Influence of density on bending resistance of wooden beams under fire situation and proposal of a new equation

https://doi.org/10.56238/sevened2024.026-028

Pedro Verona Perini[1] and Fabrício Longhi Bolina[2]

ABSTRACT

Targeting to identify the correlation between density, charring rate and bending resistance, the different methods presented by Eurocode 5 to verify wooden beams under fire exposure were compared, with the use of the software Abaqus/CAE to obtain the isotherms of the beams in the advanced calculation method, and then proposed a new equation to obtain their charring depth according to time of fire exposure. It was confirmed that the density of the wood is inverse to its charring rate and its bending resistance loss, and the advanced calculation method presents less conservative results than the simplified methods. The equation that was proposed in this study had slightly more conservative results than the advanced calculation, proving to be suitable in relation to time spent in calculation, computational effort and economy.

Keywords: Density, Charring, Fire, Eurocode 5, Advanced calculation.

[1] Polytechnic School, University of Vale do Rio dos Sinos - UNISINOS, São Leopoldo, Brazil.
[2] Department of Structures and Civil Construction (DECC), Federal University of Santa Maria - UFSM, Santa Maria, Brazil.

INTRODUCTION

Important historic buildings with timber structure were damaged by fire this century, among which can be highlighted the roof of Notre-Dame Cathedral in Paris, one of the most iconic cathedrals in the world, and the National Museum in Rio de Janeiro, America Latina's largest natural-history museum. Massive destructions in cultural and historical fields are caused by events like these, enhancing the importance of granting fire-resistance to the structures of buildings. Furthermore, they raise the skepticism of constructors and designers when it comes to timber structures under fire situation [1].

On the other hand, a growth in utilization of timber as the main material of building structures is noticed currently [2], being strongly related to its industrialization, which, along with its renewable and carbon-stocking characteristics, makes this material a good alternative to create sustainable construction systems, easing to reach the Sustainable Development Goals of the UN [3]. The raise in area of planted forests – optimizing cost, quality, and durability – also brings interest to construction [4], making the fire subject extremely important to be addressed.

Instead of burning directly, wood is affected by the effect of pyrolysis, in which high temperatures (around 300 ºC) generated by the fire decompose the material into char – producing then combustion [5]. The char forms a layer of protection when it comes to temperature raise in the interior of the timber section, as its thermal conductivity is lower than the found in ambient-condition wood [5]. Due to the variability of its natural composition, the char depth is plausible to be slightly different in each section (including sections of the same specimen, mainly in sawn or solid timber) [5].

Being the importance of understanding the behavior of timber structures under fire considered, it is reasonable to find alternatives to experimental tests, which tend to have a high cost attached. A convenient option is the Finite Element Method (FEM), that presents realistic results in cheaper yet efficient operations [6]. Eurocode 5 (EC5) indicates values to be used in what it calls advanced calculation methods [7] and different authors [6; 8] attested these numbers by running numerical analysis and comparing their results to experimental ones, even though it is known that experts may disagree with the accuracy of the values suggested by it [6].

THI et al (2016) compared experimental tests with numerical analysis based on five different approaches. One numerical analysis was built on thermal characteristics of heated wood given by EC5 using the ISO 834 curve of temperature vs time, while the others used a regression curve with four different sets of thermal properties described by different sources: EC5, Janssens, Fredlund, and Knudson. The author affirms that, due to the significant dispersal of results in the experimental tests, the five methods can be accepted [6]. However, it is essential to be stated that both EC5 analysis were similar to each other, being noticeably different from the analysis based on the other authors – which were also alike among themselves.

Although EC5 presents the advanced calculation methods to find accurate results, it also suggests simplified procedures – reduced cross-section method and reduced properties method – with constant and pre-defined charring rates as an alternative to find the residual cross-section of a timber member, giving different steps to reach its final resistance [7]. Simplified methods tend to present less accurate results when compared to FEM ones, but they are a faster way to find them, being reasonable to simple cases. The simplified procedures given by EC5 do not consider the density of the wood directly, even though experimental studies [9; 10] demonstrated it to be a characteristic that impacts the charring rate of timber.

NJANKOUO et al. [11] contrasted experimental results of the charring rate of different wood species with the recommended by the simplified values of the previous version of EC5. When comparing to the current version (0,70 mm/min for softwoods and 0,55 mm/min for hardwoods), their results showed a reasonable safety – 3 out of 20 specimens presented a higher charring rate in experimental tests, being one of a softwood species (0,71 mm/min) and two of hardwood species (0,58 and 0,59 mm/min). The tests also confirmed lower charring rates for denser wood species.

CACHIM & FRANSSEN [12] affirm that the charring rate depends on various factors, as wood species, density, moisture content, direction of burning (parallel or perpendicular to the grain), etc.; however, for practical purpose, only some of them can be deemed. In their study, they defined the charring rates of softwoods with different densities using an advanced calculation method, comparing them with the charring rates of the simplified methods. The authors state that there is an inconsistency between simplified and advanced calculation methods presented by EC5, as the second takes into account the influence of density. Their numerical analysis demonstrated higher densities of wood to result in lower charring rates, converging with the inverse relationship between density and thermal diffusivity, showing that the simplified methods suggested by EC5 may neglect a significant correlation of it with the mechanical degradation of the timber – different from the Australian Standards, for example, that uses the density of the wood as the main characteristic to obtain its charring rate for simplified procedures.

