



Assessment of the proposed wildfire curves for housing design protection

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ABSTRACT

The need to protect structures from the hazards of wildfires remains an area requiring further investigation. In this context, this study focuses on the analysis of a novel approach for defining and implementing standardized wildfire curves (WC) for the fire safety design of dwellings at the wildland-urban interface (WUI). The primary objective is to introduce the proposed WC and evaluate its representativeness in comparison to real cases documented in the literature, thereby validating its applicability. Emphasis is placed on the development of realistic standard fire time-temperature curves for natural fuels such as trees, shrubs, and litter. An extensive literature review was conducted to collect the most relevant time-temperature datasets, spanning experimental research from the 1960s to the most recent studies in 2023. These datasets were obtained using thermocouple devices positioned at various heights within the fuel bed. The study incorporates data from field tests, laboratory experiments, and real-life wildfire incidents in Portugal and other countries. Additionally, the authors present temperature curves acquired *in situ* from wildfires they monitored. Furthermore, a case study involving an external wall composed of classical construction materials commonly used in Portugal is numerically analyzed using the proposed WC. The heat transfer analysis examines the temperature distribution and internal heat flux. The results indicate that the WC effectively represents the scenario in which the highest internal temperatures within a dwelling are observed, highlighting its potential applicability in fire safety design.

1. Introduction

Wildfire attacks on the built environment in the Wildland-Urban Interface (WUI) have led to catastrophic consequences for both society and the environment. The most recent catastrophic event is the 2025 California wildfire, which occurred in January and affected Los Angeles and its surrounding areas, particularly Palisade, Altadena, and Eaton. The fire burned 50000 acres, destroyed at least 16000 structures, resulted in 27 fatalities, and forced the evacuation of 180000 people reported by Qiu [1] and in Woolcott [2]. Other notable examples include the devastating wildfires in Hawaii (USA) [3], Canada [4], Chile [5], Greece, Portugal [6], and Brazil [7]. These events result in a broad spectrum of direct and indirect impacts. From an environmental perspective, ecosystems, land use, and air quality are significantly affected, as noted by Chen et al. [8]. Additionally, wildfires impose severe societal consequences, including threats to public safety, economic

disruptions, and damage to transportation infrastructure and private properties, as cited by Rodrigo-Comino and Salvati [9]. As a result, the sustainability of the built environment—considering its social, environmental, and economic dimensions—along with its resilience, defined as the ability to recover from such disturbances [10], is increasingly at risk. Addressing the challenges posed by WUI wildfires is complex and requires a holistic approach. This paper specifically examines housing design strategies to enhance resistance against wildfire attacks. In this context, the implementation of fire safety design measures is essential to mitigate the vulnerabilities of structures exposed to wildfires. Papa-thoma-Köhle et al. [11] identified several critical factors influencing fire hazard, including the distance between structures and fire-prone vegetation, adherence to home ignition zone guidelines, and topographical elements such as slope and elevation. These factors must be considered to improve fire resilience in WUI regions. Destroyed or damaged structures during wildfires are exposed to at least one of the following heat

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transfer mechanisms: radiation, firebrands, or direct flame contact, as highlighted by Filkov et al. [12].

To minimize the risk of structural damage during fire exposure, fire resistance design (FRD), as a form of passive fire protection or non-combustible and fire resistant solutions, must be integrated into the building envelope. FRD measures applied to critical components such as cladding, façades, and roofing help mitigate vulnerability to external wildfire exposure. As discussed by Law and Bisby [13], FRD focuses on enhancing the structural performance of buildings when subjected to fire. The effects of fire on structures are typically analyzed by reproducing various time-temperature curves within a furnace, simulating real fire conditions. The fire resistance assessment, defined as a performance-based requirement, is measured by the duration (in minutes) until the structure loses stability, such as maintaining rigidity without collapsing. It also considers integrity (preventing the spread of fire, including flames and hot gases) and insulation (limiting temperature rise on the side not directly exposed to fire).

EN 1991-1-2 [14] includes time-temperature curves categorized as nominal curves, such as the ISO 834, external fire, and hydrocarbon fire curves. These curves were developed based on temperature field measurements recorded during compartment fires, meaning they were derived from indoor fire conditions rather than outdoor fire scenarios. A different approach, based on performance-based design, has been introduced by Cantor et al. [15]. They proposed an alternative time-temperature curve, referred to here as the Wildfire Curve (WC), specifically for fire resistance design (FRD).

The introduction of the WC as a new fire action model is justified due to the limitations of nominal curves, which do not account for the real-physics evolution of wildfire phenomena like ignition phase associated with a natural fuel (i.e., vegetation fuel), the relatively short duration and cooling stage due to the fast combustion of vegetative fuels (unlike nominal fire curves such as the ISO 834, hydrocarbon and external fire curves). Unlike traditional nominal curves, which maintain a monotonically increasing temperature profile, the WC incorporates the cooling phase observed in actual wildfire conditions. This more realistic representation optimizes the safety-cost balance in FRD by aligning the time-temperature curve more closely with measured wildfire temperatures and durations specifically in the context of protective housing design. Additionally, a key objective is to bridge the gap between current fire design standards and performance-based approaches, making wildfire safety measures more feasible and applicable to dwelling protection. By integrating the WC into FRD, housing design can be better tailored to real wildfire conditions, thereby mitigating fire impacts on structures. Ultimately, the WC can be incorporated into EN 1991-1-2 [14] as a thermal action representing outdoor fire exposure, as suggested by Arruda et al. [16]. This inclusion would enhance the fire safety framework by acknowledging the distinct characteristics of wildfire exposure compared to conventional compartment fires.

The primary objective of this study is to validate the proposed formulation using a large dataset, ensuring its applicability without the need to define a specific time-temperature curve based on fuel type. This research focuses on the selection of building materials for shelter walls, exploring various multilayer configurations and their thermal performance under wildfire exposure. The study specifically examines the temperature distribution on both the outer and inner sides of the wall, providing a more comprehensive thermal assessment. Furthermore, heat flux measurements have been obtained and analyzed, offering a deeper understanding of heat transfer dynamics. Another key objective is to evaluate the thermal field variations on the shelter wall resulting from the proposed wildfire curve, as well as to assess the impact of alternative time-temperature curves on the overall results. Additionally, this paper presents an in-depth investigation into the concept of safety distance, complemented by an advanced statistical analysis to enhance the robustness of the findings.

2. Methodology

For wildfire-induced fire actions, it is essential to establish a methodology for assessing fire resistance as a function of fire load. One approach is to apply an existing semi-probabilistic methodology, as outlined in EN 1990 [17], in combination with the performance-based methodology described in EN 1991-1-2 [14], in which the thermal action is based mostly directly from physical parameters and indirectly from chemical parameters. More in particular, this methodology defines fire action based on physically derived temperature field variations over time, incorporating uncertainties, characteristic values for peak temperature definition, and, safety factors. A key advantage of this approach is that it provides a reliable and simple alternative to advanced fire models, such as those relying on computational fluid dynamics (CFD) tools.

Looking at Dispatch No. 8591/2022 [18] of the National Portuguese Regulation, it mandates that buildings located in the Wildland-Urban Interface (WUI) must withstand 60 min of exposure to a wildfire attack. For instance, it establishes this for structural elements of a residential unit with a rural fire exposure class up to 12.5 kW/m². However, the regulation does not specify which fire action model should be used, leading to the assumption that ISO 834 should be applied. This assumption is unrealistic, as it inevitably results in excessively costly technical solutions under current fire design standards. Moreover, ISO 834 represents a nominal fire curve that does not account for a cooling phase, making it unsuitable for external fire exposures such as wildfires. The ISO 834 defines standard fire resistance tests based on an equivalent period of exposure, simulating structural performance under controlled fire conditions, as discussed by Law and Bisby [13] and further explained by Thomas et al. [19]. Considering a 60-min external fire exposure without cooling is an unrealistic approach when designing for wildfire resilience.

The definition of thermal action as a Wildfire Curve (WC) is based on a performance-based approach to represent wildfire attack to structures more realistically. This method aims to establish a more accurate fire exposure duration as a thermal action to be applied in structural fire assessments. In this context, Dispatch N°. 8591/2022 considers dwellings as temporary shelters for occupants during a wildfire event. However, to fulfill this function, the internal thermal conditions of the structure must be assessed to ensure a minimum level of thermal comfort under wildfire exposure. The Wildfire Shelters Report [20] establishes a maximum allowable temperature of 70 °C for unguarded interior surfaces, ensuring occupant safety upon contact. While these surface temperatures directly affect interior air temperatures, a comprehensive analysis of this interaction is not within the purview of this study. Moreover, Patterson et al. [21] indicate a maximum allowable interior air temperature of 45 °C for wildfire shelters. The dwelling acting as shelter must withstand the passage of a wildfire, which for higher temperatures it lasts less than 30 min [22,23]. Also, for a given wide dwelling with a circular perimeter of 300 m (equal to approximately 50m radius measured from the centre of the house including the external area), and a slow wildfire burning velocity below 20 m/min as found in Page et al. [24], the adopted total passage duration is also below 30 min. However, the duration of 30 min can be reached, for instance, depending on the concomitant wind action (speed and direction), fuel load, or ambient condition.

