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ADVANCED FIRE MODELLING IN SUPPORT OF PERFORMANCE-BASED FIRE DESIGN OF TIMBER BUILDINGS

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ABSTRACT: The wood products industry is growing, as evidenced by the desire to build larger and taller buildings with timber and the start-up of new manufacturers. Despite the benefits of timber, projects are still experiencing approval resistance, namely when performance-based design is proposed to demonstrate code compliance. To gain approval, testing is often required to confirm the performance of a given product or design. While large-scale testing can always be performed, it tends to be very costly and time consuming, and can be argued to be valid only for the scenarios being tested. Fortunately, greater knowledge in fire safety engineering now allows for advanced/sophisticated fire modelling techniques, including models using the computational fluid dynamic and finite element method. This paper presents a number of advanced modelling tools and an ongoing effort to develop and harmonize a material database to be used in these models. Given the complexity of advanced modelling and the variety of input parameters and properties, an initiative is being launched at FPInnovations to generate a centralized material properties database, with the intent of making it available to the design community. Guidance on the proper use of advanced models in support of performance-based design with timber elements is also being developed.

KEYWORDS: Fire safety engineering, modelling, fire dynamics, timber buildings, performance-based design.

1 INTRODUCTION

The wood products industry is growing, as evidenced by the desire to build larger and taller buildings with timber and the start-up of new manufacturers. Some of the benefits that are fuelling renewed interest in timber construction include sustainability, prefabrication, reduced construction times, and the creation of more reliable timber products suitable for larger and taller applications. This has led to a resurgence of wood-based products in markets that have been historically dominated by steel and concrete mainly due to prescriptive limitations for using wood in larger and taller buildings, as well as non-residential construction.

Despite the benefits of timber, projects are still experiencing approval resistance, namely when performance-based design (PBD), i.e., alternative solutions, are proposed to demonstrate code compliance. To gain approval, testing is often required to confirm the performance of a given product or design.

While large-scale testing can always be performed, it tends to be very costly and time consuming, and can be argued to be valid only for the scenarios being tested. Fortunately, greater knowledge in fire safety engineering now allows for much more advanced/sophisticated fire modelling techniques, including models using the computational fluid dynamic and finite element method. These modelling techniques are gaining popularity in lieu of large-scale testing to extrapolate results and support PBD, provided the input parameters and results are verified and validated appropriately.

The purpose of this paper is to outline some available tools and ongoing efforts related to PBD, such that continued developments needed towards PBD can be identified. The need for a centralized material database to be used in these models is also discussed.

2 TIMBER CONTRIBUTION

When conducting a performance-based fire design, the contribution of combustible materials to the fire growth, intensity and duration is an important behaviour that need to be properly assessed. Combustion properties such as heat release rate, ignition temperature and mass loss rate as a function of the incident heat flux, among others, are used to predict the effect of combustible components to the fire dynamics. Charring rate dictates the rate at which timber is converted to char and is typically used to evaluate the structural fire-resistance of building elements. Each of these factors is pertinent in understanding the potential fire dynamics of a compartment in which structural timber is used, essentially for a PBD.

2.1 COMBUSTION PROPERTIES

The hazard related to exposing mass timber surfaces is due to the potential fire contribution of these surfaces.

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When exposed to appropriate conditions, mass timber elements will ignite, release heat and flames, and ultimately reach self-extinction, should appropriate conditions be reached. Fire effluents, such as smoke and fractional effective dose, are also hazards to consider, namely as it relates to life safety of occupants and evacuation.

Advances in fire science and engineering have allowed for rapid progression in fire and smoke modelling. As such, the traditional prescriptive design is no longer the only compliance method for designing a fire-safe buildings [1]. Parametric modelling, zone models and field models using computational fluid dynamics (CFD) are among the most used in the fire engineering community. CFD models divide a given space into numerous control volumes where mass, momentum and energy conservation are numerically solved for each control volume.

Fire Dynamics Simulator (FDS), developed by NIST, is a commonly used CFD model. Modelling a fire source or a combustible material in FDS can be done from various methods. The most common methods, as described in FDS User Guide [2], are to use:

1) the pyrolysis model embedded in FDS following an Arrhenius function; or,
2) the use a of defined heat release rate (HRR) curve.

Both approaches require test data as input parameters.

2.1.1 Pyrolysis Kinetic Properties

Pyrolysis kinetic properties can easily and rapidly be obtained through a series of micro-scale thermogravimetric analysis (TGA). The mass change of a material as a function of time or temperature is measurement with high accuracy. The specimen is placed in either an inert environment (e.g. nitrogen) or in an oxidative environment (e.g. air). Through a series of data processing, it is relatively easy to determine the kinetic properties.