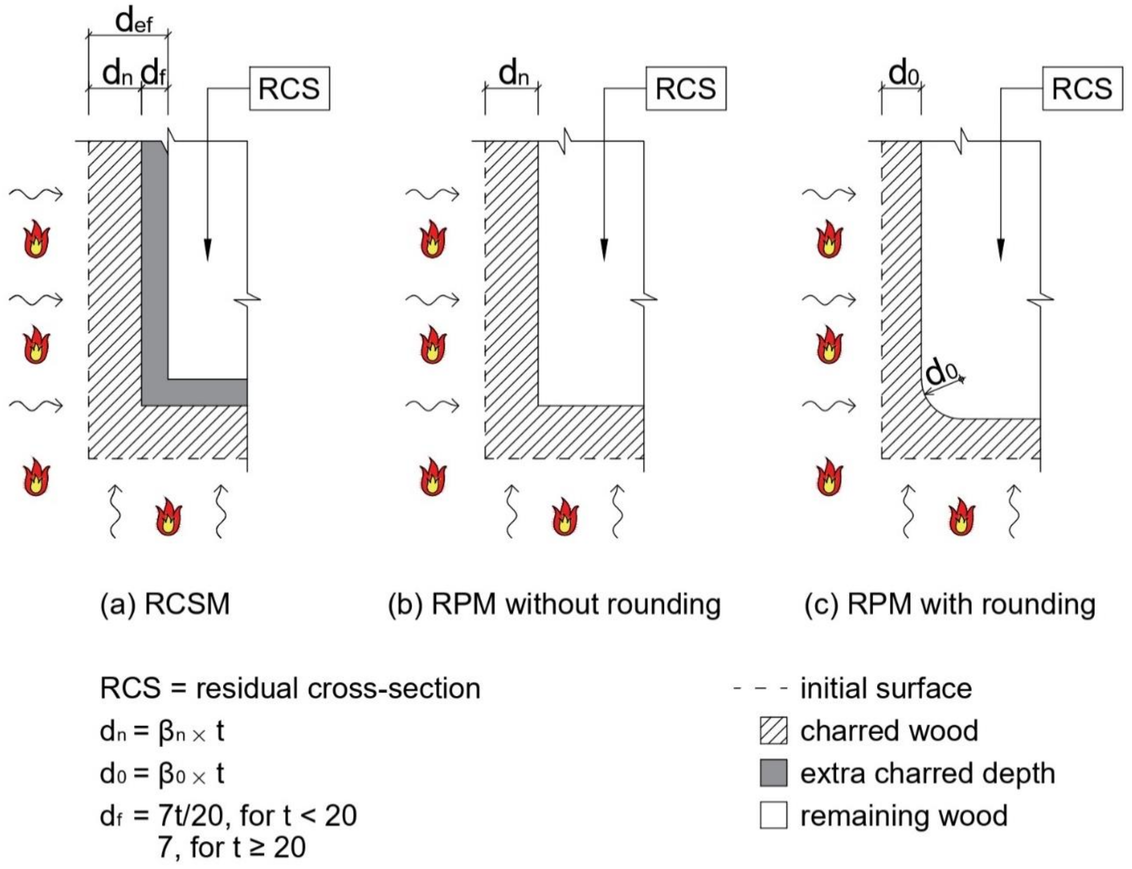
This study, more than obtaining the charring rate based on EC5 orientation for advanced calculation, compared the results of bending resistance loss on timber beams of four wood species with distinct densities in different durations of fire. It was identified the degree of conservatism adopted by the simplified methods and a new equation was proposed contemplating the influence of the wood density. The software Abaqus/CAE was used to determine the temperature isotherms on the beam sections in the different durations of fire.

EUROCODE 5 METHODS TO VERIFY RESISTANCE UNDER FIRE SITUATION

EC5 defines two simplified methods for verifying linear structural timber elements (columns, beams) under fire situation. The reduced cross-section method (RCSM) consists in determining a charring depth based on the notional charring rate (β_n) and the time of fire occurrence, adding to it an extra depth to be reduced from the cross-section (7 mm for fires lasting 20 or more minutes); the verification is made using the reduced cross-section and considering integral properties for the wood. The reduced properties method (RPM) also takes into account the charring rate and the time of fire exposure, considering a modification factor ($k_{mod,fi}$) to compensate the change in the properties of wood in high temperatures; $k_{mod,fi}$ depends on the perimeter and area of the residual cross-section and for bending strength it is given by Eq. (1). The reduced properties method can be used with two different charring rates: the notional charring rate (β_n), which is higher to compensate not considering the rounding effect of the corners, and the one-dimensional charring rate (β_0), that must consider the rounding effect. Fig. 1 demonstrates the particularities of each method, considering unprotected timber members.

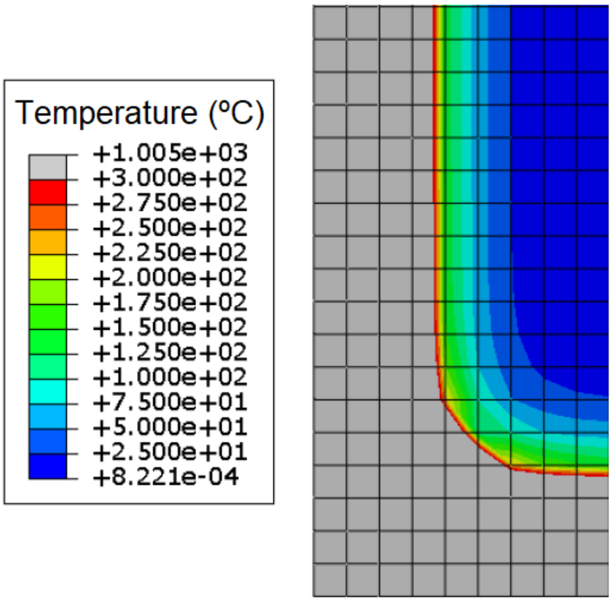
$$k_{mod,fi} = 1{,}0 - p \div (200 \times A_r) \qquad \text{Eq. (1)}$$

Fig. 1: Particularities of each simplified method proposed by Eurocode 5



Among the options that EC5 gives for advanced calculation methods, there is one that conducts to obtaining the charring depth by using the finite element method (FEM) and introducing this depth within the RPM. In this case, the FEM is used for thermal analysis and the results are presented by a software in the form of isotherms. Fig. 2 illustrates an example obtained in this study, for which the software Abaqus/CAE was used for modelling the timber element and the fire scenario proposed by EC5. The gray area – representing 300ºC or higher –, indicates the charred or faded wood, being disregarded in the calculation procedure.

Fig. 2: Result of thermal analysis on timber element with FEM modelling



DETERMINATION OF THE CHARRING DEPTH

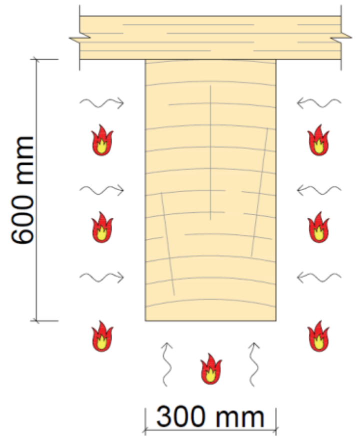
To confront the results of the simplified methods, this study used two species of softwood (*Pinus elliotti* – SW1; *Pinus taeda L.* – SW2) and two species of hardwood (*Eucalyptus saligna* – HW3; *Tabebuia serratifolia* – HW4) to determine the charring depth and the residual cross-section by FEM analysis, with the species being of distinct densities in order to enable the discussion over the influence of density on charring rate and on bending resistance. The density values used were obtained from the Brazilian Standards [13] and are shown in Tab. 1, with their respective thermophysical properties for different temperature values according to EC5.