In this case, as per definition, the defensible space, or distance, is intended to provide a buffer zone (a clear zone without vegetation) around the building and the wildland that surround it [25]. This distance is variable depending on several factors such as the country and region, based on local fire risk, climate, vegetation, and regulations. However, we can distinguish two main values: the 30m distance for countries such as the USA [25], Australia [26], and for Canada the distance is in the range of 30–50 [27]. The 50m distance is typical of the Mediterranean countries such as Portugal [28] and France [29], in the case of Spain, for example, is around 30–50m [30].

After specifying the wildfire curve in the results section, a numerical study is conducted to validate the suggested upper bound of the WC. This simulation involves a heat transfer analysis performed using Abaqus [31]. Specifically, a worst-case scenario has been considered so that the dwelling is directly exposed to the thermal action of the experimental curves and the WC. If a buffer zone or fuel break is considered, the time-temperature curves should be revised and adjusted to reflect the reduced fuel load around the building, thereby mitigating the impact of thermal action. Specifically, the WC is applied as a thermal action to a real masonry brick, representing the external surface of a structure. The interior surface temperature is then computed and compared with experimentally measured "in situ" wildfire temperature curves, assessing the internal temperature distribution within the wall layers.

Due to the rapid temperature decrease during the cooling phase, allowing heat flux penetration into the interior layers, the total simulation duration may extend beyond 120 min. The choice of 120 min was made to ensure that the maximum temperature on the inner side of the wall is reached under the thermal action of the WC. Furthermore, this duration accounts for a worst-case scenario in which occupants are unable to evacuate due to external safety hazards, such as: Blocked Road access, Reduced visibility due to Smoke, Severe air quality deterioration, Physical inability to evacuate (e.g., elderly individuals or people with mobility impairments).

The shelter building characteristics play a crucial role in governing overall time simulation. Moreover, their thermal effects on the wall persist beyond the duration of the applied thermal action due to the rapid temperature rise followed by a sharp decrease, which facilitates quick heat flux penetration into the interior layers of the structure.

The time-temperature curve, defined as the Wildfire Curve (WC) thermal action, provides a more realistic representation of wildfire exposure. Among its key characteristics are: shorter overall duration compared to nominal fire curves, higher peak temperatures, rapid heating and cooling phases. Unlike nominal fire curves for compartment fires, which lack a cooling phase (as it is normally considered), the WC better represents the real thermal behavior of outdoor fires.

This study investigates heat transfer mechanisms primarily through direct flame contact and consequently through radiation as well, modeled using the WC time-temperature curve. The thermal analysis—conducted as a thermal field evaluation—yields temperature assessments and heat flux measurements. It is important to note that firebrand effects are not considered in this study, as well as other factors that are not assessed, such as angle of exposure or environmental conditions (wind speed, orientation), among others.

2.1. Characteristic wildfire curve

During the design phase, it is not possible to predict with sufficient certainty whether the fire will start in bushes, trees, or other natural fuels. Hence, in a conservative approach, the worst scenario has to be chosen (even though a large universe of curves has been analyzed) regardless of the fuel.

WC as expressed in Equation (1), proposed by Blagojevic and Pešić [32], represents a performance-based approach able to overcome the prescriptive-based approach, and permitting a cost optimisation in terms of FRD when compared with nominal curves. A further advantage of the WC is related to the reliability based on its characteristic values of thermal action and accuracy of the data collected for describing the fire behavior.

$$T[^\circ\text{C}] = T_{\max} \left[\frac{t[s]}{t_{\max}[s]} \exp \left(1 - \frac{t[s]}{t_{\max}[s]} \right) \right]^c \quad (1)$$

In which parameter $T_{\max}$ is the maximum peak temperature, $t_{\max}$ is the time instant when it happens, c is the dimensionless parameter that measures the growth and decrease of temperature. If $c = 1$, then the cooling phase is near-linear degradation, and with $c = 1.5$ the cooling

phase presents a rapid exponential decrease. The parameter " c ," which refers to the type of natural fuel (shrub, grass, and litter), has not been modified.

As explained by Cantor et al. [15], the parameters in Equation (1) used to derive the Standard Wildfire Curve (WC) were established in accordance with Annex D of EN 1990-1-1 [33]. The methodology considered the 95 % characteristic values for the average maximum temperature ($T_{\text{avr}}^{\max}$), which were determined by analyzing Table 1—specifically, the highest recorded temperatures and their corresponding durations. To compute the characteristic value, the standard deviation of the average maximum temperature must be incorporated, as defined in Equation (3), using the formulation in Equation (2). Given that the experimental dataset contains more than 30 observations, the k_n factor is set to 1.64, as specified in Annex D of EN 1990-1-1 [33].

$$T_{k,95\%}^{\max} = T_{\text{avr}}^{\max} + k_n \times s_x \quad (2)$$

$$T_{\text{avr}}^{\max} = \sum_{i=1}^n \frac{T_{\text{max}}^i}{n} \quad s_x^2 = \sum_{i=1}^n \frac{(T_{\text{max}}^i - T_{\text{avr}}^{\max})^2}{n-1} \quad (3)$$

2.2. Experimental data set

This study investigates various vegetative fuels, including pine needle beds, shrubs, crown fires, surface fires, forests, and rural areas, across regions such as the Mediterranean, North America, and Australia. This diverse dataset enables a comprehensive assessment of wildfire behavior under different conditions. To analyze the most severe fire effects, the study focuses on peak temperature and fire duration as key evaluation criteria. Specifically, wildfire time-temperature curves were recorded from field experiments, laboratory tests, and real-life wildfire incidents conducted over the last 60 years in multiple countries beyond Portugal. In all cases, thermocouple devices were used to measure temperature at different heights, either "in situ" or in controlled laboratory settings.

The selected time-temperature curves represent gas-air temperature measurements recorded at the flame height during both field and laboratory experiments. The inclusion of such a diverse dataset, including cases that may not originate directly from a wildfire context, is justified by the uncertainty associated with direct flame exposure in real fire scenarios. External air temperature, which defines thermal action on structures, can vary significantly due to multiple factors, such as: differences in fuel types (e.g., live or dead vegetation, bark, accumulated pine needles, or litter), uncertainty in fire spread patterns, making it difficult to determine whether a structure is directly exposed to flames.

A literature review was conducted to assess the WC proposal, which included measurements of time-temperature curves using thermocouples, as summarized in Table 1. As shown in Fig. 1, experiments were conducted to study the fire spread behavior, especially of four types of fuel: trees, shrubs, grass, and litter. The authors have also undertaken an extensive "in situ" experimental campaign using thermocouple and heat flux sensors, which were also useful to complement the dataset used in the determination of the WC. It is beyond the scope of this work to present all the information of the used test setup, and further information can be found in Craveiro et al. [49].

The next paragraphs provide a brief chronological overview of the authors chosen, summarizing their experimental works about fuels, locations, experimental settings, and height positions. Furthermore, it provides detailed justification for the selection of specific authors.

Martin [34], as a pioneer in 1963, wrote about a basic approach to fire injury to tree stems, measured in palmetto-galberry fuels in Georgia (US). In 1991, Costa et al. [35] conducted laboratory and field studies in Portugal utilizing *Pinus pinaster* trees (particularly the trunk) to measure the temperature distribution inside a tree under fire condition. In the specific case, for both curves were considered the external bark and not the inner region. This was justified by the possibility to have an ignition moment related to the external part of the trunk. Jacoby et al. [36]

Table 1

Summary of wildfire tests for each experimental test.