Several timber decomposition models can be found in the literature, ranging from simple models to more complex and sophisticated models. The level of accuracy, computational time and intended use of a given model is to be carefully evaluated when selecting the type of decomposition scheme. Using a simpler model helps at minimizing the uncertainties that may arise from each additional input parameter (i.e., level of complexity) to the total model uncertainty [3]. The simplest model consists at converting a solid material (wood) into char, volatiles and residues following an Arrhenius function consecutively, as shown in Equations (1) and (2). FDS User Guide [2] presents a detailed methodology for determining the activation energy (E) and pre-exponential constant (A) for use in the Arrhenius function.

$$Wood(\%MC) \xrightarrow{r_1} Dry\ Wood + Water\ Vapour$$

$$Dry\ Wood \xrightarrow{r_2} Char + Volatiles \quad (1)$$

$$Char \xrightarrow{r_3} Residues + Volatiles$$

$$r_i = Y_i^{n_{s,i}} A_i e^{\left(\frac{-E_i}{R\,T}\right)} \quad (2)$$

Where r is the reaction rate (s^{-1}), $n_{s,i}$ is the reaction order, Y_i is the mass fraction, A is the pre-exponential factor (s^{-1}), E is the activation energy (kJ / mol), R is the universal gas constant (8.314 x 10^3 kJ / mol·K) and T is the temperature (K).

Figure 1 shows the results from a TGA analysis performed at a heating rate of 20 K/min. A first reaction (r_1) is observed between 20 and 100°C, which is the wood at a given moisture content being converted into dry wood. The second reaction (r_2) occurs between 200 and 400°C, which is the wood being converted into char and volatiles and is clearly the most important reaction. The char oxidation (r_3) then occurs up to approximatively 600°C. Beyond 600°C, the specimen is entirely converted to residues. It is noted that Figure 1 shows the reaction rate as a function of temperature rather than as a function of time. This representation is typically used to better understand the effect of temperature on the reaction rates.

It is noted that conducting TGA under an inert environment (nitrogen) or an oxidative environment (air) does not provide the same trend towards the end of the decomposition. As reported and observed in [4, 5, 6], TGA performed in an oxidative environment provides more complex and detailed results than those done in an inert environment. The char oxidation occurring towards the end of the second reaction is not well captured when done in an inert environment, as shown in Figure 1. The maximum reaction rates are also greater when evaluated in an oxidative environment. The heating rate in a TGA is also affecting the decomposition, where a low heating rate typically increases the yield of char and a fast heating rate increases the yield of volatiles. As such, performing TGA in an oxidative environment should be favoured, as well as using a fast heating rate to evaluate the yield of volatiles, which would essentially be the pyrolysis gazes fueling the flaming combustion of wood.

Another method embedded in FDS is to directly enter the TGA test parameters and some data processing. Only, the TGA heating rate (K/min), the reference temperature (°C or K) and the pyrolysis range (°C or K) can be provided and FDS will calculate the E and A. The pyrolysis range can be estimated as the width of the reaction rate curve, assuming it to be of a triangular shape (pyrolysis range would be about ±120°C in Figure 1).

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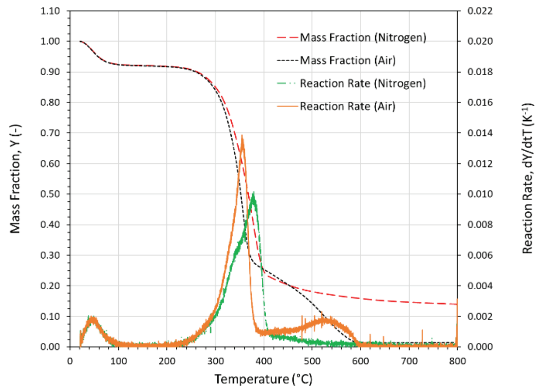

Figure 1: *TGA results conducted in an oxidative environment (air) at 20 K/min*

2.1.2 Heat Release Rate Curve

Heat release rate (HRR) of a material is among the most important combustion parameter to assess its potential contribution to fire growth. Heat release rate of materials or components can be evaluated using oxygen calorimetry, such as a small-scale cone calorimeter conforming to ISO 5660 standard [7], to a large-scale calorimeter, which was used to measure the HRR of mass timber compartments during a study in 2018 [8]. Intermediate-scale calorimeter can also be used to evaluate smaller components and assemblies, such as office cubicles, upholstered furniture, etc.

When the HRR of a given material or component is known, it can be implemented into FDS so that its fire development will follow that of the calorimeter test. The HRR values can be adjusted as a function of time using the RAMP function in FDS. It is noted that the RAMP values are to be determined after ignition occurs (i.e., RAMP time increment starts at the ignition time and not at the test/modelling time – thus once the material ignites). Other parameters can also be used to determine more realistic behaviour, such as ignition and extinction temperatures, as well as the recently implemented FDS function CONE_HEAT_FLUX. This function allows to scale up or down the HRR of a material exposed to a given constant or transient incident heat flux, based on its reference heat flux value (e.g., at 50 kW/m²). As reported by Hernouet *et al.* [9], a combustible material exposed to a radiant heat flux will be subjected to a greater incident heat flux due to flame irradiance generated from the combustion. As such, this increases in incident heat flux should be explicitly considered when determining the RAMP values in FDS.

However, at the time of writing this paper and based on discussion on the online Google FDS-SMV forum, the FDS developers confirmed that the CONE_HEAT_FLUX function is still under development and not yet ready for proper use. As such, the option of using a HRR curve will not be further detailed herein.