Tab. 1: Thermophysical properties of species of wood according to Eurocode 5

Temperature (ºC)	Density				Conductivity (W/m.K)	Specific heat (kJ/kg.K)
	SW1	SW2	HW3	HW4		
20	560	645	731	1068	0,12	1530
99	560	645	731	1068		1770
99	560	645	731	1068		13600
120	500	575,9	652,7	953,6		13500
120	500	575,9	652,7	953,6		2120
200	500	575,9	652,7	953,6	0,15	2000
250	465	535,6	607	886,8		1620
300	380	437,7	496	724,7		710
350	260	299,5	339,4	495,9	0,07	850
400	190	218,8	248	362,4		1000
500					0,09	
600	140	161,3	182,8	267		1400
800	130	149,7	169,7	247,9	0,35	1650
1200	0	0	0	0	1,5	1650

The charring depth was determined for fire durations of 30, 60, 90, 120 and 150 min, being also considered a “zero-minute fire”, representing the instant of ignition, in which the calculation method considers the integral initial cross-section with fire-verification procedures, so there is no discrepancy in the development of the resistance loss due to different adopted modification factors. A rectangular cross-section of 300 mm x 600 mm was chosen and the fire incidence considered on three of the four sides of the structural element, simulating a slab leaning on the thinner side of a beam, as shown in Fig. 3.

Fig.3: Cross-section with corresponding fire incidence



The results of the charring depth for the simplified methods are shown in Tab. 2, Tab. 3 and Tab. 4. It can be seen that results are not determined by species, but by their class, and the charring depth is higher for hardwoods, as EC5 adopts lower charring rate values for this class.

Tab.2: Charring depth for the Reduced Cross-Section Method

Beam	Charring depth (mm) – RCSM				
	30'	60'	90'	120'	150'
SW1/SW2	31	55	79	103	127
HW3/HW4	23,5	40	56,5	73	89,5

Tab.3: Charring depth for the Reduced Properties Method without rounding effect

Beam	Charring depth (mm) – RPM without rounding effect				
	30'	60'	90'	120'	150'
SW1/SW2	24	48	72	96	120
HW3/HW4	16,5	33	49,6	66	82,5

Tab.4: Charring depth for the Reduced Properties Method with rounding effect

Beam	Charring depth (mm) – RPM with rounding effect				
	30'	60'	90'	120'	150'
SW1/SW2	19,5	39	58,5	78	97,5
HW3/HW4	15	30	45	60	75

On the other hand, results from calculation with FEM show that density plays an important role in determining the loss of wooden material of timber beams, agreeing with different authors [9 – 12, 14] and with the AS 1720.4 [15]. Tab. 5 presents the charring depth values found with the numerical analysis, while Fig. 3, Fig. 4, Fig. 5 and Fig. 6 compare them with the results of the simplified methods.

Tab. 5: Charring depth for the Finite Element Modelling numerical analysis

Beam	Charring depth (mm) – FEM				
	30'	60'	90'	120'	150'
SW1	18	36	51	65	78
SW2	17	34	47	60	73
HW3	16	31	45	57	68
HW4	15	26	36	46	56