Author	Year	Fuel	Country	Field/Lab	TP height [m]	T_{max} [°C]	t_{max} [s]
Martin [34] a	1963	palmetto/galberry (s)	US, GA	Field	1.2	468	19
Martin [34] b	1963	palmetto/galberry (s)	US, GA	Field	0.3	708	23
Costa [35] a	1991	pinus pinaster (t)	Portugal	Lab	0	618	244
Costa [35] b	1991	pinus pinaster (t)	Portugal	Field	0	733	75
Jacoby [36]	1992	honey mesquite (t)	US, TX	Field	0.3	616	18
Ansley [37] a	1998	honey mesquite (t)	US, TX	Field	0.3	891	48
Ansley [37] b	1998	honey mesquite (t)	US, TX	Field	0.3	511	58
Ansley [37] c	1998	honey mesquite (t)	US, TX	Field	1	597	44
Butler [38] a	2001	honey mesquite (t)	US, ID	Field	0.45	839	61
Butler [38] b	2001	grassland	US, FL	Field	0.3	872	20
Mendes-Lopes [39] a	2003	pinus pinaster (n)	Portugal	Lab	0.125	789	51
Mendes-Lopes [39] b	2003	pinus pinaster (n)	Portugal	Lab	0	704	57
Mendes-Lopes [39] c	2003	pinus pinaster (n)	Portugal	Lab	0.125	701	75
Mendes-Lopes [39] d	2003	pinus pinaster (n)	Portugal	Lab	0	761	32
Mendes-Lopes [39] e	2003	pinus pinaster (n)	Portugal	Lab	0	951	67
Mendes-Lopes [39] f	2003	pinus pinaster (n)	Portugal	Lab	0	676	41
Mendes-Lopes [39] g	2003	pinus pinaster (n)	Portugal	Lab	0.125	694	41
Mendes-Lopes [39] h	2003	pinus pinaster (n)	Portugal	Lab	0	706	40
Kremens [40]	2003	pine/scrub oak (t)	US, NY	Field	0	807	58
Butler [41] a	2004	jack pine (t)	Canada, NT	Field	13.8	543	40
Butler [41] b	2004	jack pine (t)	Canada, NT	Field	12.3	676	62
Butler [41] c	2004	jack pine (t)	Canada, NT	Field	12.3	750	51
Butler [41] d	2004	jack pine (t)	Canada, NT	Field	9.2	861	45
Butler [41] e	2004	jack pine (t)	Canada, NT	Field	13.8	1200	28
Butler [41] f	2004	jack pine (t)	Canada, NT	Field	12.3	1194	27
Butler [41] g	2004	jack pine (t)	Canada, NT	Field	9.2	1337	24
Taylor [42]	2004	jack pine (t)	Canada, NT	Field	0.5	1026	12
Mell [43]	2009	honey mesquite (t)	US	Lab	2	723	27
Cruz [44] a	2010	shrub - heath	Australia, SA	Field	0	1006	30
Cruz [44] b	2010	litter - mallee	Australia, SA	Field	0	932	38
Rodriguez [45] a	2017	pinus pinaster (t)	Spain	Field	8	687	29
Rodriguez [45] b	2017	pinus pinaster (t)	Spain	Field	4	976	24
Roise [46] a	2022	brush - chaparral	US, CA	Field	0.6	1016	53
Roise [46] b	2022	brush - chaparral	US, CA	Field	0.6	986	92
Mrad [47] a	2022	grassland	US, NC	Lab	2	638	25
Mrad [47] b	2022	grassland	US, NC	Field	2	643	26
Majlingová [48] a	2022	litter	Slovakia	Lab	0	611	26
Majlingová [48] b	2022	litter	Slovakia	Lab	0	618	44
Majlingová [48] c	2022	litter	Slovakia	Lab	0	585	70
Majlingová [48] d	2022	litter	Slovakia	Lab	0	639	40
Majlingová [48] e	2022	litter	Slovakia	Lab	0	457	43
Majlingová [48] f	2022	litter	Slovakia	Lab	0	583	26
Majlingová [48] g	2022	litter	Slovakia	Lab	0	614	59
Majlingová [48] h	2022	litter	Slovakia	Lab	0	521	24
Majlingová [48] i	2022	litter	Slovakia	Lab	0	659	48
Majlingová [48] l	2022	litter	Slovakia	Lab	0	689	19
Majlingová [48] m	2022	litter	Slovakia	Lab	0	468	39
Majlingová [48] n	2022	litter	Slovakia	Lab	0	342	41
Craveiro [49]	2023	shrub - gorse	Portugal	Field	1	898	106
Sahila [50]	2023	shrubs	Portugal	Lab	1	666	102
Sahila [51]	2023	shrubs	Portugal	Lab	1	587	87

TP height = Thermocouple height, Lab = laboratory test (n) = needles, (t) = tree, (s) = shrub, NT = Northwest territory, CA = California, NY = New York, TX = Texas, NC = North Carolina, GA = Georgia, SA = South Australia, ID = Idaho, FL = Florida.

described a field test conducted in Texas (US) in 1992 that involved burning the woody overstory of honey mesquite trees. The test's objective was to enhance the procedure for taking temperature readings during range fires. Later, in 1998, Ansley et al. [37] reported an experiment also conducted in Texas relating herbaceous fuel, weather, and fire temperature. The experiment involved a predominance of woody overstory honey mesquite canopy, but it also included the presence of fine fuel, which was primarily warm grasses. In Florida (US), Butler and Putnam [38], in 2001, realized an exploratory study about fire shelter performance in a simulated wildfire where the natural fuels were consisted of honey mesquite and grassland fuels. The maximum external air temperature outside the shelter was around 1000 °C. In Portugal, in a laboratory experiment carried out in 2003, Mendes-Lopes et al. [39] wrote about a long series of experiments with output time-temperature curves in a bed of *Pinus pinaster* needles. The choice to

consider pine needles also represents a worst-case scenario, however still possible, in which the needles can accumulate around and at the base of the wall of the dwelling.

Kremens et al. [40], described the measurements of the time-temperature of the burn scar carried out in New York State in 2003. One year later, in 2004, Butler et al. [41] measured (beyond 9 m-height) temperatures in a Canadian boreal forest crown fire (composed of jack pine trees) with peak air temperatures exceeding 1330 °C. The purpose of including these data was to assess the potential threat to shelters from a crown fire, where flaming trunks or branches could fall around the dwelling.

In 2004, Taylor et al. [42] presented findings from a field test experiment on crown fire behavior in a northern jack pine and black spruce forest in the Canadian Territories. The laboratory experiment conducted by Mell et al. [43] in 2009 provided validation for a

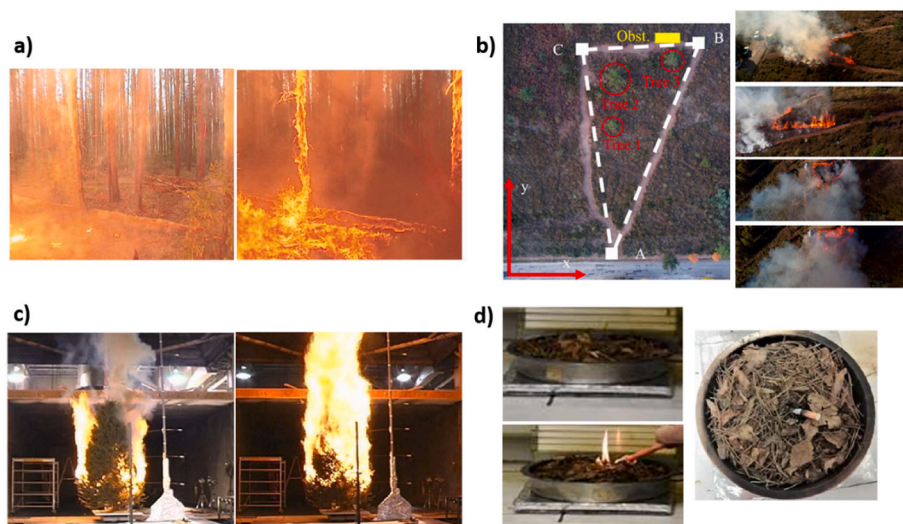


Fig. 1. Field and laboratory tests: (a) Taylor et al. [42], (b) Craveiro et al. [49], (c) Mell et al. [43], (d) Majlingová et al. [48].

numerical model designed to simulate the combustion characteristics of Douglas fir trees. Even the moisture content variation was significant; the test was conducted with a very low moisture content, “almost a dead tree”. This case was included because dead trees are common in forests and such fuel significantly contributes to wildfire behavior.

Cruz et al. [44] published a study in 2010 on fire dynamics in Mallee-Heath, describing fuel, weather, and fire-behavior prediction in south Australian semi-arid shrublands.

In 2017, Rodriguez et al. [45] investigated in Spain crown fire initiation and spread models in Mediterranean conifer forests using data from field and laboratory tests. More recently, in 2022, Roise et al. [46] reported field fuel data for brush-chaparral fuel in California. In this regard, the decision to include these curves is the similarity of a possible scenario in which a small dwelling is set in the same condition of the prototype fire shelter. In the same way, the investigation conducted by Butler and Putnam’s [38], aimed to test prototype wildland fire shelters in the field and in full-scale laboratories. In the same year, Mrad et al. [47] investigated the upscaling of wildland fire behavior (in grassland) from laboratory to field in North Carolina (US). Majlingová et al. [48], in 2022, examined litter fuels (from the Slovak Republic in central Europe) in laboratories to determine flame properties, showing the importance of the classification of wildland fires. Regarding the inclusion of litter fire tests, these tests were relevant for analyzing the initiation of surface fires in forests. In such cases, time-temperature curves recorded in experimental tests were used to compare fire behavior across different test conditions and measurement equipment.

In 2023, Craveiro et al. [49] described a field test conducted in the center region of Portugal in 2022. The field test was conducted by the ISISE research institution as part of the INTERFACE SEGURA project, financed by Portuguese Foundation for Science and Technology FCT with research project PCIF/AGT/0062/2018. More specifically it was realized by prescribed fires of shrubs and eucalyptus trees attacking steel sandwich panels to investigate heat transmission mechanisms and fire behavior. Also, Sahila et al. [50,51] in 2023, conducted an experimental laboratory investigation on the burning capabilities of dead fuels and conducted a comparative analysis of the flame attributes and combustion dynamics of dead Mediterranean plants in Portugal.

3. Results and discussion

3.1. Curves and statistical analysis

In this study, a total of 51 time-temperature curves, extracted from seventeen different authors, were analyzed. Specifically, 26 curves were

obtained from field experiments, while 25 were recorded under laboratory conditions. Among the various natural fuel types studied, 19 curves corresponded to trees, whereas the remaining 32 curves included shrubs, grass, pine needles, or litter. The average fuel thermocouple (TP) height was 2.1 m, within a range of 0–13.8 m.

