurement from Woods Based on Their Combustion Products Temperature Rise. Processes 11.4, 1206, 2023.

https://doi.org/10.52202/080513-0452