Fig. 4: Charring depth of SW1 for the different methods

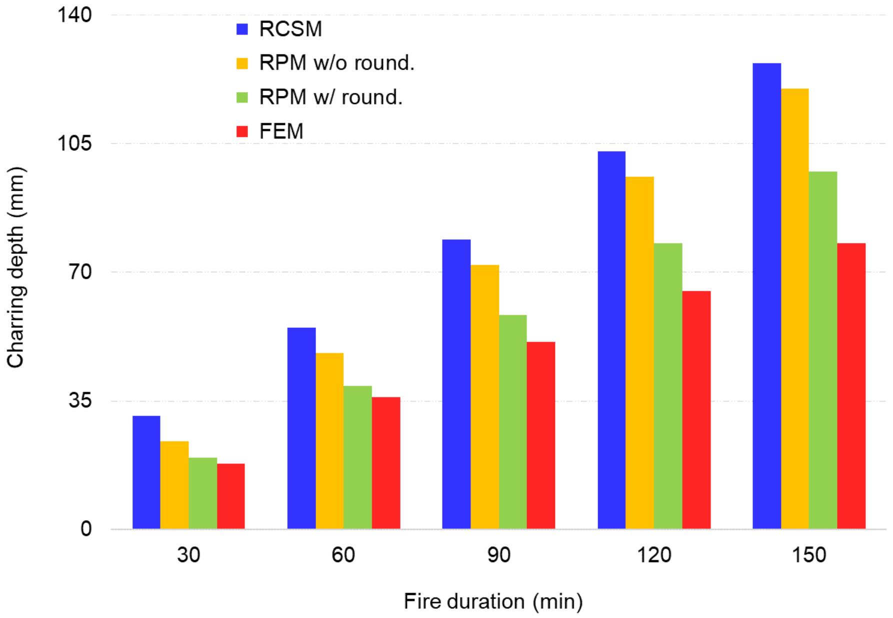


Fig. 5: Charring depth of SW2 for the different methods

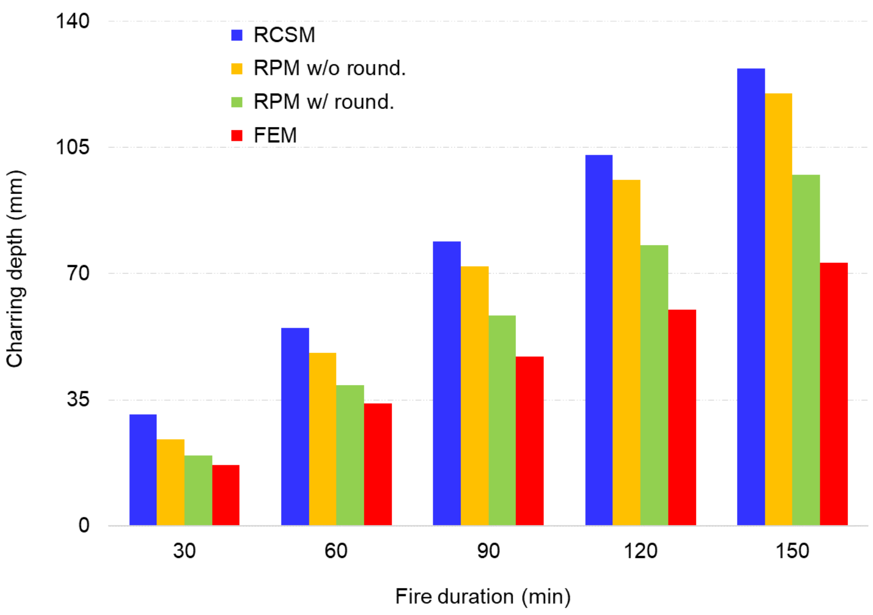


Fig. 6: Charring depth of HW3 for the different methods

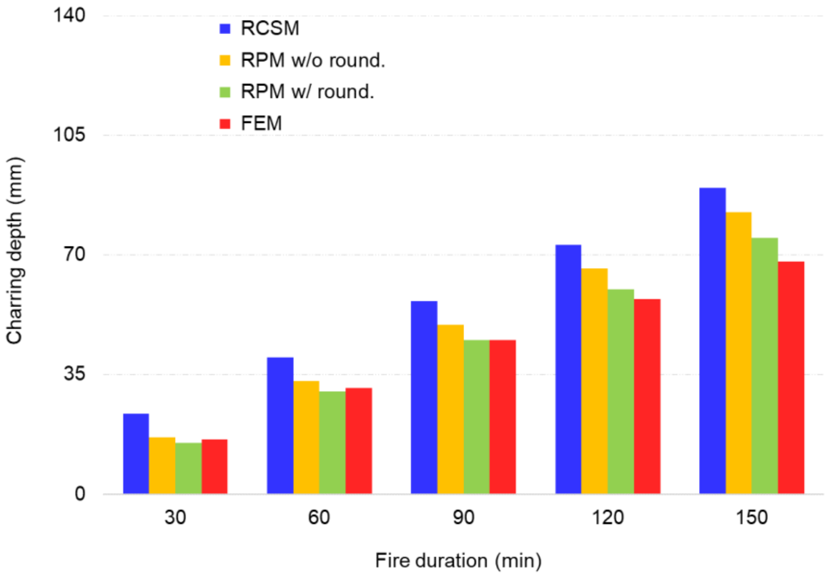
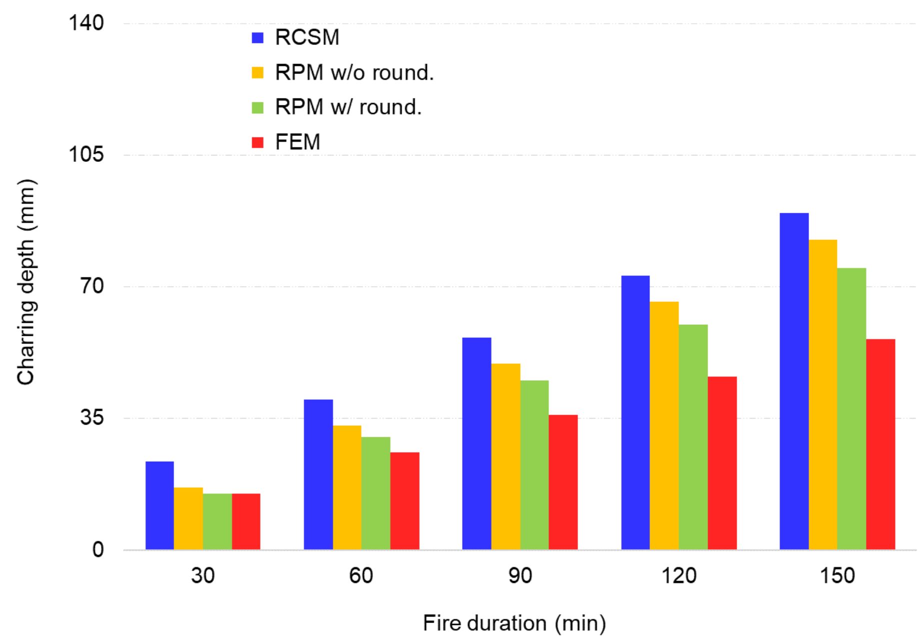


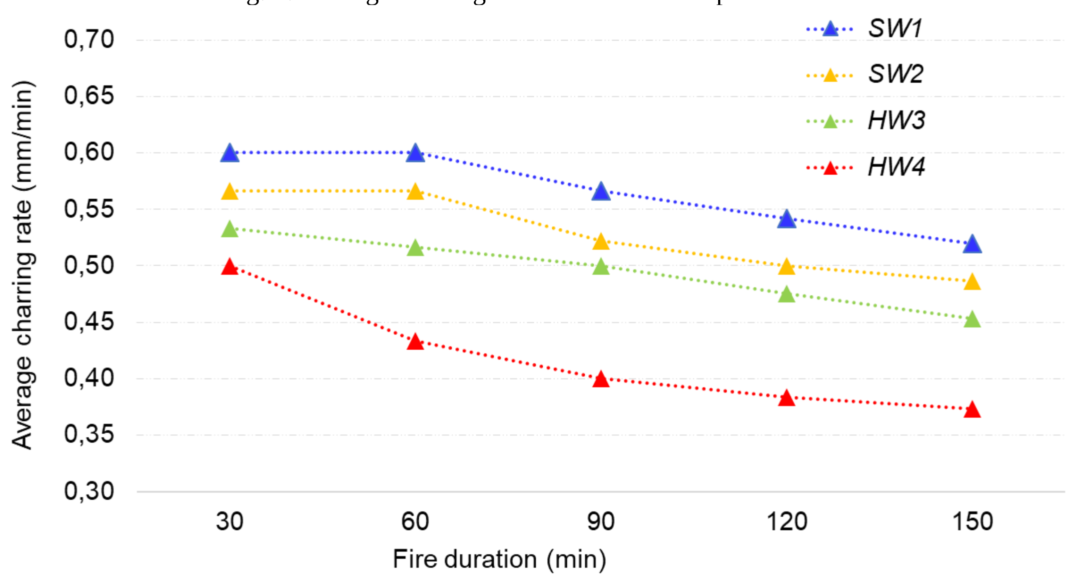
Fig. 7: Charring depth of HW4 for the different methods



It can be seen that the charring depth is higher for lower densities and, except for HW3 with 30 and 60 min, they were inferior for numerical analysis if compared with the use of simplified methods.

Evaluating the average charring rate resulted from the numerical analysis, which is presented by Fig. 7, it can be seen that it decreases as further the fire occurs, due to the thermal conductivity of the char being lower than the conductivity of the wood that originated it, as indicated by EC5 and FRIQUIN [5, 7]. The average charring rate tends to be constant for infinite times of fire exposure, corroborating with [5, 16].

Fig. 8: Average charring rate of the different species studied



DETERMINATION OF BENDING RESISTANCE

With the charring depths defined, the resistance of the elements can be verified. As the established element simulates a beam, usually related to loadings perpendicular to it, verification was made over the bending resistance. Fig. 8, Fig. 9, Fig. 10 and Fig. 11 illustrate the variance of the results for the different species with each method, using the instant of ignition resistance as the relative value.