The eight graphs in Fig. 2 illustrate the 51 experimental curves, distinguishing in the legend between field test (/F) and laboratory (/L). The average peak temperature recorded was 740 °C, with a minimum of 341 °C and a maximum of 1337 °C. Among these, six curves exceeded 1000 °C, including two for shrubs and four for trees. However, this does not necessarily indicate a more severe fire scenario. As demonstrated in the following section, a rapid increase and decrease in temperature may not represent the most critical case, particularly when heat flux penetration into the interior wall layers is considered.

The average time to reach peak temperature was 52 s, with a range from 12 s to 244 s. Of the 51 curves analyzed, 48 exhibited both development and decay phases within 250 s, while only three curves sustained temperatures above 400 °C beyond 250 s. These three cases were observed in the studies by Costa et al. [35] for *Pinus pinaster*, and Butler & Putnam [38] in grassland fire experiments.

An analysis of experimental fire duration curves reveals that some exceed 250–300 s, lasting significantly longer due to various influencing factors. For instance, in Costa et al. [35] a, b experiments, the curves exhibited extended durations because the measurements were taken on the bark of the tree trunk in a laboratory setting. The thick thermal mass of the bark required more time to burn, prolonging the recorded duration. Similarly, in Butler [38] a, the longest recorded duration was attributed to the fuel load available for combustion. In Kremens [40], the extended fire duration (beyond 250 s) was justified by the effects of convective heat transfer and the increase in ground temperature caused by the flames. The experiments conducted by Sahila [50], Sahila [51] indicate that longer burn durations are correlated with higher fuel loads.

Additionally, the average temperature rise rate during the heating phase was 20 °C/s, with a range of 2.2 °C/s to 78 °C/s. In this context, the temperature rise rate (°C/s) is defined as the ratio between the temperature difference from initial to peak temperature (in °C) and the corresponding time interval (t_{max} in seconds).

Based on the data presented in Table 1 (representing the original values) and applying a multivariate regression analysis (as shown in Table 2), we can observe a strong relationship between peak temperature and the other variables considered. This is confirmed by the correlation coefficient ($R = 0.75$). Additionally, the R^2 value of 0.56 indicates that nearly 56 % of the variance in dependent variables is explained by the independent variables.

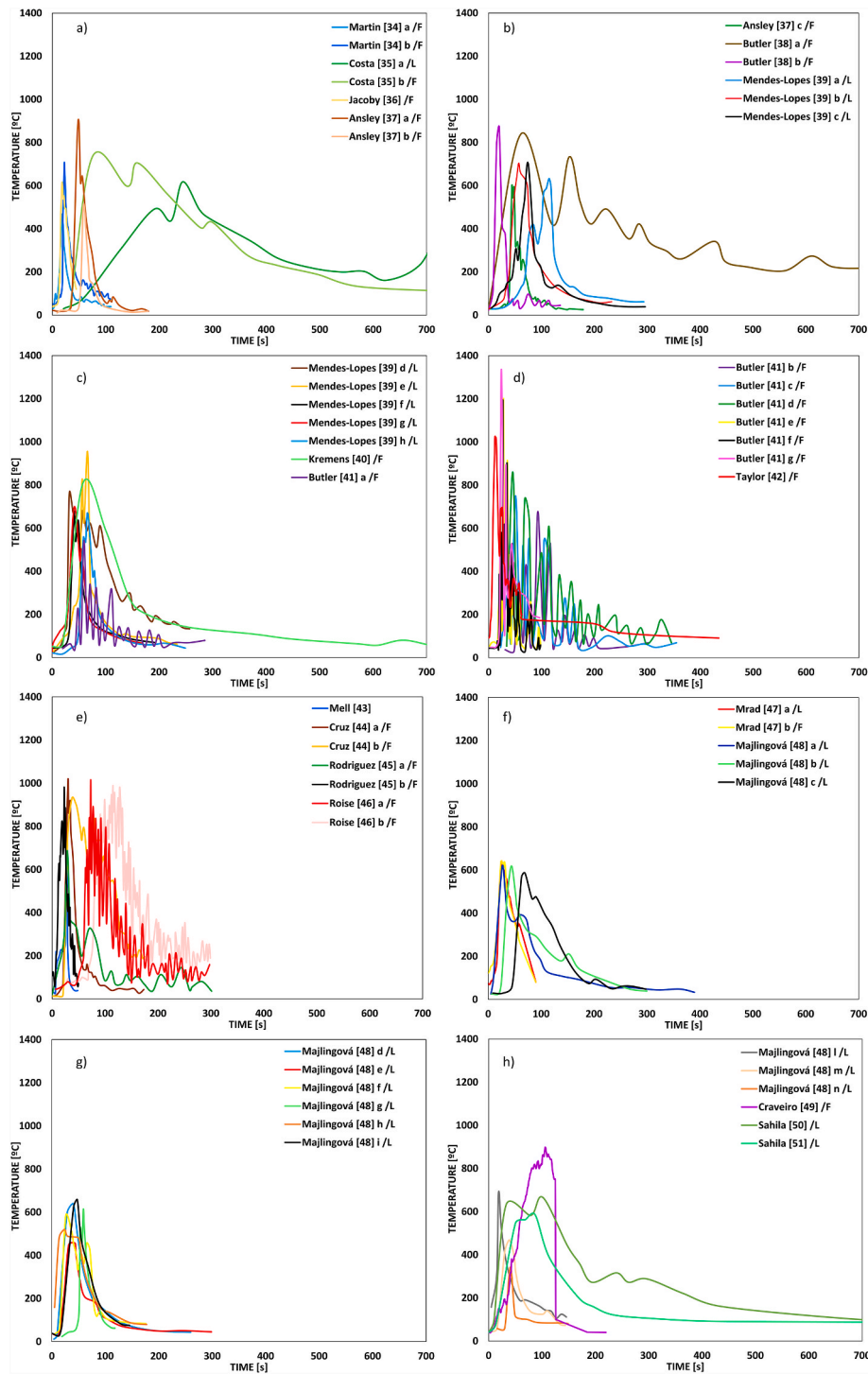


Fig. 2. Time-temperature curves for wildfire from a-h), and ordered as in Table 1, (/F = field test and/L = laboratories).

Regarding the standard error, it is 143 °C, which, when compared to the mean temperature of 741 °C, suggests a reasonably good fit. From the ANOVA results, the most relevant information extracted from the table is that the F-value (8) is relatively high, and the significance level ($F \approx 3E-06 \ll 0.05$) confirms the statistical validity of the model.

When analyzing individual independent variables, we find that the three most statistically significant factors in explaining temperature variation across the complete dataset are: type of experiment (laboratory vs. field testing), temperature rise rate (TRR), final time of the experiment. Even though there are large temperature variations in the dataset (e.g., 342 °C vs. 1337 °C), an outlier analysis was conducted by

calculating the standard residual error. The maximum standard residual error was 2, which is below the threshold of 3, confirming that all 51 data points were valid within the assessment. More specifically, only 8 of 51 observations showed absolute value of standard residual error higher than 1.5 and a unique value reaching 2.01.

As shown in Table 3, a more detailed analysis was conducted to examine individual fuel types, ranked into five groups: trees, shrubs, grass, needles, and litters.

Notably, the minimum peak temperatures of grass and needles (638 °C and 676 °C) are higher than those of other fuels, indicating that these fuel types maintain moderately high temperatures even in the

Table 2
Multivariate regression analysis.

Regression statistics						
Multiple R					0.75	
R Square					0.57	
Adjusted R Square					0.50	
Standard Error					143.65	
Observation					51	
ANOVA						
	df	SS	MS	F	Significance F	
Regression	7	1169054.65	1670007.80	8.09	2.91E-06	
Residual	43	8887371.74	20636.55			
Total	50	2056426.39				
	Coefficient		Standard Error		t - Stat	P-value
Intercept	87.24		174.27		0.50	0.62
1)height	11.12		6.06		1.83	0.07
2)exp	153.94		69.61		2.21	0.03
3)PTIM	0.93		0.53		1.75	0.09
4)TRR	7.64		1.67		4.59	3.9E-05
5)Duration	0.04		0.04		0.95	0.35
6)FT	0.96		0.48		1.99	0.05
7)fuel	41.05		24.91		1.65	0.11

1)Height of thermocouple 2) experiment (field or laboratory) 3) PTIM=Time for reaching peak temperature.

4)Temperature rise rate 5) Duration experiment 6) FT = final temperature 7) Kind of fuel.

Table 3
Analysis for fuel group.

	tree	shrub	grass	needle	litter
Min-temperature [°C]	511	468	638	676	342
Max-temperature [°C]	1337	1016	872	951	932
Mean-temperature [°C]	820	792	718	748	594
Standard-deviation [°C]	228	198	109	84	134
Ratio: St-dev/Mean-temp	0.28	0.25	0.15	0.11	0.23

"worst-case scenario". Conversely, maximum peak temperatures for trees and shrubs (1337 °C and 1016 °C) are the highest recorded values, suggesting that these fuels generate greater thermal energy than the others. Needles and litter exhibit similar maximum temperatures, both exceeding 900 °C, with a difference of less than 2 % between them. Regarding the ratio of standard deviation to the mean temperature, the analysis reveals that for all five fuel categories, this ratio remains below 0.3, with a minimum value of 0.11, indicating good data consistency. For trees, specifically, a correlation analysis reveals that peak temperature is more strongly correlated with the temperature rise rate ($r = 0.71$) than with the height ($r = 0.32$).