2.2 CHARRING RATE

When exposed to an adequate heat source (e.g., fire), timber will experience pyrolysis and ultimately charring. Charring is a fundamental property for timber and is the main parameter used to estimate the structural capacity of timber elements in fire (i.e., residual cross-section method). A thorough review of factors affecting the charring rate of timber was recently done by Bartlett et al. [10]. Among others, charring is influenced by various factors, such as wood density, moisture content, oxygen concentration and exposure conditions (fire severity).

Butler [11] reported charring rates as a function of radiant heat fluxes varying from 20 to 3000 kW/m² using a linear regression. The data were obtained using timber slabs having sufficient thickness to behave as a thermally-thick solid. Babrauskas [12] reported that this linear regression is however arguable given that some of the charring data was indirectly obtained from mass loss data and assumed that the residual char density as being nil. It was also mentioned that the linear regression over-estimates the charring rate when exposed to high levels of heat flux, suggesting that charring rate is not linearly proportional to the heat flux level. White & Tran [13] found a similar relationship whereas the charring rate is proportional to the ratio of external heat flux ($\dot{q}$) over wood density (ρ) based on oven-dry mass and volume, per Equation (3).

$$\beta = 5\left(\frac{\dot{q}_{rad}}{\rho}\right) + 0.374 \tag{3}$$

Mikkola [14] evaluated the parameters affecting charring of timber, such as density, moisture content, external heat flux and oxygen concentration of the surrounding air. Spruce specimens with a density of 490 kg/m³ and a 10% moisture content were subjected to external heat fluxes of 25, 50 and 75 kW/m² and exhibited charring rates of 0.56, 0.80 and 1.02 mm/min, respectively. The author suggested that a linear relationship exists between the charring rate and the external heat flux in the early phase of charring (first 20 minutes after ignition) when the protective char layer is in its growing phase. When the char layer reaches its maximum thickness, the effect of the external heat flux is less pronounced, and the charring rate decreases considerably. Experiments that used white pine specimens exposed to a constant heat flux and oxygen concentrations of 21%, 10.5%, and 0% showed that the mass loss rate decreased by 50% when the oxygen concentration decreased from 21% to 0%. It is noted that typical cone calorimeter tests are conducted in normal oxygen concentration (ambient, thus 21%), while it can drastically reduce to less than 5% in a standard furnace test and in compartment fire tests, as mentioned by Schmid & Frangi [15]. This suggests that as a fire grows within a compartment and the oxygen concentration declines, the charring rate is expected to decrease and should be determined accordingly.

2.3 STRUCTURAL FIRE-RESISTANCE

Modelling structural fire-resistance involves three fundamental components. It includes 1) a fire model, 2) a heat transfer model, and 3) a structural model, as illustrated in Figure 2. The fire model generates a specific fire exposure (temperature boundary conditions) for the thermal simulation using the heat transfer model which in turn develops thermal gradients in the structural components / connections. The structural model will calculate the response of the components / connections under fire and loads (mechanical boundary conditions).

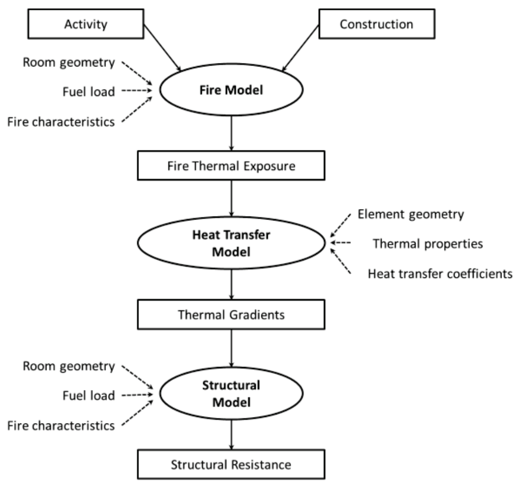

Figure 2: *Flow chart for calculating structural fire-resistance, redrawn from Buchanan & Abu* ***[16]***

The performance of structures exposed to fire can be evaluated from models that are using the finite element method, in which the results of a transient heat transfer are typically sequentially imported into a structural model (i.e., a 1-way coupling). A fully coupled analysis (i.e., 2-way coupling) should however be used when the thermal and mechanical solutions affect each other, as with timber.

A fully-coupled constitutive model, called WoodST, was developed at FPInnovations for assessing the structural fire-resistance of timber elements and connections. “S” means “Structural” and “T” is for “Thermal”. This unique finite element model (FEM) combines several mechanics-based submodels, as detailed in Chen et al. [17]. The model has been verified and validated against a number of fire tests. It has also been used in support of PBD for evaluating the performance of timber structures in fire.

Additional guidance for advanced modelling of timber structures can be found in a recently published modelling guide for timber structures [18].

3 ADVANCED FIRE MODELLING

Several validation scenarios are presented herein. Additional information and details of the modelling parameters can be found in [17, 19].

3.1 FIRE DYNAMICS

With the main objective to develop and to validate fire dynamics combustion properties and CFD models in support of performance-based fire design, several verification and validation scenarios were conducted. The modelling properties were implemented in Fire Dynamic Simulator (FDS) version 6.7.9. Simple models (TGA) were easily run on a personal computer with an Intel® Core™ i5-8265U CPU @ 1.60GHz. The more complex models (cone calorimeter, wood cribs and mass timber fires) were run using high-performance computers from the Digital Research Alliance of Canada.