Fig. 9: Fire duration x bending resistance for SW1

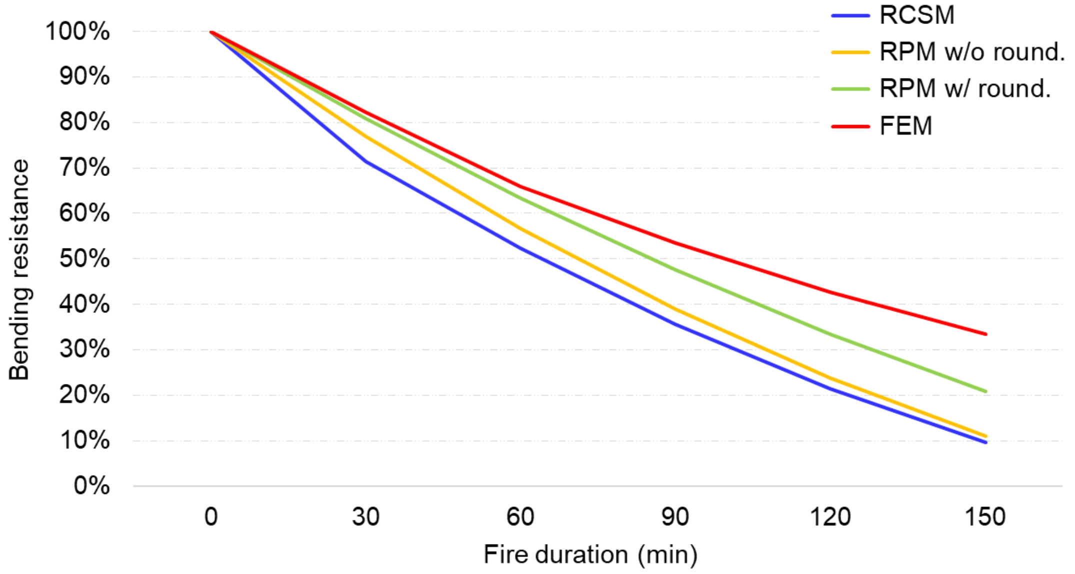


Fig. 10: Fire duration x bending resistance for SW2

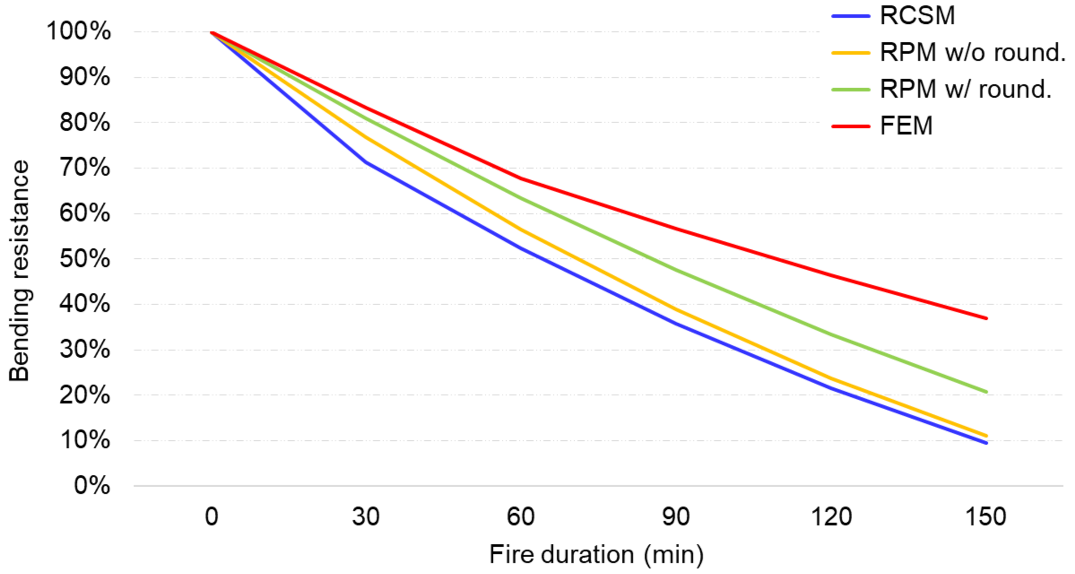


Fig. 11: Fire duration x bending resistance for HW3

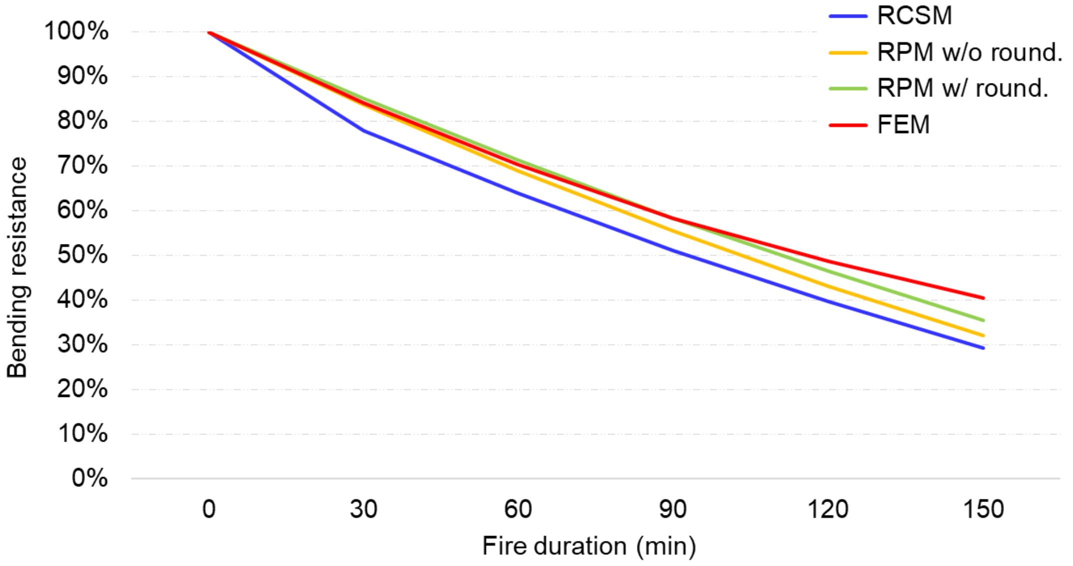
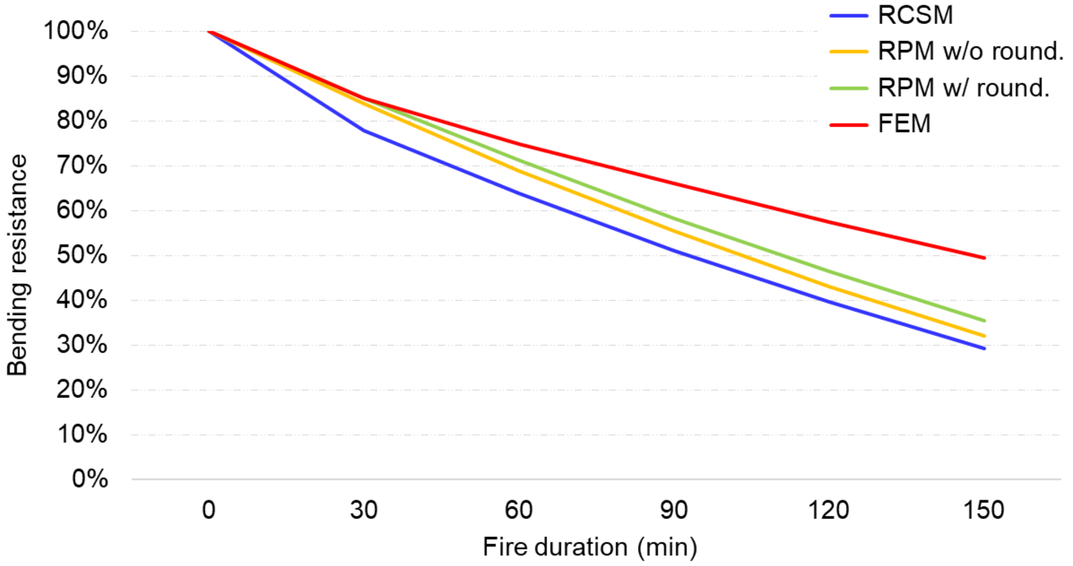