3.1.1. Proposed WC as thermal action

In this section are presented the 51 experimental curves in agreement with equation (1) and with data presented in Table 1. Further the WC, as thermal action, is proposed and plotted (as black dashed line) in the four graphics as comparison with remaining curves, as shown in Fig. 3. The WC is obtained by considering the maximum peak temperature of 1073 °C as defined by equation 2 and as found on the last row of Table 4.

Notably, the difference compared to the maximum peak temperature reported by Cantor et al. [15] is very small 2.2 % (1050 °C). Regarding t_{max} , the average time at which the maximum temperature occurs was found to be 53 s. However, t_{max} is not a characteristic value since the action is based on temperature rather than time. Therefore, a conservative approach was adopted by applying a duration three times longer – approximately 150 s. This multiplier of three is based on an assumed reliability of 0.95, as reported in Ref. [52], which corresponds to a safety factor of 3. The safety factor concept can be associated with the criteria used for the application of the structural safety assessment

methodologies. As explained by Newman and Choo [53], loads are increased and resistances are decreased using a partial factor.

To confirm the characteristic values from a statistical point of view, the Kolmogorov-Smirnov test [54] was used to validate the adoption of a normal distribution curve to calculate the standard deviation coefficient. The Kolmogorov-Smirnov test was done considering the experimental curve and the proposed fire-performance based curves for wildfire presented in Fig. 2 applied on the maximum temperature of each curve. The plot depicted in Fig. 4 shows the observed (black line) versus normal cumulative relative frequencies (red line) for the 51 case, in which for a level of significance equal to 0.05, the maximal absolute difference equal to 0.1525 is less than the maximum possible value (0.1902) as defined by the Kolmogorov-Smirnov table found in Ref. [55].

3.2. Assessing the impact of WC in a masonry wall

3.2.1. Introduction

For this case study, all the 51 curves described in the preceding section were tested in a conventional external brick masonry wall with internal insulation and mortar for internal and external cover. Furthermore, the proposed WC (defined in equation (1)), was evaluated and compared with the 51 experimental curves reformulated as the fitted curve plotted in Fig. 3. To better represent an existing wall, it was admitted the thicknesses shown in Fig. 5. This geometry was chosen with the purpose of representing a classical external clay brick wall, with section configuration used in south Europe, south and north America. A mock-up of this configuration is presented below in Fig. 5.

In agreement with Annex B of EN 1996-1-2 [17], the fire resistance classification for this masonry brick wall section configuration is below EI30, where E means integrity, I means insulation, and 30 is the number of minutes in which the part retains its functionality under an indoor fire. Therefore, according to the Portuguese Dispatch 8591/2022 [18], this type of wall would not have survived the passage of a wildfire.

3.2.2. Developing the FEM model

The non-linear heat transfer analysis has been conducted with Abaqus software 2021 [31]. The standard time step integration procedure was used. To reduce computational costs, the model was analyzed as a 2D solution, although in this case a one-dimensional analysis would have been enough. However, for didactic and visual reasons 2D solution was preferred. The dimensions used were respectively m and Kelvin. Physical condition of absolute zero and the Stefan-Boltzmann constant equal to $5.67 \cdot 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ were considered.

Fig. 6 shows a sketch of the composition. The model has a unique part. A rectangle shape with a dimension of $0.085 \text{ m} \times 0.020 \text{ m}$ was partitioned into four divisions. Three different materials were considered: mortar (applied on the external and internal side), brick, and expanded polystyrene EPS. Regarding the non-linear thermophysical characteristics for mortar and brick, these were found, respectively, in Pupo Correia et al. [56] and in Annex D of EN 1996-1-2 [17]. About EPS, since in the literature there are no studies with high temperatures, the values were based on ratios presented by Duarte et al. [57], obtained with similar materials like polyethylene terephthalate (PET) and rigid polyurethane (PUR). Table 5 resumes the thermophysical characteristics (conductivity, density, and specific heat) at ambient temperatures. As supplementary material the thermophysical characteristics depending on the temperature are provided.

A key assumption regards the thermal load applied. The temperature applied in the Abaqus represents the adiabatic surface temperature (AST), i.e., there is no exchange of heat flux on the material surface as found in Wickström et al. [58]. This condition is not real. However, it is a conservative approach (upper bound condition) that permits to evaluate how the structure thermally reacts. The amplitude thermal curves are established, including the initial temperature on the external side. As a predefined field for temperature the environment temperature of 293 K

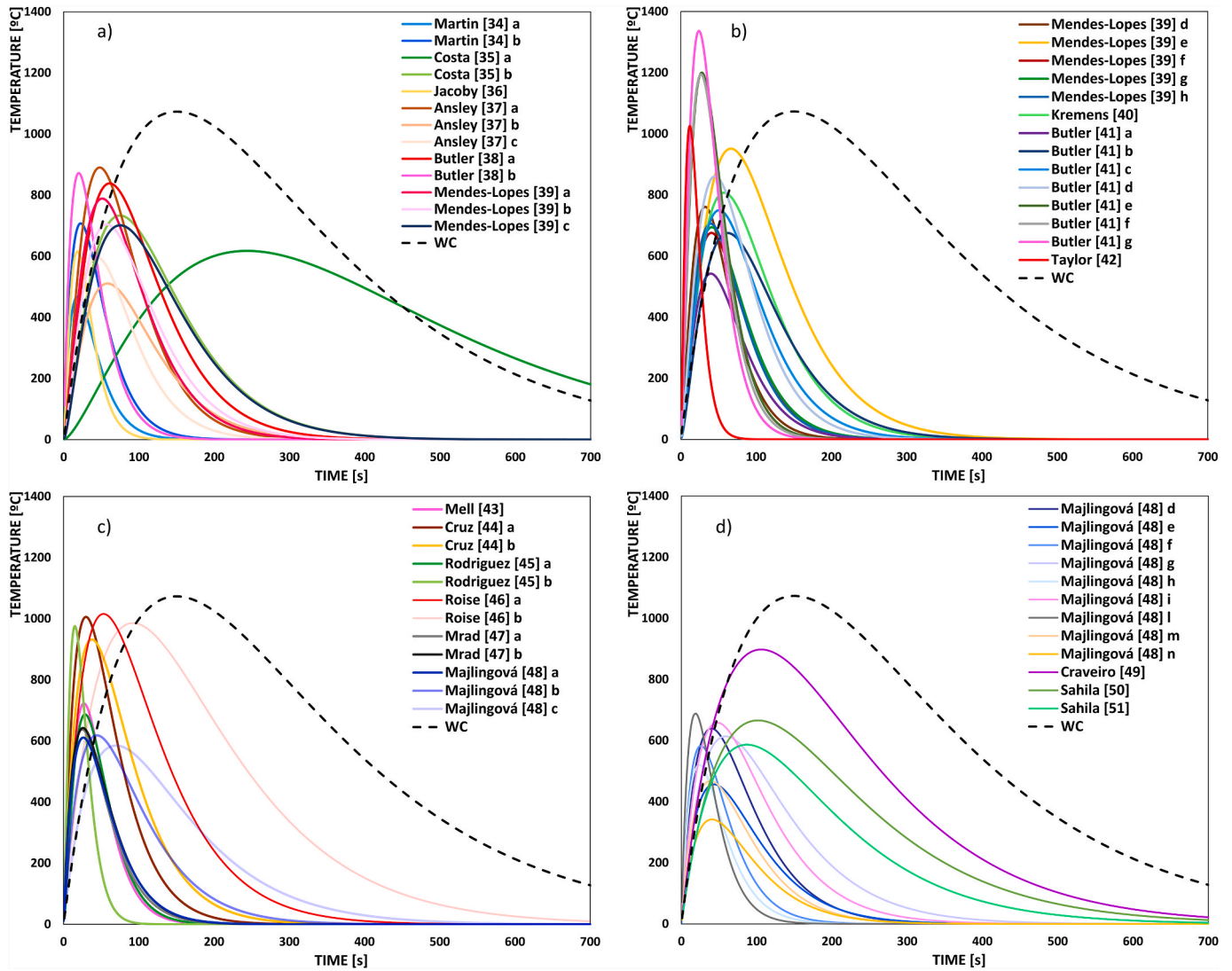


Fig. 3. Proposed fire-performance-based curves for wildfire.

Table 4
Summary of characteristics test.

