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TOWARDS AN IMPROVED METHOD FOR PREDICTING THE CONTRIBUTION TO FIRE GROWTH AND STABILITY OF STRUCTURAL MASS TIMBER IN NATURAL FIRES

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ABSTRACT: The use of mass timber in construction is becoming increasingly prevalent, particularly in the context of mid- and high-rise buildings. This is due to the need to decarbonise the building sector and recent amendments to public policies that support the development of bio-sourced materials. However, these significant environmental and comfort benefits are often precluded by restrictive prescriptive provisions in local or national regulations which typically require structural timber to be completely encapsulated by fire protection components. In addressing this challenge, an enhanced methodology for quantifying the impact of exposed mass timber on fire dynamics, including the charring rate and total char depth, has been developed. This approach builds upon existing two-zone fire dynamics models, which facilitate fast and accessible calculations. The effectiveness of the method, verified against 53 compartment fire experiments totalling 85 char depth measurements are discussed in addition to future work to improve the accuracy of the predictive calculation in a wide range of timber construction typologies and configurations. The method could then be utilised to evaluate the absence of fire spread (both internal and external) and the load-bearing capacity of exposed timber for the requisite minimum specified period under natural fire conditions, as part of a performance-based design approach.

KEYWORDS: Performance-based design, Exposed mass timber, Fire safety, Structural stability in fire, Natural fires, Advanced modelling.

1. INTRODUCTION

The use of mass timber in construction is gaining popularity, particularly in the context of mid- and high-rise buildings. This trend can be attributed to the imperative to reduce carbon emissions in the building sector, compounded by recent policy shifts that favour the development of bio-sourced materials. However, these substantial environmental and comfort benefits are frequently rendered unattainable due to restrictive local or national fire regulations that mandate the protection of the timber, also called encapsulation. Indeed, the imposition of such stringent fire regulations, which require timber structures to be completely encapsulated, leads to a triple penalty on builders: higher carbon costs due to fire protection materials, higher works costs per square metre, and fewer opportunities to increase real-estate property value in the absence of visible timber. In order to circumvent the "in fact ban" on timber structures resulting from the implementation of conservative prescriptive provisions, there is a need to formulate simple approach that would enable the proposal of novel design limits on exposed mass timber in building codes. This would obviate the necessity for costly, large-scale fire compartment tests. However, such tests would be useful in setting such an approach; nevertheless, they are too costly in the case of a performance-based approach for each new project.

The estimation of the increase in heat release rate due to the contribution of structural timber elements, the charring rate and the char depth are pivotal parameters for performance-based fire design. As discussed in Girompaire & Dagenais [1] and Brandon [2], several methodologies have been proposed over the last decade to take into account the contribution of timber to fire kinematics, with different levels of complexity. The objective of this study is to develop a numerical approach based on two-zone models allowing for fast and accessible calculations that could accurately estimate, for a given

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proportion of unprotected structural timber, incident heat flux and hot layer temperature in the mass timber compartment as well as the resulting char depths. This will allow for the assessment of whether fire safety objectives (e.g., no spread of fire and structural stability) could be met for a given configuration as presented in other paper of WCTE 2025 [27].

The present paper presents the procedure, encompassing an evaluation of four distinct methodologies for timber contribution. It also provides preliminary conclusions and proposed future work to enhance the overall accuracy of the method.

2. PROJECT DESCRIPTION

The proposed method is estimated through an iterative process similar to that proposed by [2]:

1) The process has to be initiated by calculating the HRR (Heat Release Rate) of the movable fuel load, i.e. furniture and/or wood crib in the compartment, using its calorific loads.
2) Then, the temporal evolution of temperature, hot layer height, and oxygen concentration are calculated taking into account the HRR and the geometrical properties of the compartment and ventilation conditions using a two-zone model.
3) The charring rate and char depth of exposed mass timber elements for each time steps is then calculated from the values obtained in Step 2.
4) The timber contribution to the heat release rate is estimated from the charring rate and char depth.
5) The HRR generated from the exposed timber is added to the HRR of Step 1 to determine a new increased HRR.
6) An iterative process is then initiated, whereby Steps 2 to 5 are repeated with the newly increased HRR of the previous iteration (n-1). This process is repeated until reaching convergence criteria (set as the difference between the charring depths of iterations n and n-1 becomes negligible, with a threshold of less than 0.5 mm for the present study).

2.1 EXPERIMENTS

From the review presented in [3] and from recent experiments with protected, partially or fully exposed timber elements, a list of 53 compartments listed in *Table 1* have been used to evaluate the accuracy of the predictive methods.