3.1.1 Validation of pyrolysis kinetic properties

With the desire to increase the amount of exposed mass timber in buildings, specimens of commercially-available mass timber products have been used. Specimens from Douglas fir lumber used in the manufacturing of glue-laminated (glulam) timber beams and columns, as well as specimens of the Spruce-Pine-Fir (SPF) species group used in glulam and CLT elements were evaluated. These products have been selected given their wide use in North American mass timber construction and that they are among the two main wood species group used for structural applications.

Thermogravimetric analysis (TGA) was modelled in FDS at the same heating rates as the actual TGA tests, i.e., 5, 10, 20, 50 and 100 K/min. The FDS model used to replicate a TGA analysis was adapted from [20], with the pyrolysis kinetic properties detailed in [19]. The thermal properties from EN1995-1-2 [21] were assumed. The density relationship given in EN1995-1-2 is ignored as it is explicitly being considered by the pyrolysis kinetic properties obtained from TGA. Moreover, the sharp peak in specific heat at a temperature of 100°C is neglected, also due to the explicit consideration of water evaporation through the 1st reaction kinetics.

During the verification and validation of the pyrolysis kinetic properties, it was found that the 1st reaction (moisture evaporation) was best modelled using the alternative method embedded in FDS – that is to input the TGA heating rate, the reference temperature and the pyrolysis range (taken as 100°C) – rather than explicitly using the E and A of that reaction. The 2nd and 3rd reactions were modelled using their respective E and A.

Table 1 summarizes the pyrolysis kinetic properties obtained from TGA performed at 50 K/min. The mass fraction and reaction rate predicted by FDS are shown in Figure 3 and Figure 4 for Douglas fir and SPF, respectively, at a heating rate of 50 K/min and in an oxidative environment (air). It can be observed that the

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pyrolysis properties provide reasonable predictions of the mass fraction and reaction rate when compared to test data. Although not shown herein, it was also found that faster heating rate (e.g., TGA at 50 and 100 K/min) provides better predictions in FDS when compared to slower heating rates (e.g., 5, 10 and 20 K/min).

Table 1: *Pyrolysis kinetic properties for Douglas fir and Spruce-Pine-Fir from TGA at 50 K/min*

Property	Douglas fir	Spruce-Pine-Fir
1st reaction (r_1)		
T_{ref} (°C)	54	55
Pyrolysis range (°C)	100	
Heating rate (K/min)	50	
2nd reaction (r_2)		
E_2	1.142×10^5	9.923×10^4
A_2	3.692×10^7	1.479×10^6
3rd reaction (r_3)		
E_3	2.525×10^4	3.042×10^4
A_3	1.344×10^{-1}	3.602×10^{-1}

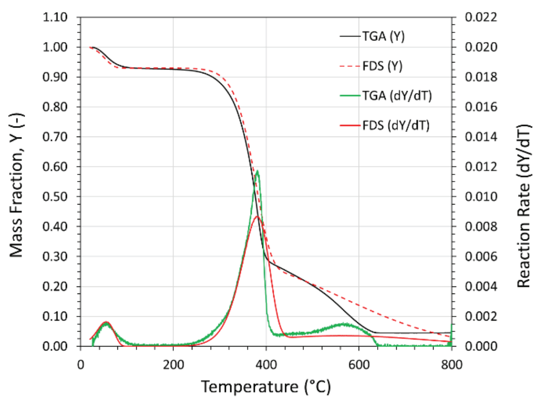

Figure 3: *TGA predictions from FDS compared to test data – Douglas fir at 50 K/min in oxidative environment (air)*

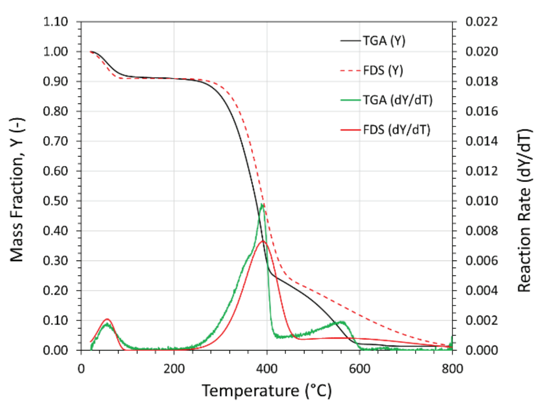

Figure 4: *TGA predictions from FDS compared to test data – Spruce-Pine-Fir at 50 K/min in oxidative environment (air)*

During the verification and validation, it was found that all pyrolysis kinetic properties showed a strong relationship with the heating rate, which was also found by Bakar [20]. Figure 5 shows the relationship for the reaction rate of SPF specimens.