Case	T _{max}	(T _{i,max} -T _{max}) ²	Case	T _{max}	(T _{i,max} -T _{max}) ²	Case	T _{max}	(T _{i,max} -T _{max}) ²
–	[°C]	[°C] ²	–	[°C]	[°C] ²	–	[°C]	[°C] ²
1	342	158933	18	639	10232	35	789	2324
2	457	80611	19	643	9599	36	807	4444
3	468	74283	20	659	6687	37	839	9586
4	468	74151	21	666	5576	38	861	14487
5	511	52739	22	676	4234	39	872	17313
6	521	48405	23	676	4191	40	891	22473
7	543	39222	24	687	2887	41	898	24775
8	583	24883	25	689	2712	42	932	36609
9	585	24175	26	694	2130	43	951	44432
10	587	23741	27	701	1539	44	976	55277
11	597	20539	28	704	1323	45	986	60168
12	611	16767	29	706	1183	46	1006	70420
13	614	16000	30	708	1077	47	1016	75718
14	616	15563	31	723	325	48	1026	81307
15	618	15117	32	733	53	49	1194	205572
16	618	14915	33	750	88	50	1200	211049
17	638	10475	34	761	421	51	1337	355694
T _{k,95 %_max}			T _{m_max}			s _x ²		
1073.2 °C			740.6 °C			41129 °C ²		
						203 °C		

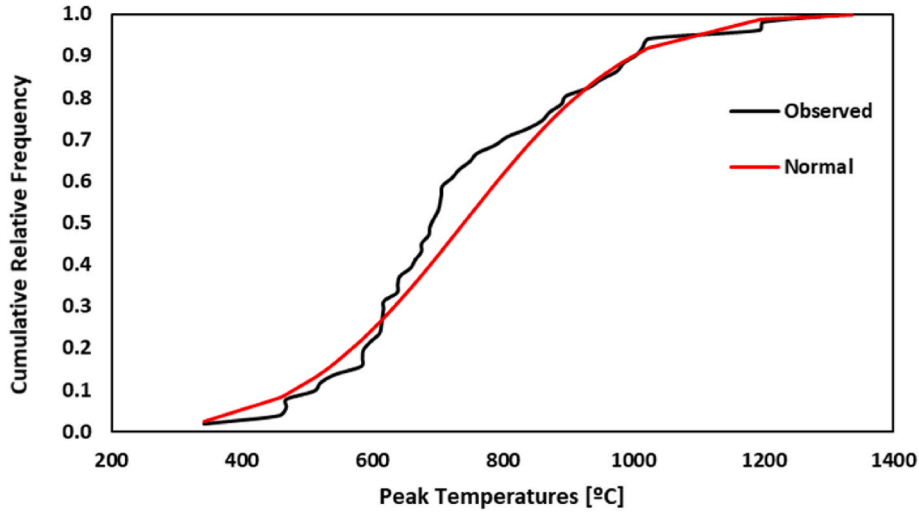


Fig. 4. Observed versus normal cumulative relative frequency.

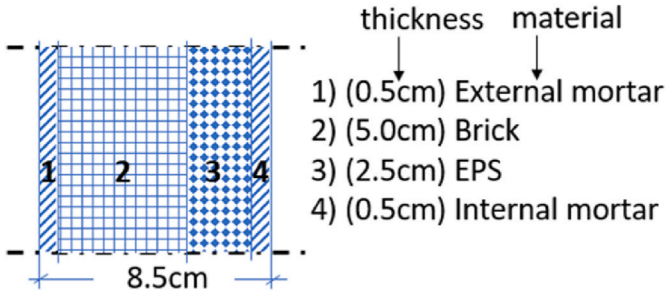


Fig. 5. Mock-up of wall.

(20 °C) was defined for all the domain in the beginning of the analysis.

The boundary condition between material inside the wall (conditions between mortar and brick, brick and EPS and between EPS and mortar) was considered as perfectly in contact. Further, no boundary conditions were defined for the transverse condition, assuming that the heat transfer is acting just in the longitudinal direction. For the numerical thermal model in Abaqus it was necessary to define the thermal boundaries on the external and internal faces of the mock up, using interfaces with radiation and convection surfaces.

More specifically the mathematical formulation used for determining the temperature inside a multilayer wall, based on Cengel [59], is the following:

$$\frac{\partial T_n(\mathbf{x}, t)}{\partial t} = -\alpha_n(T) \cdot \frac{\partial^2 T_n(\mathbf{x}, t)}{\partial x^2} \quad (4)$$

In which $T_n(\mathbf{x}, t)$ is the temperature [K] in the n-th layer, $\alpha_n(T)$ is the

thermal diffusivity [m^2/s] of the nth layer and in which $\alpha_n(T) = k_n(T) / (\rho_n(T) \cdot c_n(T))$ where $k_n(T)$, $\rho_n(T)$, and $c_n(T)$ are the thermal conductivity, the density, and the heat capacity (with unit measure as expressed in Table 3). Subscript n represents the nth layer as represented (from left to right) in Fig. 5 from 1 to 4. Layer 1 is the external mortar and Layer 4 is the internal mortar layer. x is the position between x_n^- and x_n^+ that delimit the thickness of the nth layer.

Boundary conditions are set as following externally and internally respectively in equations (5) and (6) as expressed below:

$$-k_1 \frac{\partial T_1}{\partial x} \bigg|_{x=L} = h_e (T_{AST,e} - T_1(L, t)) + \varepsilon \cdot \sigma \cdot T_{AST,e}^4 \quad (5)$$

$$-k_4 \frac{\partial T_4}{\partial x} \bigg|_{x=0} = h_i (T_{AST,i} - T_4(0, t)) \quad (6)$$

$T_{AST,e}$ and $T_{AST,i}$ are respectively the temperature of the thermal load applied externally and the temperature of air-temperature inside the dwelling. h_e and h_i are the convective heat transfer coefficients for external and internal side. For the external surface both radiation and convection surfaces are used. For the wildfire curves, it was admitted a convective heat transfer coefficient of 35 kW/m², according to the recommendation for natural fires with the possibility of cooling EN

Table 5

Thermophysical properties of materials at ambient temperature.

Quantity	Mortar	Brick	EPS
ρ - Density [$\text{kg} \cdot \text{m}^{-3}$]:	1676	1050	55
c - Specific heat [$\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$]	360	564	1210
k - Conductivity [$\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$]	0.500	0.420	0.027

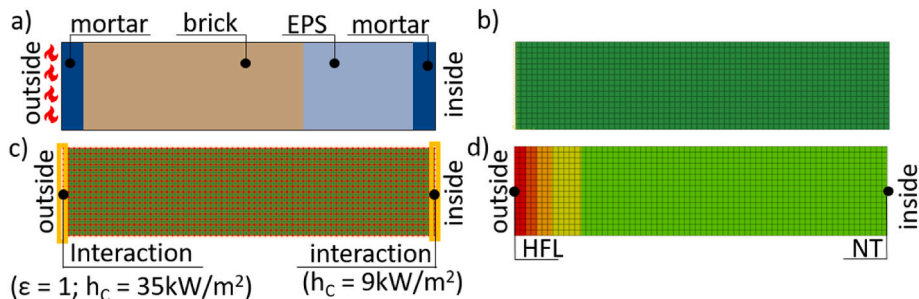


Fig. 6. a) Parts, b) mesh, c) interaction, d) thermal distribution.

1991-1-2 [14]. For the ISO 834 the coefficient changes to 25 kW/m², since it is a nominal curve and is according to the rules in EN 1991-1-2 [14].

For the radiation surfaces, since it is admitted a white color porous wall, the emissivity coefficient is approximately equal to 0.85 according to some commercial manufactures, however, to be more conservative in the calculation an emissivity equal to 1 was used. For the internal surface, according to EN 1991-1-2 [14], it is possible to apply only a convection surface with a convective heat transfer coefficient of 9 kW/m^2 . These surfaces were always applied in the surface elements of the mortar material according to the information in Fig. 6 c.

About the mesh, the type element DC2D4 is a 2D heat transfer element used for diffusive-thermal conduction. The DC2D4 is a linear quadrilateral element (also, called a four-node plane element) with bilinear interpolation for temperature. The x and y dimensions of the square element after meshing is 0.00125 m, generating 1173 nodes and 1088 elements. After some testing it was concluded that the size of mesh presented stable, therefore the need for more refined mesh was unnecessary.

A non-linear transient thermal analysis is performed for a total duration of 7200 s (120 min). The initial increment size is 0.1, and the maximum is 100. At the beginning of the time step, a lower time step integration is necessary for better representing the temperature rise rate. The maximum allowable temperature change per increment is 20 K, while the maximum allowable emissivity change per increment is 0.1. These restrictions are needed since, for small time steps, the time integration algorithm may change its convergence efficiency if the heat flux between elements increases too quickly. About the solver for the time, it

was chosen the explicit mode using a direct solution solver and applying a full Newton solution.

The scope of this case study is to conduct a thermal analysis for evaluating the heat transfer conditions between external temperature in which the thermal load is applied (as shown on outside part of Fig. 6 a) and the internal temperature computed (inside part) after the heat transfer analysis. The field output request is regarding thermal information such as nodal temperature (NT) and heat flux (HFL). The internal nodal temperature value was obtained at the middle point of the right side of the block (as shown in Fig. 6 d), whereas, the heat flux value was calculated as average value of integration points of elements pointed on the left side (as shown in Fig. 6 d). More specifically the mathematical formulation used for the heat flux (see equation (7)) was based on the Fourier's law of heat conduction

$$HFL(x, t) = -k(x, T) \cdot \nabla T(x, t) \quad (7)$$

In which $HFL(x, t)$ is the heat flux [$\text{W}\cdot\text{m}^{-2}$], the $k(x, T)$ is the thermal conductivity [$\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$], the $\nabla T(x, t)$ is the temperature gradient [$\text{K}\cdot\text{m}^{-1}$] and where x and t are respectively the position [m] and the time [s].