These experiments represent a total of 85 measurements of char depth on walls, ceilings, floors, beams, or columns. They are representative of the state of the art worldwide and cover a wide range of real situations in terms of surface area, fire load and openings. Columns are coloured from lower value (green) to higher (red) except for opening factors where it is inverted (from higher to lower) as lower values are more restrictive regarding char depth (under ventilated experiments)

Table 1: List of experiments used for benchmarking

Nomenclature		Experimental Data (Input)					
		Fire	*Area*			*openings (vents)*	
Aut	Ref	Fd[(a)]	Af	At	Aexp/At	Av	O[(b)]
[""]	[""]	[MJ/m²]	[m²]	[m²]	%	[m²]	[m1/²]
Autor	Reference	Fire density	Floor Area	Total enclosure area	Exposed timber	Opening Area	Opening factor
Carlton University McGregor 2013 [4]	McGregor 1	*482*	15.35	69.3	0%	2.14	0.044
	McGregor 2	533	15.35	69.1	0%	2.14	0.044
	McGregor 3	*182*	15.75	71.5	75%	2.14	0.042
	McGregor 4	553	15.35	69.3	0%	2.14	0.044
	McGregor 5	529	15.75	71.5	75%	2.14	0.042
Carlton University Medina 2014 [5]	Medina 1	532	15.55	70.03	28%	2.14	0.043
	Medina 2	532	15.52	69.98	31%	2.14	0.043
	Medina 3	532	15.64	71.14	16%	2.14	0.042
NRCC & NIST Su et al. 2018 [6]	NRCC & NIST 1	549	41.86	157.7	0%	3.63	0.032
	NRCC & NIST 2	548	41.86	157.7	0%	7.23	0.065
	NRCC & NIST 3	556	41.86	157.7	16%	7.23	0.065
	NRCC & NIST 4	548	41.86	157.7	27%	3.63	0.032
	NRCC & NIST 5	556	41.86	157.7	16%	3.63	0.032
	NRCC & NIST 6	550	41.86	157.7	42%	3.63	0.032
NRCC Su et al. 2021 [7]	NRCC Room 1	550	10.48	57.7	0%	1.52	0.037
	NRCC Room 2		10.82	59.1	23%	1.52	0.036
	NRCC Room 3		10.70	58.7	23%	1.52	0.037
	NRCC Room 4		10.70	59.1	29%	1.52	0.036
	NRCC Room 5		10.82	59.6	40%	1.52	0.036
Su&Muradori[8]	NRCC Elevator 1	790	23.69	100.1	0%	4.70	0.064
Edinburgh University Hadden et al. 2017 [9]	Edimb 1	132	7.26	44.4	34%	1.40	0.043
	Edimb 2		7.26	44.4	34%	1.40	0.043
	Edimb 3		7.33	44.4	33%	1.40	0.043
	Edimb 4		7.33	44.4	33%	1.40	0.043
	Edimb 5		7.26	44.1	50%	1.40	0.043
Emberley et al.[10]	Emb 1	100	11.98	60.3	35%	1.79	0.043
USDA Zelinka et al. 2018 [11]	USDA 1	570	82.38	262.9	0%	17.86	0.106
	USDA 2		82.38	262.9	3%	17.86	0.106
	USDA 3		82.96	264.4	12%	17.86	0.106
	USDA 4		82.96	264.4	34%	17.86	0.106
	USDA 5		82.96	264.4	34%	17.86	0.106
CERIB Epernon Fire Test 2019 [12]	Epernon 1	891	24.00	98.4	21%	10.00	0.144
	Epernon 2		24.00	98.4	21%	4.50	0.050
	Epernon 3		24.00	98.4	21%	2.20	0.032
NRCC Su et al. 2023 [13]	NRCC LS 1	613	22.40	99.9	0%	4.84	0.072
	NRCC LS 2		22.40	99.9	30%	4.84	0.072
	NRCC LS 3	15	22.40	99.9	55%	4.84	0.072
	NRCC LS 4	224	51.1	179.4	69%	14.08	0.116
	NRCC LS 5	362	201.3	687.3	42%	52.00	0.107
RISE Brandon et al. 2021 [14]	RISE 1	560	47.07	169.1	31%	8.00	0.063
	RISE 2				53%		
	RISE 3				59%		
	RISE 4				48%	31.17	0.267
	RISE 5				59%	8.00	0.063
ARUP/CERIB Kostovinos et al. 2023 [16,17]	CodeRed 1	374	351.95	980.1	37%	56.63	0.070
	CodeRed 2	377	351.95	980.1	37%	28.36	0.039
RISE Boe et al. [18,19]	FRIC 1	353	94.00	308.0	29%	37.40	0.180
	FRIC 2	353	94.00	308.0	44%	37.40	0.180
CODIFAB AdivBois [20]	AdivBois 0	350	28.58	112.81	0%	5.40	0.059
	AdivBois 1	968	28.58	112.81	13%	5.40	0.059
	AdivBois 2	809	28.58	113.66	25%	12.15	0.131
	AdivBois 3	795	28.58	113.66	22%	12.15	0.131
	AdivBois 4	822	28.58	113.66	25%	12.15	0.131

a) Fuel type cribs and/or furniture's except for experiments McGregor 1 and 3 where it is propane burner. NRCC LS 3 is a construction fire scenario with garbage bin fire source

b) The opening factor is defined as $O = A_v\sqrt{H_v}/A_t$ where $A_v = \sum A_i$ is the sum of all openings areas (Ai, m2), $H_v = (\sum H_i\ A_i)/A_v$ is the sum of each opening height (Hi, m) multiply by their area divided by the total opening area, and At is the total enclosing area (including openings)