Fig. 12: Fire duration x bending resistance for HW4



As the bending resistance of the elements is directly related to its charring depth during fire occurrence, the results were lower for FEM analysis when compared to RPM considering the rounding effect for the beam HW3. For HW3 at time of 90 min and HW4 for time of 30 min of fire, results were the same. And for all the other comparisons between FEM and simplified methods for different species and different times, the advanced calculation method presented higher values of bending resistance.

Opposing the equality between different species of the same class (softwood or hardwood) brought by EC5, FEM showed difference depending on the wood density: resistance results of SW2 were 10,41% higher than SW1 at minute 150 of fire occurrence, while results of HW4 were 22,36% for the same time. For lower times, difference was smaller, demonstrating that the difference is higher for longer fires.

When compared the different methods for each species, it can be seen that results using FEM analysis were noticeably higher than simplified methods for the longest fire durations analyzed in this study. For the time of 150 min, FEM showed results:

- For SW1:
    - 60,3% higher than RPM with rounding effect;
    - 203,89% higher than RPM without rounding effect;
    - 250,51% higher than RCSM;
- For SW2:
    - 77,14% higher than RPM with rounding effect;
    - 235,53% higher than RPM without rounding effect;
    - 287,1% higher than RCSM;
- For HW3:
    - 14,7% higher than RPM with rounding effect;
    - 2643% higher than RPM without rounding effect;
    - 3,59% higher than RCSM;
- For HW4:
    - 39,57% higher than RPM with rounding effect;
    - 54,70% higher than RPM without rounding effect;
    - 69,58% higher than RCSM.

Again, as for charring rate, results with FEM analysis showed lower bending resistance for 30 and 60 min for HW3 when compared with RPM with rounding effect. The difference was 1,12% and 1,25% for the times mentioned.

DEVELOPMENT OF NEW EQUATION FOR DETERMINING CHARRING RATE

In the FEM analysis carried on in this study, it was verified that the charring rate varies according to the wood density. Also, its values are higher for lower durations of fire, making it become lower as the time of fire occurrence increases. These two behaviors are observed in two different international standards: Australian Stantards approach the charring rate as dependent of the wood density, while the AWC uses the time of fire occurrence to the power of 0,813 in order to insert the peak of charring rate that occurs in the border of the cross-section in the initial instants of fire. As the behavior of each international criteria is close to the behaviors found in the FEM analysis, both equations that guide the standards (Eq. 2 for the Australian, with charring rate in mm/min, and Eq. 3 for the North-American, with charring rate in in/h) were gathered in one (Eq.4).

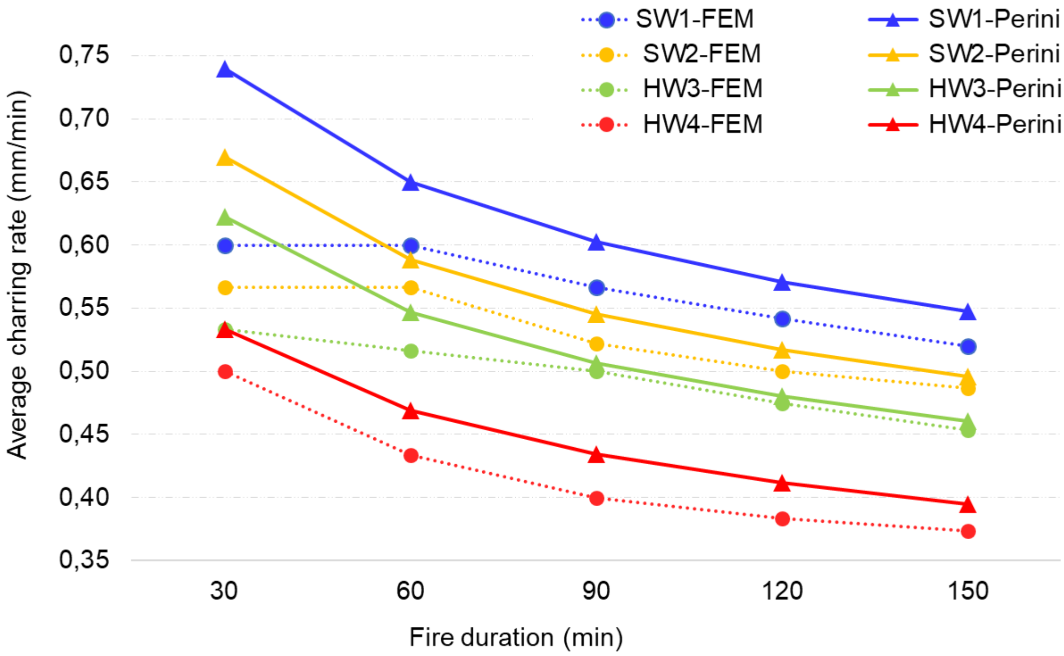
$$\beta = 0{,}4 + (280 \div \rho_{12})^2 \qquad \text{Eq. (2)}$$

$$\beta = d_{char} \div t = (\beta_x \times t^{0,813}) \div t \qquad \text{Eq. (3)}$$

$$\beta = \frac{60^{0,187} \times \left[0,4 + \left(\frac{280}{\rho_{12}}\right)^2\right]}{t^{0,187}} \qquad \text{Eq. (4)}$$

With the new equation, new curves were determined for each species analyzed, being then compared with the results of the FEM analysis. Fig. 13 illustrates the comparison (new equation results are identified as 'Perini').