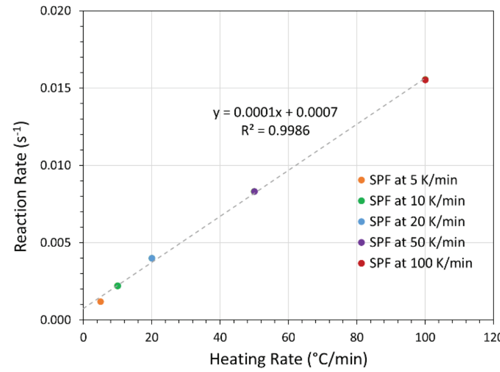

Figure 5: *Reaction rates as a function of the heating rate for Spruce-Pine-Fir specimens (2nd reaction)*

Currently, FDS does not allow to adjust the pyrolysis properties as a function of the heating rate. A single set of properties can only be used (e.g., those from 50 K/min) for modelling. However, given that the pyrolysis properties are sensitive to the thermal conditions, there would be a merit for FDS to allow such adjustments using a specific function (i.e., as with the RAMP function used for HRRPUA). This would be more realistic of a transient exposure from a fire exhibiting a growth, steady-state and decay phases.

3.1.2 Validation of combustion properties

Cone calorimeter conforming to ISO 5660 were also modelled in FDS, using the same radiant heat levels as the actual tests, i.e., 25, 50 and 75 kW/m². The FDS model used to replicate a cone calorimeter consists in a simplified domain where the specimen properties are assigned as a simple surface (called VENT in FDS). The specimen is then subjected to an external heat flux of the required magnitude. The surface properties (specimen) consisted of a fraction of water (moisture content) and dry wood. The specimen surface was 100 x 100 mm with a thickness set to 25 mm, with its back being set to "insulated" to replicate a cone calorimeter test. Due to equipment malfunctioning, the heat of reaction used in this study is taken from the literature [3]. Values of reaction of 355 kJ/kg and 205 kJ/kg were assumed for the Douglas fir and SPF, respectively. Based on cone calorimeter tests, an average effective heat of combustion of 12.35 MJ/kg and 13.30 MJ/kg is used for Douglas fir and SPF, respectively.

Table 2 summarizes the HRR obtained from test data and FDS modelling. It can be observed that FDS provides reasonable HRR when compared to test data (taken over an 1800 s burning period), while being slightly lower. The results suggest that using the properties from TGA tests done at a fast heating rate (e.g., 50 and 100 K/min) provides better HRR predictions when compared to actual test data. Lastly, it was found that for both wood species, the modelling predictions were in much better agreements with the test data when exposed to greater heat flux levels (50 and 75 kW/m²). At 25 kW/m², the ignition time is always predicted too early.

Table 2: *Heat release rate – Test data compared to FDS for Spruce-Pine-Fire specimens of 25 mm in thickness*

Cone calorimeter tests		FDS Predictions	
Heat flux (kw/m²)	**HRR$_{tig+1800s}$ (kW/m²)**	**Heating Rate (K/min)**	**HRR$_{tig+1800s}$ (kW/m²)**
		5	25.25
	45.23	10	27.46
25	49.92	20	34.45
	52.99	50	32.52
		100	40.94
		5	71.63
	77.76	10	76.94
50	90.56	20	81.33
	77.89	50	78.33
		100	80.30
		5	80.67
	87.05	10	80.64
75	91.25	20	81.83
	93.28	50	80.66
		100	80.61

Figure 6 illustrates the heat release rate (HRR) profile obtained by the numerical modelling for the 25 mm Douglas fir exposed to 50 kW/m². The modelling provides consistent results when compared to actual test results, while being slightly underpredicting.

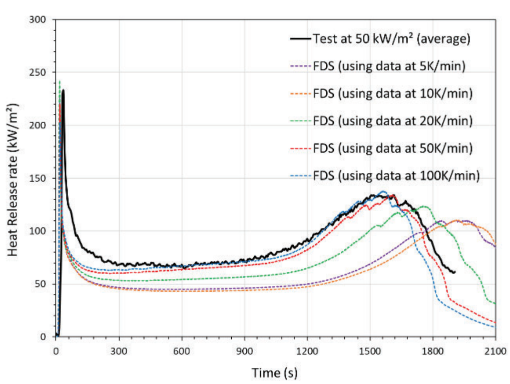

Figure 6: *Heat release rate predictions from FDS compared to test data – Douglas fir at 50 kW/m²*

For all 3 heat flux levels (i.e., 25, 50 and 75 kW/m²), TGA data from heating rates of 50 and 100 K/min provided the best profiles with respect to HRR and THR. These faster heating rates support the assumption where faster heating rates should be favoured in attempt to better predict the yield of volatiles (i.e., pyrolysis gazes). The mass loss was evaluated by calculating the consumed mass of reacting fuel (i.e., dry wood) and water vapor, and compared to actual tests. As shown in Figure 7, the mass losses obtained in FDS are in good agreement when compared to test data.

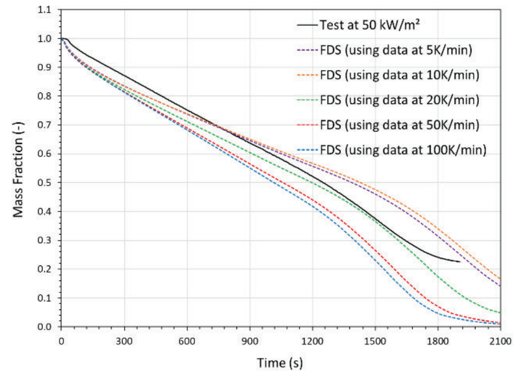

Figure 7: *Mass loss predictions from FDS compared to test data – Douglas fir at 50 kW/m²*

3.1.3 Wood crib packages

In attempt to develop fuel packages for use in advanced modelling in support of performance-based fire design, wood cribs were also modelled in FDS using the pyrolysis kinetic properties presented herein and detailed in [19]. Wood cribs are widely used in large-scale fire tests to simulate moveable fuel load.