2.2 METHODS OF TIMBER CONTRIBUTION IMPLEMENTED

All experiments from *Table 1* have been calculated using four methods of timber contribution:

1) The "original" method as described by Girompaire & Dagenais [1] where timber contribution is set with an iterative process from hot layers temperature and oxygen concentration. Those two values are calculated for each iteration via a two-zone model. All parameters and formula

used by the algorithm (including reduction factor for ceiling contribution) are described in [1].

2) "Flux" method, is the same method as 1) except for the calculation of the incident heat flux $\dot{q}''$ which is estimated using Equation (13) in [1]:
$$\dot{q}'' = \Phi \varepsilon \sigma T_f^4. \quad (1)$$
where, Φ is the view factor, ε is the emissivity taken as 0.8 as defined in the EN 1995-1-2 [26], and σ is the Stefan-Boltzmann constant (σ =5.67 10^{-11} kW/m^{2}K^4) and T_f the temperature of gas in K. This calculation is replaced by the value of the total incident heat flux received for each part of timber (lower and upper wall, ceiling and floor) given by the two-zone model calculation. This allows to take into account the convective and the radiative heat fluxes from the fire and other parts of the compartments.

3) "MLR*" method with timber contribution law via Mean normalized Mass Loss Rate as a function of the char front position as define by Lardet & Coimbra in [21]

4) The "EC5" method is a cumulative temperature charring model where the design charring depth of unprotected timber members is calculated using the compartment temperature as follows, as proposed by Werther [22]:
$$d_{char,t} = \left(\frac{\int_0^t (T^2)dt}{1{,}35\times10^5}\right)^{\frac{1}{1{,}6}} \quad (2)$$
where $d_{char,t}$ is the charring depth in mm and *T(t)* is the upper layer temperature in K and *dt* is the time differential in minutes.
This model is currently under study by CEN/TC 250/SC 5 "Eurocode 5: Design of timber structures" to be implemented in a future Annex "Design of timber structures exposed to physically based design fires" of EC5-1-2 and used (2) presented above.

The two-zone model B-RISK [23] was used for the calculation of wood contributions for each iteration of the process.

As an enhancement to the original method [1], the contribution of protected timber is taken into account via a fall-off time value set in the calculation for each component (wall, ceiling, beam or column) with this value being taken from the relevant experiment reports. Subsequent to this failure time, the algorithm calculates the incident heat flux received by this newly exposed timber and increases the timber contribution to the HRR accordingly. Additionally, a majoration factor k_n has been introduced for beams and columns. The char depth (and corresponding contribution to the HRR) for these linear members is increased by the conversion factor k_n, according to Eurocode 5 [26], to account for the effects of corner rounding's and the presence of cracks and fissures on the surface (k_n = 1.08 for rectangular and 1.3 for circular cross-sections for timber components other than those made of softwood or beech).

In the case of walls, a calculation of cumulative char at several heights (approximately every centimetre) has been introduced. This calculation involves the summation of the char thickness at each time step, which is dependent on the height of the upper hot layer at that particular time step. These values enable the calculation of the mean, maximum and minimum char depth for the wall, thereby providing a precise profile of char depth along the height of the wall. This profile can then be compared to the measurements.

3. RESULTS

3.1 METHODS OF TIMBER CONTRIBUTION

All tests enumerated in *Table 1* have been calculated with each of the four methods described in Section 2.2. The results of each method have been summarised in the following qualitative discussion.

1) For the original method, introducing the fall-off time of the gypsum protection and modified charring rate of the beams and columns, all results are not directly comparable to those given in [1]. Furthermore, the results presented for NRCC and Medina experiments in [1] are not at the same time of fire development. For those tests in [1], the char depth corresponds to the position of the 300℃ isotherm measured during the experiment before heat delamination of the first CLT lamella (and gypsum fall-off time). Therefore, the predicted char depth is calculated at a given (by experiment reports) time where the 300℃ isotherm has reached a given depth in [1]. While the char depth in the present paper is generally calculated at the end of duration of the experiment. Nevertheless, despite the difference between the two-zone model used, the evaluation of the char depth at the same time of the fire development, results are in good accordance with those discussed by Girompaire & Dagenais [1].

2) The "Flux" method yielded more conservative values of char depth. As illustrated in *Figure 1* for a compartment test involving only exposed timber on ceiling, it can be observed that the final HRR was almost identical. This corroborating the hypothesis in [1] that "external heat flux is estimated... considering only the radiation emitted from the hot gases, as the proportion of the convective heat flux would be small in comparison". Nevertheless, even in this case, the slight increase in heat flux compared with (1) has a measurable impact on char depth. This difference is more pronounced in the vertical part and lower layer (with contribution from flame radiation). The cumulative effect of increasing the HRR, due to greater contributions which in turn increases the heat flux in subsequent iterations, leads to those more conservative values of char depth (approximately 15% to 20% on average).