3.2.3. Results and discussion

Fig. 7 presents four plots for the numerical thermal responses of all the wildfire curves. To emphasize, all temperature curves (dashed lines) derived from experimental data showed values lower than those achieved by applying WC (red solid line). As a result, the upper bound load is guaranteed. So, the WC can be utilized as a design fire curve. In detail, the WC achieved a maximum value of 36 °C on the internal surface of the

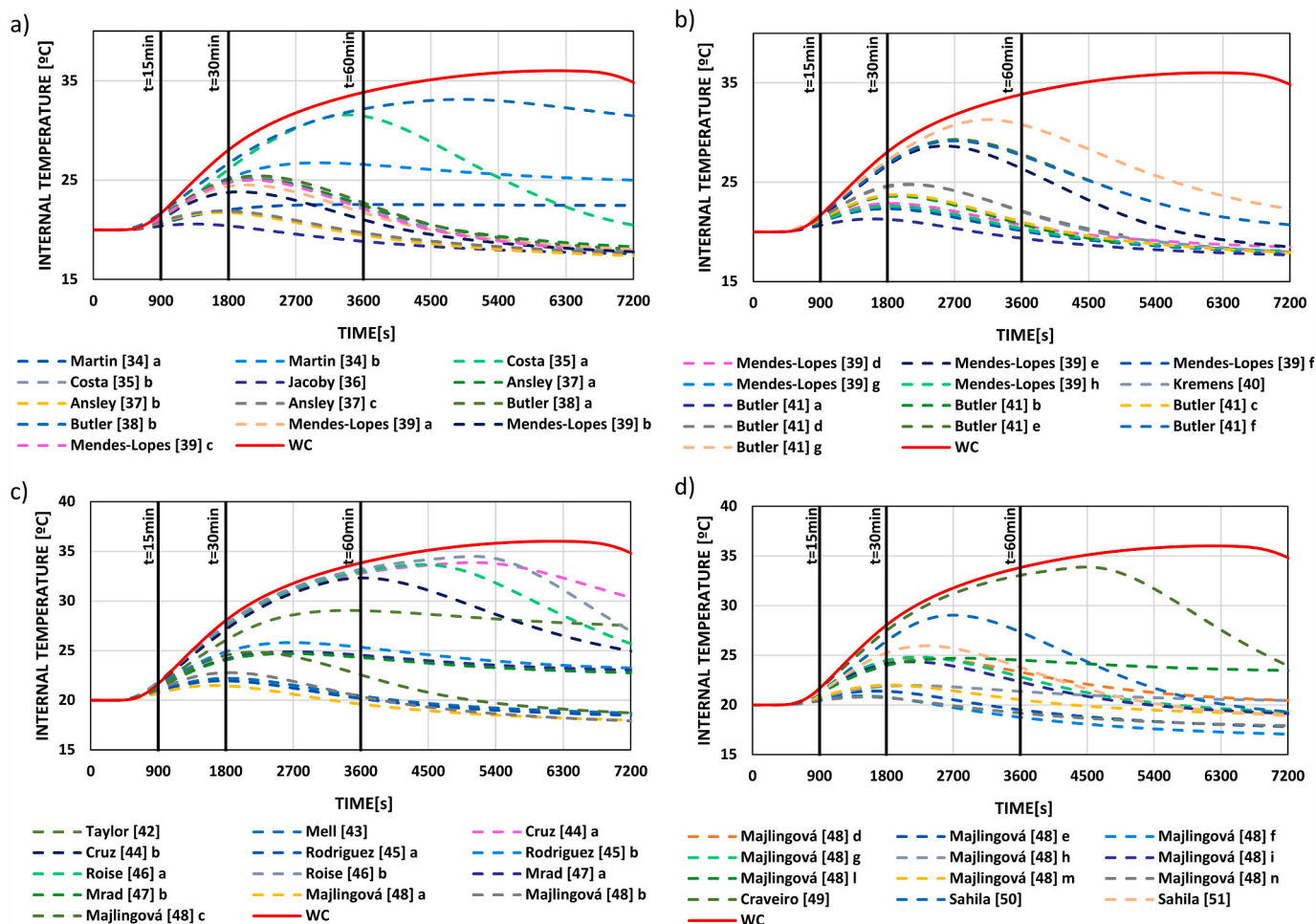


Fig. 7. Time-temperature curves.

wall. To underline that this is not the air temperature of the room, but the surface temperature, and according to the wildfire shelters report [20], its temperature is below 70 °C, therefore, it is expected the dwellers to withstand the passage of the wildfire. To verify the air temperature, it is necessary a CFD model, and it is beyond the scope of this work to present these results.

Observing Fig. 7 just four curves reached peak temperatures with a difference of less than 10 % compared with maximum value of 36 °C. These were Cruz et al. [44] a, Roise et al. [46] a-b, and Craveiro et al. [49], all of which reached 34 °C, after passing 1 h from the beginning of the thermal action. This means that the effect of heat transfer has to be assessed on a larger time-scale. Further, observing that four mentioned curves they have following characteristics in common such as peak temperature range (900–1016 °C), mean temperature rise rate of 17 °C/s, and TP height range (0–1 m) from ground. Even when considering a shorter period, equal to 30-min duration, the temperature curves (dashed lines) obtained remain lower than those produced by applying the Standard Wildfire Curve (WC), which reaches 28 °C (as shown in Fig. 7).

The wall section configuration, as depicted in Fig. 6, has also been tested for the thermal load as defined by the standard ISO 834, reaching an extreme value of 535 °C after 2 h, as shown by the solid black line in the plot of Fig. 8. The advantage of the proposed wildfire fire curve compared with the standard ISO 834 was confirmed since it was still a critical temperature (36 °C) but much less severe. However, the low peak value of 36 °C was justified by the choice of the wall section configuration in Fig. 6 a).

Regarding the cooling phase, analysis of the plots in Fig. 7 indicates that the model does not yet perfectly represent the underlying physical phenomena, as it frequently predicts final temperature lower than initial temperature. Thus, a more in-depth study is required to refine the calibration of the exponential parameter 'c' within equation (1), by establishing a relationship with physical parameters. A mathematical solution involves applying a lower bound to equation (1) during the cooling stage, ensuring that temperatures do not decrease below the initial temperature. However, observing the values obtained in this study (shown in Fig. 7), two groups have been identified: one group of 30 cases in which the final temperature is below 20 °C, and a second group of 21 cases where the final temperature is 20 °C or higher. In the first group, final temperatures range from 17 °C to 19 °C, representing a difference of 1 °C to 3 °C from the initial temperature. This discrepancy is due to the current formulation of Equation (1) for WC, which assumes an initial value of 0 °C and a return to 0 °C at the end of the curve's duration. Moreover, data presented in the third row of Table 6 show that the ratios (group 1/group 2) for the maximum external temperature (measured at the wall's exterior), maximum internal temperature (measured at the wall's interior), and t_{max} (the time to reach T_{max} as shown in Table 1) are 2.21, 1.22, and 1.33, respectively, while the ratio for T_{max} is 1. This suggests that the composition of the first three parameters plays a significant role in ensuring that the final temperature does not fall below the initial condition.

Two further configurations (with the same characteristics as shown

Table 6

Temperatures and time for different groups.

	Max_ext	Max_int	t_{max}	T_{max}
Mean for group 1 (≥ 20 °C)	469.3 [°C]	28.8 [°C]	62.1 [s]	742.7 [°C]
Mean for group 2 (< 20 °C)	212.8 [°C]	23.7 [°C]	46 [s]	739.2 [°C]
				11
Ratio group1/group2	2.21	1.22	1.33	1.00

in Table 5) were studied for assessing the inside temperature field. The second configuration, similar to Fig. 6 a, with all the same materials and thickness but with an inversion of the position of EPS (from left to right: mortar, EPS, brick, and mortar), meaning that the EPS was located on the external side of the wall. This is the classical wall assembly ETICs recommended by the European Union to enhance the thermal comfort [60]. The third configuration, in this case without EPS, was represented by the wall, which was simply made of brick and covered on both sides by mortar layers. As depicted in the plot of Fig. 8, for the WC in the second configuration (red dotted line) was 73 °C. This value was higher compared with first configuration, since the EPS was not being protected by the brick, but just by the mortar, on the external side. Also, this configuration that resembles the ETICs system, does not verify the maximum of 70 °C temperature in the internal surface according to the fire shelter requirements of [20]. The justification is that the behavior of the EPS is weak for elevated temperatures above 100 °C, therefore, since it is located in the exterior surface, the insulation properties are easily lost, allowing heat flux to rapidly penetrate the brick. For the third configuration (red dash-dotted line), the peak temperature was the highest equal to 92 °C. This was justified by the absence of the EPS in the section wall configuration. Further, the WC represented the worst scenario compared with the 51 curves analyzed also for the second and third configurations. So, in summary, the first configuration showed that the investment in protecting the existing dwelling is more useful in terms of efficiency and maintenance when the EPS is applied on the inside of the wall.