HRR and THR were calculated using the analytical model presented in the SFPE Handbook of Fire Protection Engineering [22]. FDS predictions were compared to the calculations as well as test data by Bwalya *et al.* [23]. Figure 8 illustrates the total heat release (THR) for a large wood crib (8 layers). Interestingly, the mesh size used in FDS influenced the HRR and THR. A mesh size of 5 cm was found to provide the best predictions (vs. 10 cm). In addition to the recommendations about mesh resolution in the FDS User Guide [2], it is strongly suggested to conduct a sensitivity analysis when trying to use fuel packages in advanced modelling.

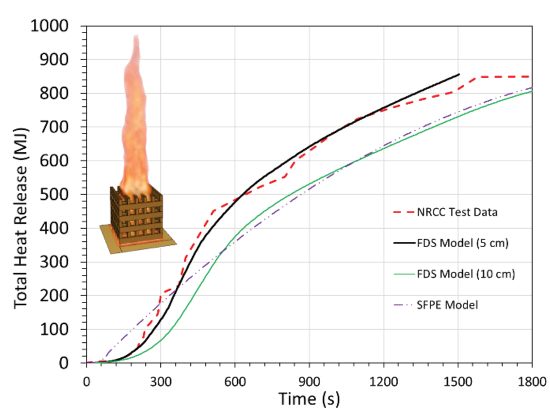

Figure 8: *Total heat release rate of a large wood crib*

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3.2 CHARRING AND CHAR DEPTH

During a series of demonstration fires in Canada, large-scale mass timber constructions were subjected to various fire scenarios (https://firetests.cwc.ca/). Among those, pilot-scale tests were conducted in Richmond (BC) in June 2021 to demonstrate the fire performance of mass timber construction during the construction phase, thus when not protected or encapsulated.

3.2.1 Mass timber 1

Mass timber 1 (MT1) was constructed using glulam and CLT elements. The cube was 3 m x 3 m x 3 m (10' x 10' x 10') and subjected to a fire developed by two (2) large wood cribs (8 layers of wood sticks). All timber elements, including the CLT back wall, were fully exposed to fire. A partition protected by gypsum board was installed to simulate a corner effect. Four (4) thermocouples were positioned in each quadrant underneath the ceiling.

Wood cribs and mass timber elements were modelled in FDS using the pyrolysis properties presented herein (Figure 9). In the modelling, in addition to monitoring the temperature underneath the CLT ceiling, devices were added to monitor the oxygen concentration and incident heat flux at each quadrant. Figure 10 shows the temperature profiles obtained from the test data and those from FDS. When combining the charring rate, calculated per Equation (3), to the reduction effect due to the oxygen concentration, a char depth of 13 mm is obtained. When not considering oxygen concentration, a char depth of 17 mm is obtained. A char depth varying between 10 and 15 mm was obtained from hand measurements after the demonstration fire (Figure 12).

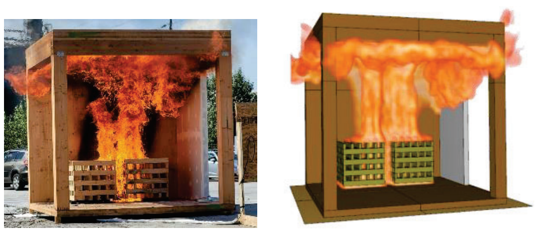


Figure 9: *MT1 – left is the actual test, right is FDS modelling*

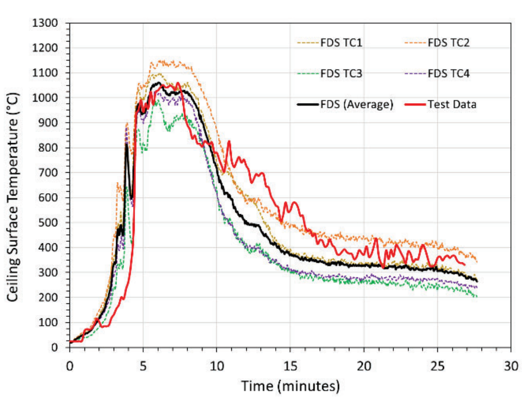


Figure 10: *Temperature at the MT1 ceiling – Test data compared to FDS predictions*

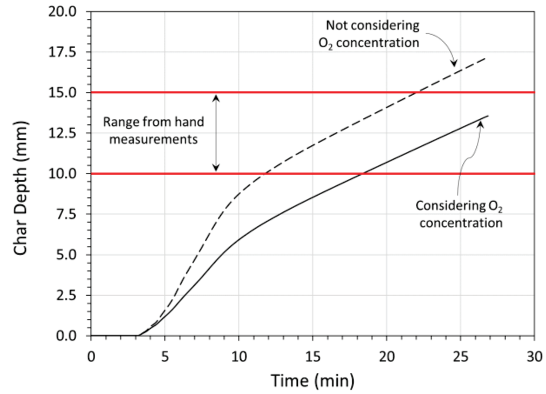


Figure 11: *Char depth of MT1 ceiling as a function of time compared to hand measurements*

Figure 12: *MT1 charred specimens cut for hand measurements*

While the difference between the charring predictions and hand measurements may not be large, it is noted that the fire was left to burn in the open for only 27 min and subjected to a low moveable fuel load (±190 MJ/m²). In an actual compartment scenario where a greater fuel load is present and oxygen may be limited, the difference between considering and neglecting the effect of oxygen concentration will further increase, which would ultimately impact the structural fire-resistance if the char depth is overly estimated.