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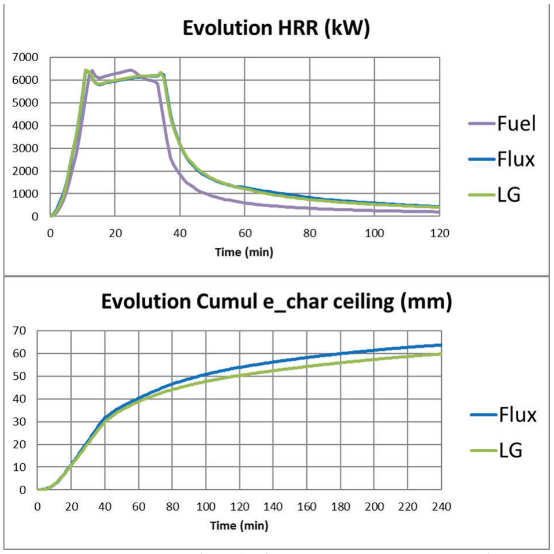

Figure 1: Comparison of results for EPERNON 2 experiment between original method 1 "LG" and method 2 "Flux"

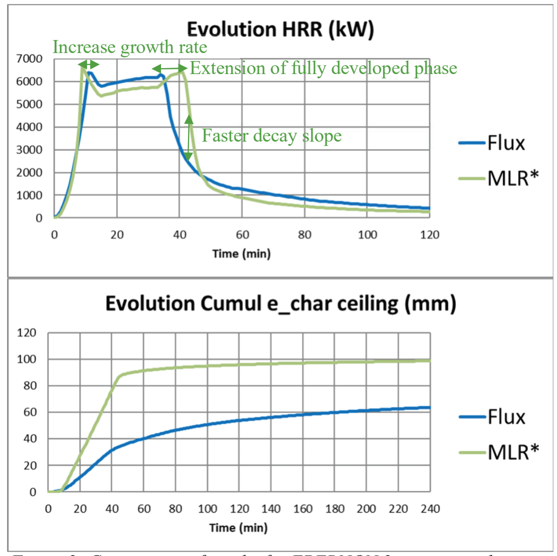

Figure 2: Comparison of results for EPERNON 2 experiment between method 2 "Flux" and method 3 "MLR"*

This leads the current model to be more from safety-side but less accurate compared with the measured values. It can also be noticed that experiments with opening factor greater than $0.12m^{1/2}$ (as RISE 4, FRIC 1 and 2, ADIVBOIS 2 to 4) the original and the flux methods underestimate the char depth. In those cases, the gas temperatures and heat flux are underestimated for the first iteration with the movable fuel load contribution only, leading to an underestimation of the timber contribution.

3) The "MLR*" method has been found to produce overly conservative values of char depth in comparison to the initial implementation of methods 1 and 2. This is likely attributable to the utilisation of the MLR* as the law proposed in [21], with a two-standard-deviation margin, and, in the absence of any reduction factors used in the original and "Flux" methods for the ceiling charring rate or effect of the oxygen concentration on the charring rate. However, it has been observed that these methods result in an increase of the duration of the fully developed phase of the fire and a reduction of the timber contribution during the decay phase. Consequently, the charring rate is higher during growth and lower during the decay phase in comparison to the previous method (see *Figure 2*). The observed behaviours can be seen in the results of several experiments and in the thermomechanical analysis of the evolution of isotherm 300°C. The application of the gas temperature curve indicates that further exploration of this method is warranted.

4) For the "EC5" method, despite the accelerated fire growth (and the earlier one, which is likely due to the lack of a low threshold for temperature in (2)), the initial implementation of the method provides more accurate (and still conservative) values for wall components and more conservative (and less accurate) values for the remaining components. For the same reasons as the MLR* method, it warrants further exploration.

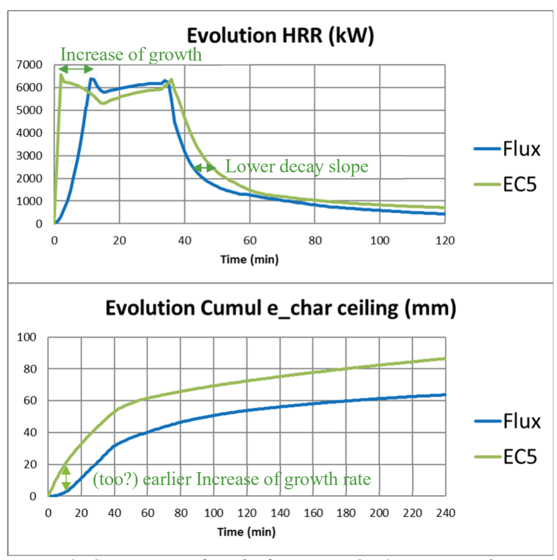

Figure 3: Comparison of results for EPERNON 2 experiment between method 2 "Flux" and method 4 "EC5"

For the following sections, only results for method 2 ("Flux" i.e. timber contribution from total incident flux) are then discussed.