Another aspect to be clear when comparing WC with ISO 834 is that WC is not a monotonically increasing curve like ISO 834, since WC is composed of two parts: the first part has a heating initial condition and a cooling final condition (less evident for the first configuration but much clearer for the second and third configuration), as depicted in the plot of Fig. 6. This characteristic is more realistic in cases where the vulnerability of building materials to ignition is still not considered, as in this study. For example, windows, roofs, and doors represent weak points at which compartment fires can start. These building elements need sufficient protection to resist the exposure of wildfire attacks. However, the key idea to be defined is demonstrating that the existing dwelling can be adequately used since its internal thermal field is still capable of sheltering humans. Therefore, in case it wouldn't be possible to evacuate from the dwelling for any reason during the extreme thermal load provoked by a wildfire attack along the path, the safety of the dwellers may still be maintained.

About the heat flux values recorded, as shown in Fig. 9, a range value

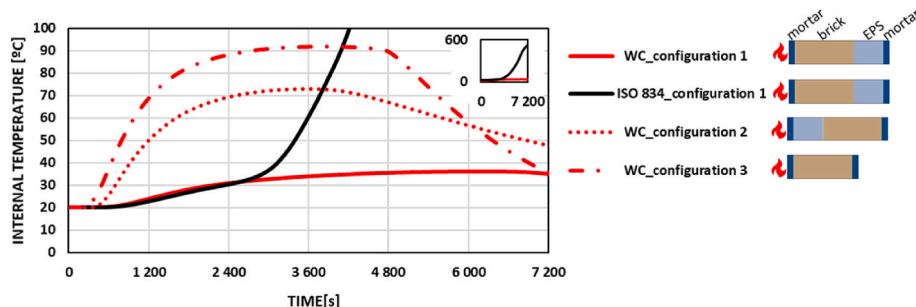


Fig. 8. Time-temperature curves for different wall section configuration.

of 13–370 kW/m² lasting around 60 s. The highest value is reached by Butler et al. [41] g. Most of them (32 of 51) have peak values higher than 40 kW/m², meaning that they are higher than the fourth bush fire attack level (BAL) as defined in AS3959 [61]. Recently some works of Hendawitharana et al. [62,63], have demonstrated in laboratory that near a BAL flame zone (BAL-FZ) the peak in heat flux can reach values above 50 kW/m², although lasting less than a minute. The heat flux range value is aligned with the numerical result from Fiorini et al. [64], in which the highest RHF values were around 180 kW/m² with a lasting time of about 60 s. The maximum radiative heat flux reported in the literature is 300 kW/m², as documented by Frankman [65] during a crown fire test at 1 m above ground level. Additionally, the heat flux magnitude shows a strong correlation with both the temperature rise rate and the maximum temperature (with correlation coefficients of 0.81 and 0.85, respectively). This relationship helps explain the higher value of 100 kW/m² obtained by Mendes-Lopes, whose peak temperature was nearly 951 °C.

Furthermore, although a value as high as 370 kW/m² was observed, no similar values were reported in other studies. This 370 kW/m² value can be justified by the combined effect of the highest recorded temperature (1337 °C) and the second-highest temperature rise rate (51 °C/s) in the dataset.

Regarding the heat flux curve derived from the WC, it is less conservative compared to the maximum values obtained from the experimental curves. Nevertheless, the WC's peak value of 88 kW/m² aligns closely with the average value of 89 kW/m² calculated from 51 experimental curves.

4. Conclusion

Despite numerous studies, the mathematical formulation for representing natural wildfire time-temperature curves remains insufficient for adoption as a standard thermal action model. Further research is needed to develop formulations that accurately capture all phases of the thermal event. Nevertheless, the literature consistently indicates that a wildfire curve (WC) typically lasts only a few minutes rather than hours. In this study, various experimental conditions and types of natural fuels were considered, thereby enhancing the reliability of the proposed WC.

Additional analysis is required to refine the proposed curve pattern, particularly to improve the representation of the decay phase and to ensure robust structural safety assessments. The Kolmogorov-Smirnov statistical method was employed to confirm that the characteristic curves meet the necessary probabilistic criteria for design purposes.

In the case study involving a classical external wall system found in old dwellings in southern Europe, the proposed characteristic curve proved more severe than any of the experimental curves implemented in the Abaqus thermal numerical model. In contrast, the nominal fire curves from ISO 834 produced an even more severe thermal load, suggesting that they may be overly conservative and unrealistic for fire-proofing dwellings against wildfires. Notably, the interior surface temperature did not exceed 70 °C, implying that even walls with less than an EI30 rating might survive a wildfire attack. The placement of insulation is critical; for the WC considered here, the traditional ETICS system with external insulation may be not the most adequate.

In conclusion, the proposed WC effectively represents an external fire

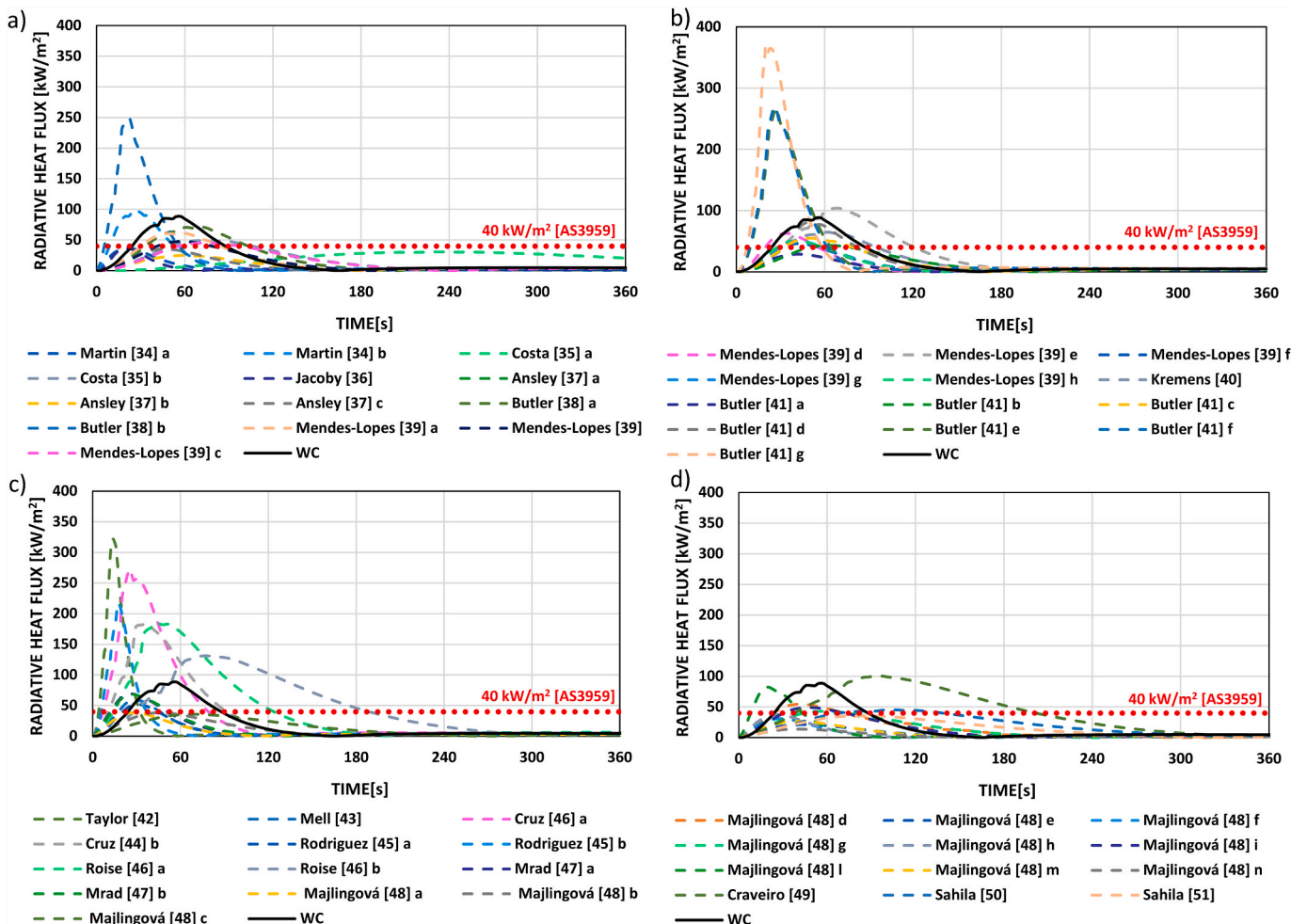


Fig. 9. Radiative Heat Flux results (on the external side) for different cases.

load for structural reliability assessments, and with further validation, it may serve as a basis for new methods in building codes.

4.1. Limitations of the proposed wildfire curves

This study does not include data on the time-temperature curve measured on contact surfaces affected by firebrand accumulation. It also does not examine windows, doors, or roofs—elements that are typically more vulnerable and permit greater heat flux penetration. Furthermore, the focus here is on the ignition risk phase of building materials. Although other factors, such as radiative heat flux, directly influence structural behavior, these parameters are not considered in the current study but will be addressed in future research.

CRediT authorship contribution statement

Cesare Fiorini: Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Mario Arruda:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Hélder D. Craveiro:** Writing – review & editing, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, Formal analysis. **Aldina Santiago:** Supervision, Methodology, Formal analysis. **Fernando Branco:** Supervision, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.firesaf.2025.104409>.

Data availability

Data will be made available on request.

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