3.3 STRUCTURAL FIRE RESISTANCE

Structural modelling of timber elements and connections exposed to a standard fire was performed using WoodST. A laminated veneer lumber (LVL) beam and a bolted connection were modelled to assess the time-displacement curve as well as the time to failure and failure mode [17]. The constitutive model was also used to assess the performance of a timber structure in fire, in support of a Technical Report ISO/TR 24679-5 [24] developed by FPInnovations for ISO TC92/SC4/WG12.

3.3.1 Beam

Structural composite lumber (SCL) beams were tested for fire-resistance by the American Wood Council. The beams were exposed to the standard fire on 3 sides. One of them was used to verify and validate WoodST – that is LVL beam #7 of 89 x 241 mm subjected to 50% of its allowable bending strength. It was assumed that SCL has the same thermal properties as timber (i.e., those of EN1995-1-2).

A static stress/displacement analysis was first performed. Under a total load of 16.8 kN, the predicted deformation at mid-span was 15.1 mm, compared to 14.5 mm in the actual test. Then, a transient thermal analysis was carried out to assess the temperature distribution and charring rate. The charring rates for the LVL model were 0.79 mm/min on its side and 0.94 mm/min at the bottom, respectively. The higher charring rate at the bottom is caused due to corner rounding affecting the bottom of the beam. These verifications suggest that the input properties were satisfactory.

Lastly, a coupled thermal-stress analysis was performed. The finite element analysis (FEA) showed that the deformation of LVL beam #7 increased with time and temperature, as shown in Figure 13. Elements of the LVL beam were first charred and then removed once the strain met the criterion. The model predicted a failure time of 28.5 mins, based on the mean properties obtained by converting the allowable stress design values from the LVL evaluation report. The test failure time was recorded as 33.7 min. The prediction would be expected to be closer to the actual test result if the actual material properties of the specimen were known.

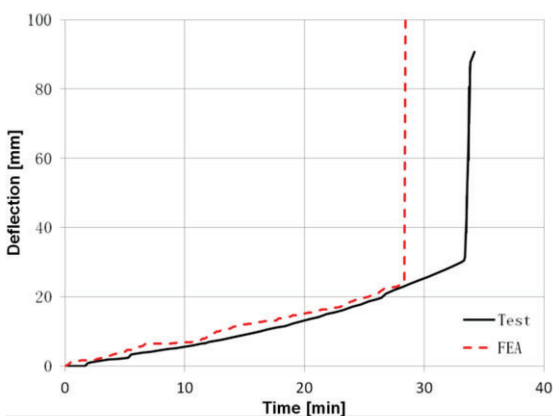
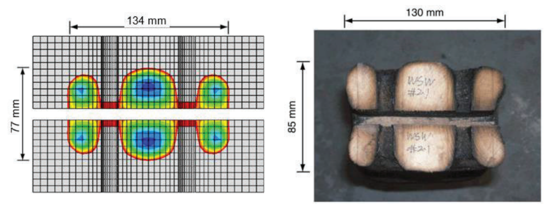


Figure 13: *Deflection as a function of time – LVL beam #7*

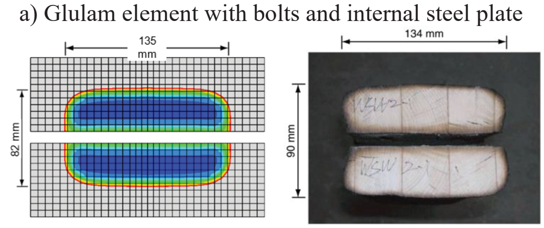
3.3.2 Bolted connection

A wood-steel-wood (WSW) bolted assembly was modelled in WoodST. Glue-laminated (glulam) timber elements of 130 x 190 mm were connected axially using 12.7 mm diameter bolts and a 9.5 mm internal steel plate. During the fire-resistance test, a constant axial tension load of 11.5 kN was applied, which represented 10% of the ultimate resistance at ambient conditions [25]. As with the LVL beam modelling, the mechanical properties were soft-converted to their mean values in accordance with CSA O86 standard procedures [26].

The static stress/displacement analysis predicted an ultimate capacity of 111.3 kN, which is within 5% of the test result of 115 kN. The transient heat transfer allowed to assess the temperature profiles of the glulam elements and metallic parts, as well as the charring rate of the glulam with great precision (Figure 14).



a) Glulam element with bolts and internal steel plate



b) Glulam element and internal steel plate

Figure 14: *Residual cross-section*

The coupled thermal-stress analysis showed that the deformation increased in time and temperature (Figure 15). The displacement increased shortly after 10 min, which was caused by the wood crushing in the bolt holes due to the effects of load and fire (Figure 16). The model predicted a failure time of 23.5 min, while it failed at 28.0 min in the test.