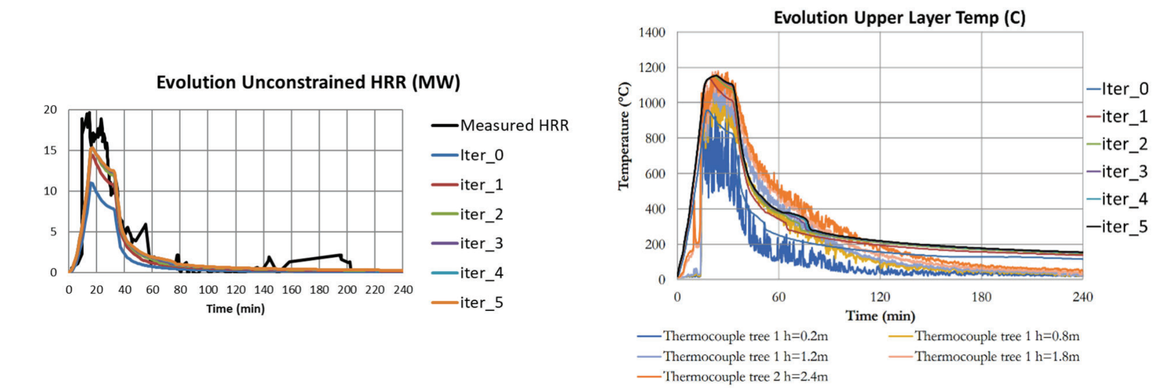

Figure 4: Experiment RISE test 1. Comparison (superposition) of calculated (smooth curves) and measured (noisy curves): Unconstrained (i.e. total, including vent fire) HRR (left) upper layer temperature and measured temperature at different level (right)

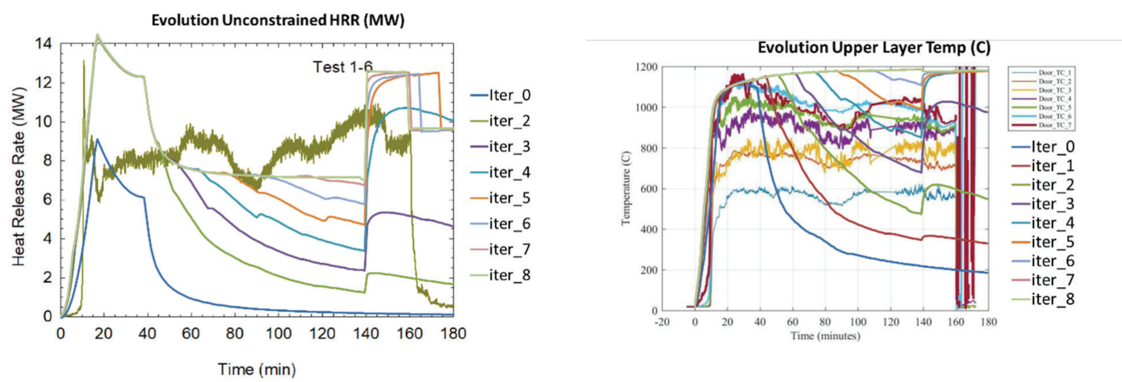

Figure 5: Experiment NRCC&NIST test 6. Comparison (superposition) of calculated (smooth curves) and measured (noisy curves): Unconstrained (i.e. total, including vent fire) HRR (left) upper layer temperature and measured temperature at different level (right)

3.2 FIRE DEVELOPMENT AND TIMBER CONTRIBUTION

A comparison of the predictions of the HRR and temperature of the upper layer, with the experimental data for the "Flux" method are presented in *Figure 4**Erreur ! Source du renvoi introuvable.*** for RISE test 1 and in *Figure 5**Erreur ! Source du renvoi introuvable.Erreur ! Source du renvoi introuvable.*** for NRCC&NIST Test 6. For the experiment RISE 1, self-extinction of structural timber was reached, whereas for the NRCC & NIST 1-6 test as reported in [4], the fire continued to grow after the fall-off of the gypsum boards from protected walls at 125 min and has been extinguished at 160 min. Therefore, the fall-off time of the gypsum board has been set at 125 min in the model for the predictions of test 1-6 from NRCC & NIST (see 2.2). It results in a re-growth of the predicted HRR and upper layer temperature as shown in the *Figure 5*. Both calculations show a good prediction when compared to the experiment measurements regarding: the fire dynamics, the timber contribution to the fire and the temperatures reached in the compartment.

3.3 SELF-EXTINCTION

Some experiments of *Table 1* have been deliberately excluded from the comparison for self-extinction and char depth (in the following chapter). These experiments include those:

- where there is no exposed timber or charring;
- where the CLT delamination is pronounced.