Fig. 13: Average charring rate for FEM and new equation



It can be seen that the curves of the new equation were closer to the results found in the FEM analysis, if compared the proximity between FEM results and simplified methods results. For the time of 30 min, the highest difference was around 23,3% for SW1. Excluding 30 min results – which diverged from the curve pattern –, difference was close to 8,6%.

When it comes to bending resistance, Fig. 14, Fig. 15, Fig. 16 and Fig. 17 show that results between FEM analysis and results using the new equation adapted to the RPM with rounding effect are very close, having the highest difference verified in around 8,4%, for SW1 at the time 150 min of fire duration.

Fig. 14: Fire duration x bending resistance for SW1

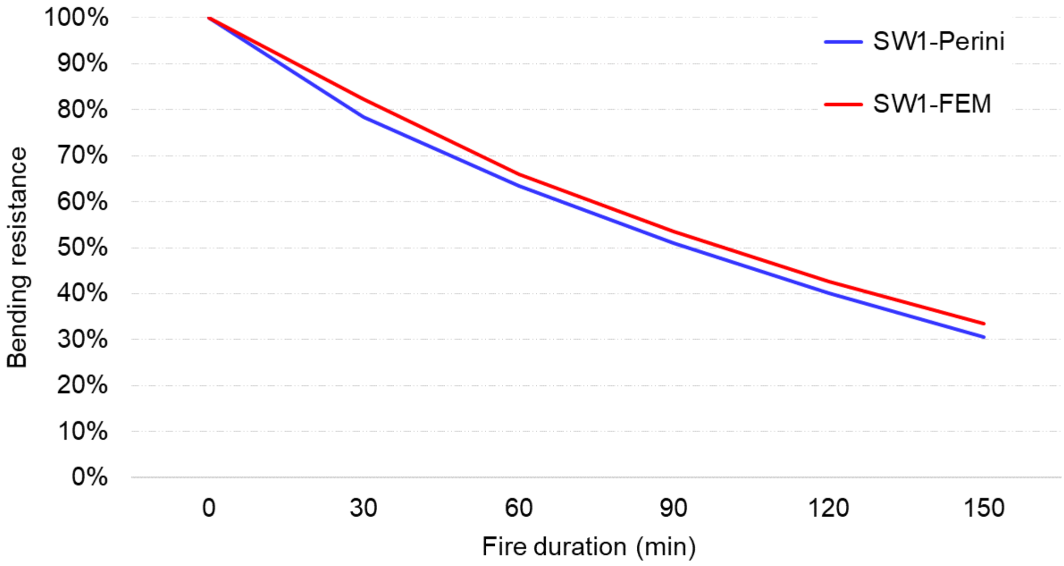


Fig. 15: Fire duration x bending resistance for SW2

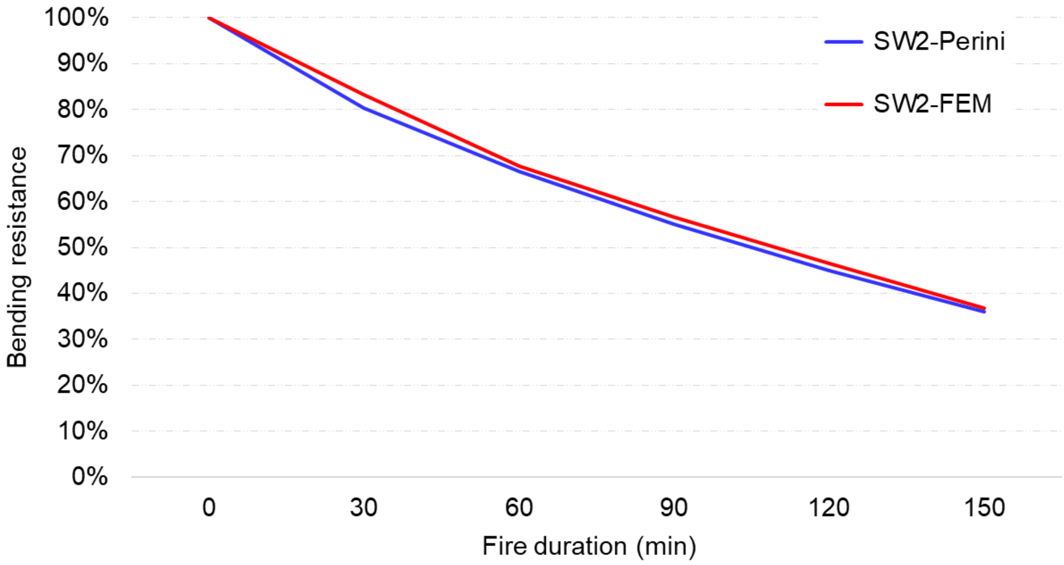


Fig. 16: Fire duration x bending resistance for HW3

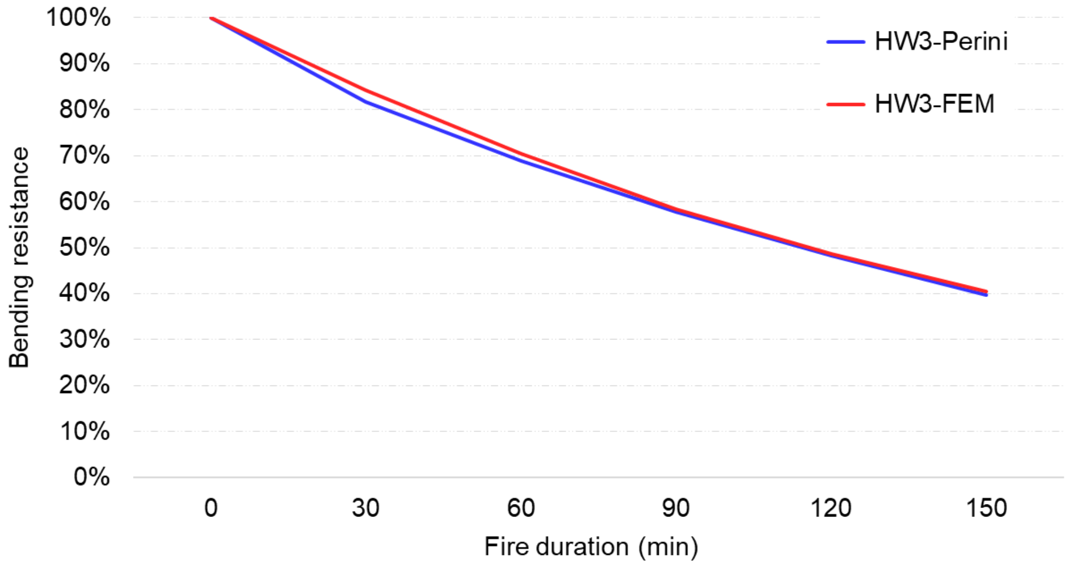
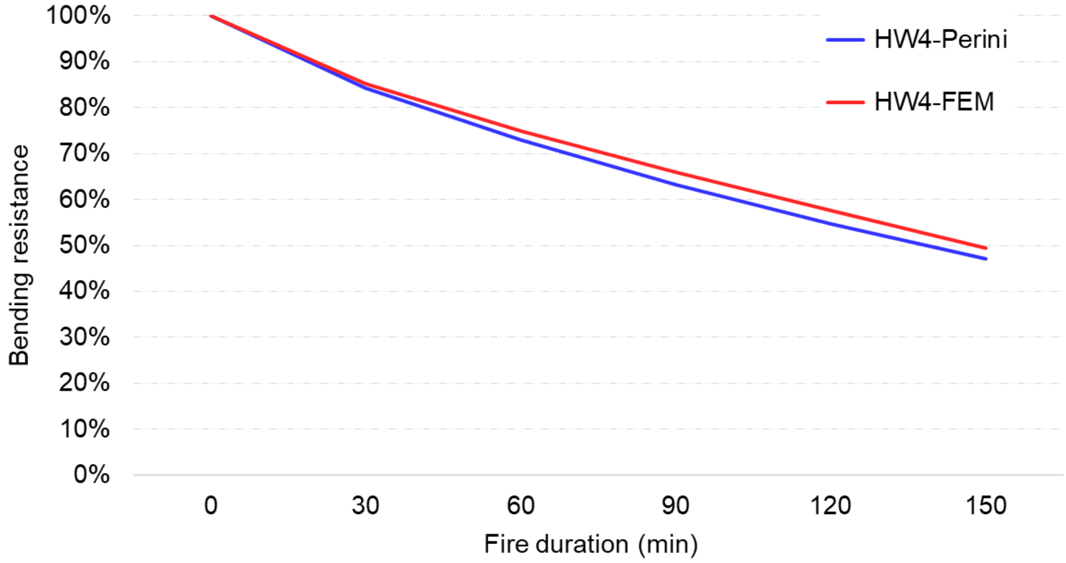


Fig. 17: Fire duration x bending resistance for HW4



CONCLUSION

It was verified that the charring rate depends strong and directly on the density of the wood that is being used in the timber element, being lower for higher densities. That converges to what was mentioned by various authors and is brought by the Australian standards.

The difference between simplified methods and FEM analysis according to the parameters proposed by EC5 are higher than the difference found between the same FEM analysis and the RPM with rounding effect using the results of charring depth originated from the new equation proposed in this study. Moreover, the use of the new equation reached lower bending resistance results than advanced calculation in all times for all species studied, meaning that it respected a certain degree of conservatism in these cases.

Considering that calculation tools used for projecting buildings are no longer limited as they were decades ago, simplified methods as the ones brought by EC5 present little interest economically wise. Solving more complex equations as the one proposed in this study is simple with tools of daily use by professionals who project structures, and its proximity with FEM analysis justify their adoption.

Despite the use of EC5 criteria for FEM analysis being accepted by different authors, it must be enhanced that the results presented in this study are based on theoretical values, being of great interest that similar analysis were run experimentally to check if they corroborate with these results.

REFERENCES