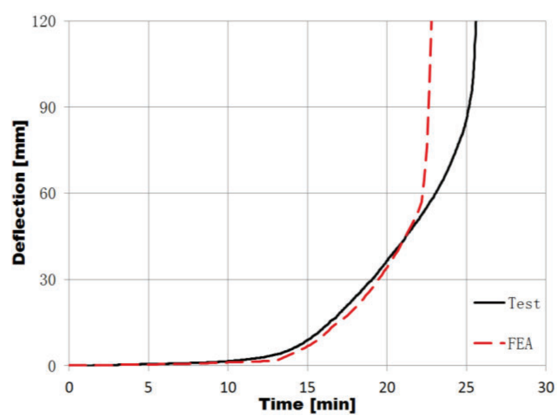


Figure 15: *Deflection as a function of time – Bolted connection*

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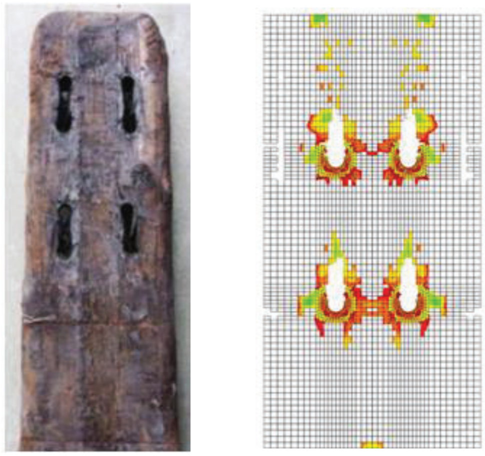

Figure 16: Bolt elongation in the glulam element

3.3.3 Performance of structures in fire

The results of design fire scenarios from FDS were used as imposed thermal fields in WoodST, namely the incident heat flux, surface temperature and oxygen concentration at the vicinity of timber elements' surface. This allowed to determine the residual cross-section of elements exposed to a design fire, along with their structural performance. This work was done during the development of a Technical Report (TR) on the performance of structures in fire under the aegis of ISO TC92 SC4 WG12 [24]. ISO/TR 24679-5 should be published during 2023.

The analysis was made for a glulam beam and column, both were partially exposed to fire. The load-displacement curves of both elements were obtained and compared to analytical calculations using CSA O86 [27]. The performance criteria were evaluated accordingly. The incident heat flux and oxygen concentration at the vicinity of the surfaces were explicitly considered for the charring rate. Figure 17 and Figure 18 show the deflection as a function of time (fire exposure) for a beam and column, respectively. Analytical calculations are also presented for comparison between simplified (calculations) and advanced (FEM) methods.

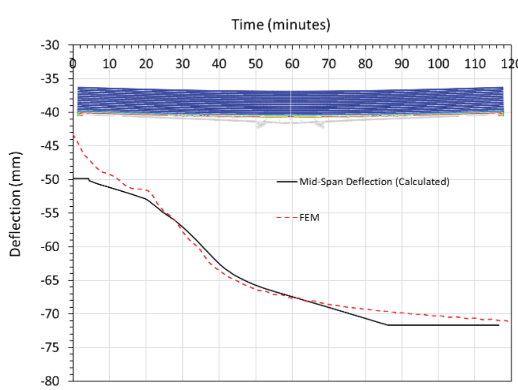

Figure 17: Assessment of mid-span deflection of beam B1

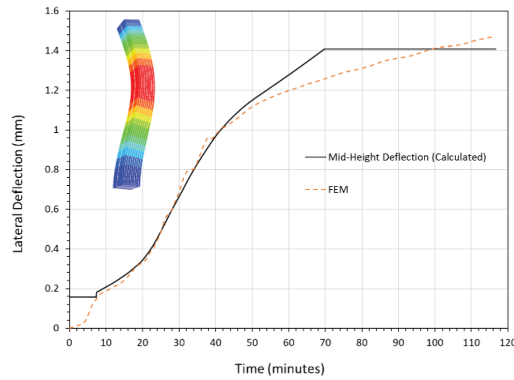

Figure 18: Assessment of lateral deflection of column C2

4 DEVELOPMENT OF DATABASE

While all models should be verified and validated appropriately, the quality and accuracy of their results remain at the discretion and knowledge of the users. FDS and models using the FEM require a large number of data entry, including material combustion behaviour and thermo-mechanical properties. Timber is an anisotropic material and therefore its properties vary as a function of the grain orientation between the longitudinal, radial and tangential directions, and should be explicitly considered.

Given the complexity of advanced modelling and the variety of input parameters and properties, the creation of a centralized database becomes relevant. An initiative has been launched at FPInnovations to generate a database of commonly-used products such as those of interior linings and structural elements, with the intent of making it available to the design community. Research organizations members of WoodRise are involved in this initiative, namely FCBA (France) and RISE (Sweden). The material database will be made available through various publications as well as a web platform (host of the platform is yet to be determined).

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