Therefore, the comparison for self-extinction and char depth is made under 44 experiments.

In 15 of the experiments given in *Table 1*, no self-extinction of the timber was observed.

With the exception of McGregor 1, all simulations predicted the absence of self-extinction. For McGregor 1 strong delamination occurred at 105 and 115 min. It is noteworthy that the present models do not take into account the effect of heat delamination of CLT. However, this is no longer expected to occur if the current specifications regarding risk of delamination in North America or Europe are followed. Thus, this particular case does not alter the good prediction of self-extinction.

Of the 29 other experiments where self-extinction occurred, the models also predicted self-extinction in 26

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of them. Furthermore, two of these could predict self-extinction with additional iterations (limited to 20 in our procedure) due to the small increase in carbonisation observed in the final iterations (inferior to 1.5 mm, but not 0.5 mm taken as convergence criteria).

This demonstrates that the method is suitable (conservatively) in predicting the self-extinction phenomenon.

3.4 CHAR DEPTH

The predicted mean char depth was examined for 74 values of mean char depth measurement in 44 experiments, of which 69 exhibited a mean char depth equal to or greater than the measured value. The sole experiments in which the predictions were found to be lower than the test data were RISE 4 (wall, ceiling, beam and column) and McGregor 3 (wall):

- It is noteworthy that RISE 4 is a particular experiment with an extremely high opening factor of O=0.267 $m^{1/2}$, representing more a canopy (open on three sides) than a unit inside a building, which is a scenario beyond the applicability of a two-zone model. This underestimation was also observed during the same experiment and discussed in [2].
- For the McGregor 3 experiment, the predicted mean value of char depth for the walls part was 24mm, which is comparable to the measured value of 30mm. It is noteworthy that, for McGregor experiments, the "measured value" was conservatively derived from the visual interpretation of a char depth graph using a four-colour scale ranging presented in the experiment report. In retrospect, the preponderance of the range of 20–30 mm on this graph suggests that the predicted value of 24 mm is consistent.

Consequently, it can be concluded that, with regard to self-extinction, the method predicts conversely the char depth for all representative compartments as illustrated on figures below.

The results pertaining to the "EC5" method have been incorporated into *Figure 8*. However, the results for the "MLR*" method have not been included, as they exhibit greater dispersion (as discussed in Section 3.1)

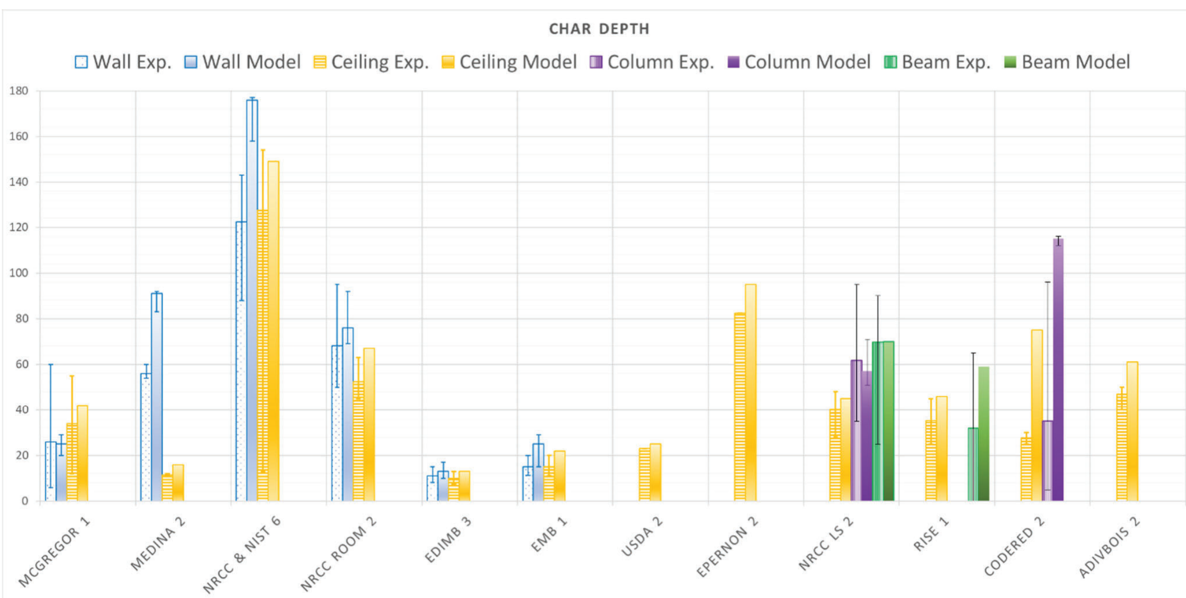

Figure 6: Comparison between measured and predicted values for one of each experiment highlighting a generally good prediction for different configuration and a large range of char depth