1. Toppinen, A., et al. (2018). The future of wooden multistory construction in the forest bioeconomy: A Delphi study from Finland and Sweden. *Journal of Forest Economics, 31*, 3-10. https://doi.org/10.1016/j.jfe.2017.05.001

2. Zubizarreta, M., et al. (2019). Modeling the environmental sustainability of timber structures: A case study. *Environmental Impact Assessment Review, 78*, 1-11. https://doi.org/10.1016/j.eiar.2019.106286

3. United Nations (UN). (2024). The 17 goals. https://sdgs.un.org/goals#goals

4. Shigue, E. K. (2018). *Difusão da construção em madeira no Brasil: Agentes, ações e produtos* [Thesis, Universidade de São Paulo].

5. Friquin, K. L. (2011). Material properties and external factors influencing the charring rate of solid wood and glue-laminated timber. *Fire and Materials, 35*, 303-327. https://doi.org/10.1002/fam.1055

6. Thi, V. D., et al. (2016). Finite element modelling of the pyrolysis of wet wood subjected to fire. *Fire Safety Journal, 81*, 85-96. http://dx.doi.org/10.1016/j.firesaf.2016.02.001

7. CEN. (2004). *Eurocode 5 – Design of timber structures. Part 1-2: General – Structural fire design* (EN 1995-1-2). Brussels, Belgium: European Committee for Standardization.

8. Quiquero, H., Gales, J., & Abu, A. (2019). Finite element modelling of post-tensioned timber beams at ambient and fire conditions. *Fire Technology*. https://doi.org/10.1007/s10694-019-00901-0

9. Adetayo, O. A., & Dahunsi, B. I. O. (2018). Development of models for charring rate of selected construction timber species in South-Western Nigeria. *FUOYE Journal of Engineering and Technology, 3*, 17-21. https://doi.org/10.46792/fuoyejet.v3i1.115

10. Wen, L., Han, L., & Zhou, H. (2015). Factors influencing the charring rate of Chinese wood by using the cone calorimeter. *BioResources, 10*, 7263-7272.

11. Njankouo, J. M., Dotreppe, J. C., & Franssen, J.-M. (2004). Experimental study of the charring rate of tropical hardwoods. *Fire and Materials, 28*, 15-24. https://doi.org/10.1002/fam.831

12. Cachim, P. B., & Franssen, J.-M. (2008). Comparison between the charring rate model and the conductive model of Eurocode 5. *Fire and Materials, 33*, 129-143. https://doi.org/10.1002/fam.985

13. Associação Brasileira de Normas Técnicas (ABNT). (1997). *NBR 7190 – Projeto de estruturas de madeira*. Rio de Janeiro, Brasil.

14. Fahrni, R., et al. (2017). Fire tests on glue-laminated timber beams with specific local material properties. *Fire Safety Journal*, 1-9. https://doi.org/10.1016/j.firesaf.2017.11.003

15. AS 1720.4. (2019). *Timber structures Part 4: Fire Resistance of Timber Elements*. North Sydney, Australia: Standard Australia.

16. Mikkola, E. (1991). Charring of wood-based materials. *Fire Safety Science, 3*, 547-556. http://dx.doi.org/10.3801/IAFSS.FSS.3-547