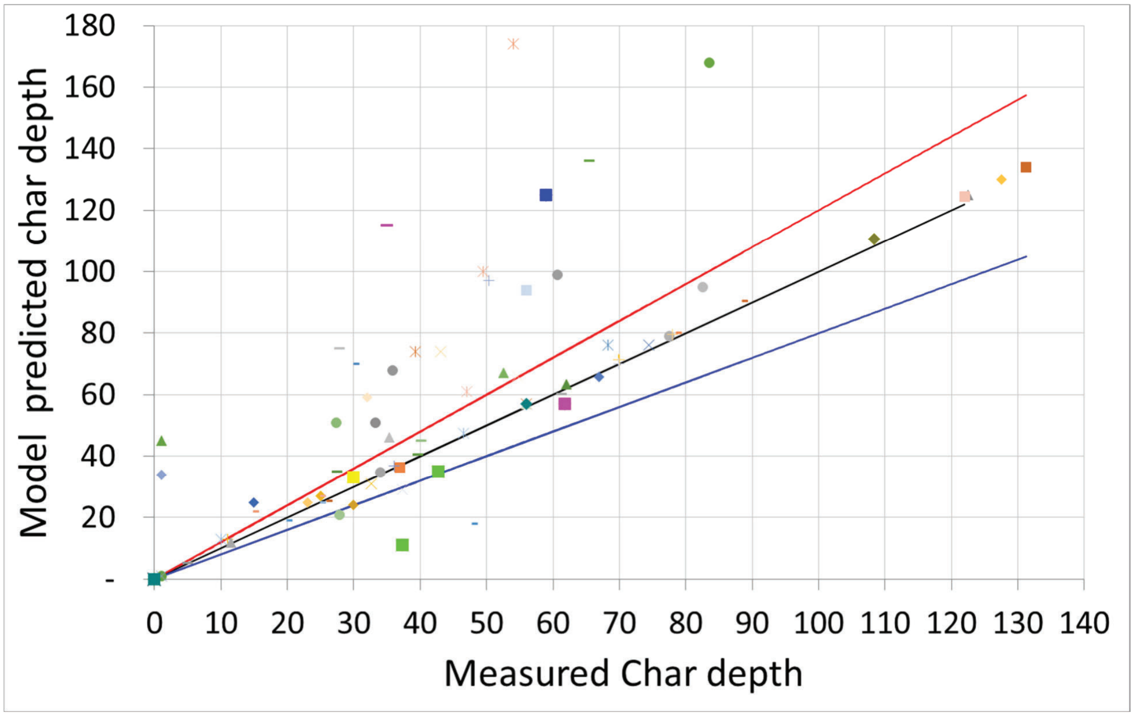

Figure 7: char depth results for "Flux" method for the 74 values discussed in 3.4. Nota: underestimated values are from experiment RISE 4 and two overestimated values for beam and column of NRCC Room 4 (more than 250mm) are out the graph.

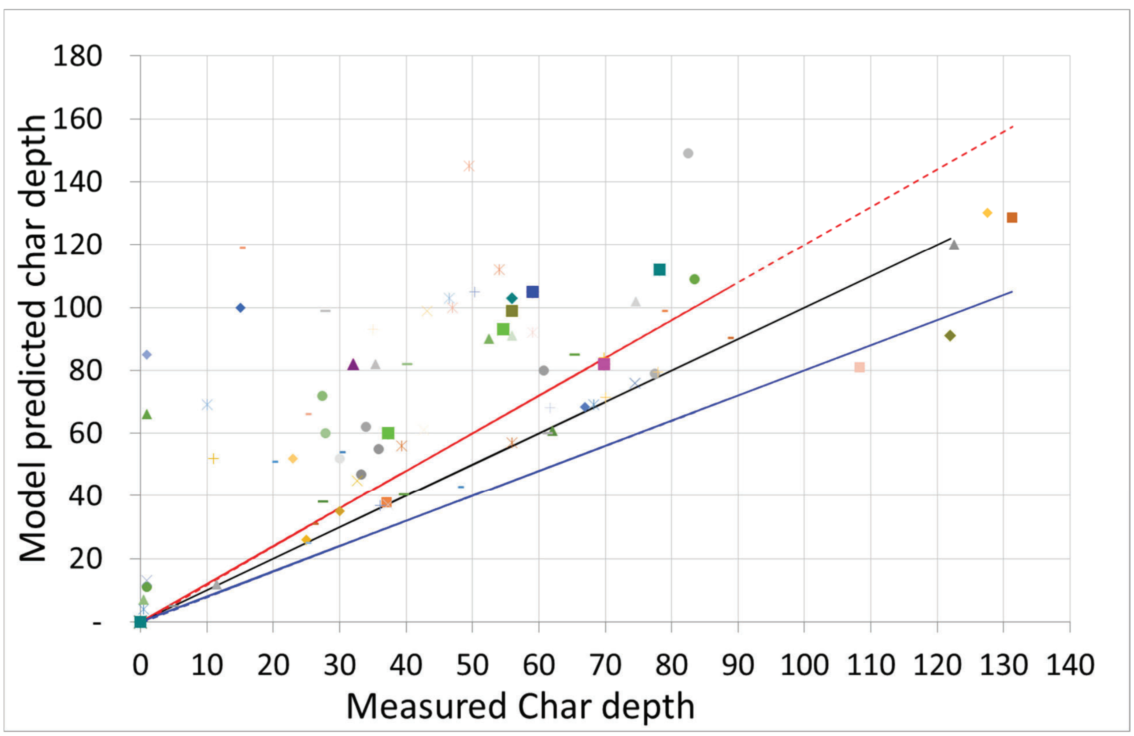

Figure 8: char depth results for "EC5" method

Note: on *Figure 7* and *char depth results for "EC5" methodFigure **8*** as predicted char depth can become high in case of no self-extinction, thereby affecting the scale of the y-axis. In order to address this issue, the decision has been taken to position the series that predicted no self-extinction (see 3.3) in close proximity to the 1/1 axis (as successful values).

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4. FIRST CONCLUSIONS AND FUTURE WORK

The objective of this study was to develop a model capable to accurately estimate the heat release rate and char depth of exposed timber elements during mass timber compartment fires. The model was adapted from the method described by Girompaire & Dagenais in [1] (see 2.2), and the present study evaluates the implementation of 4 different timber contribution methods. To assess the model's accuracy, its predictions were compared to over 50 experimental compartment fires with and without exposed timber surfaces. This enhanced version corroborates on larger range of configuration the conclusions and perspectives discussed in [1]:

- The qualitative and quantitative comparisons of the HRR and temperature predictions demonstrate that the model effectively captures the general dynamic of the experimental fires (as discussed in 3.1 and 3.2).
- Furthermore, the self-extinction of the structural timber and char depth are well predicted when compared to the experimental data, while being conservative (as discussed in 3.3 and 3.4).
- As outlined briefly in 3.1 this study has also revealed the potential for enhanced robustness and accuracy of predictions of time dependant temperatures and char depth through the implementation of alternative methods, such as "MLR*" or "EC5", or a combination of these methods.

As shown in *Figure* ***6*** and *Figure* ***7***, char depth can attain overly conservative values for a number of configurations. Further research is currently underway to enhance the robustness and accuracy. This involves:

- Substituting the B-RISK model with the CFAST model and conducting a thorough analysis and discussion of any potential discrepancies in the final results;
- Conduct a sensitive study on the primary parameters of the model, including timber combustion parameters, the thermal properties of the enclosure, movable fuel load and its growth speed, HRRPUA (Heat Release Rate Per Unit Area, kW/m²), location and size, in order to evaluate the range of errors of the method and/or explain some dispersions between predicted and measured values;
- The methods 2), 3) and 4) described in 3.1 will be set with homogeneous parameters and hypotheses (such as the [O_2] reduction factors) and discussed regarding their accuracy.

The benchmarking of the model predictions highlighted limitations and improvements that need to be made (some of them could be fixed by the ongoing work described above):

1) Set a validity domain for the opening factors covered by the method.
   This domain is to be delineated through meticulous research, aiming to strike a balance between the breadth of the validity domain, which encompasses the prediction, and the accuracy of this prediction. For instance, conservative values for certain factors (such as [O_2] reduction, ceiling reduction, timber heat of combustion, etc.) could potentially enhance the prediction for a specific configuration with a high opening factor, but this will increase the predicted charring depth for all configurations and reduce the accuracy of the method. This approach is not desirable if it covers only a very low probability of occurrence in buildings constructed today.
2) Replace the manual setting of the fall-off time of protection by predicting the evolution temperature at the interface between the protection and the wood given by the two-zone model. This approach assumes that the calculations based on fixed thermal properties of materials (whereas thermal properties of the gypsum are temperature-dependent), provides a correct variation of this interface temperature as a function of time. This assumption will be examined by comparing experimental data to values predicted using a thermal-dependent method, as proposed by Janssens [28].

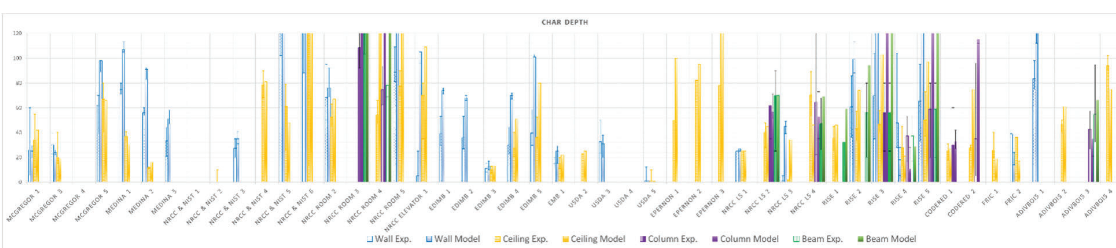

Figure 9: Frieze of results: Comparison of predicted and measured char depth for 48 of the experiments

CONFLICT OF INTERESTS

The authors declare that they have no conflicting interests concerning the publication of this article.

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