Probabilistic Models for Temperature-Dependent Compressive and Tensile Strengths of Timber

Ester Garcia-Castillo[1]; Thomas Gernay, Aff.M.ASCE[2]; and Ignacio Paya-Zaforteza[3]

Abstract: Reliable reduction factors for timber mechanical properties at elevated temperatures are needed to design timber structures for fire safety as well as to assess the safety of historic timber structures against fire hazards. In this paper, a compilation of the available data on the compressive and tensile strengths of timber at elevated temperatures is carried out. Then, a probabilistic modeling approach to predict the temperature-dependent reduction factors applicable to fire design is proposed. The collected data cover both solid and engineered timber at temperatures from 20°C to 300°C, with a variety of sample sizes, wood species, test protocols, and moisture content used in the experiments. The data revealed a large scatter in elevated temperature strengths, and a large conservativeness of the relationships of the current European standard, which is commonly used for the advanced design of timber structures under fire. To address this variability, multiple probability density functions were calibrated across the temperature range, quantifying the goodness of fit with statistical criteria. Two-parameter Weibull functions provided the best fit, and continuous temperature-dependent relationships were derived for the parameters of the distribution. The proposed probabilistic models can be implemented in a numerical code, facilitating their use in analytical and computational approaches, and can be applied to the probabilistic assessment of the structural performance and reliability of timber structures against fire. **DOI: 10.1061/JSENDH.STENG-11369.**

Introduction

The application of performance-based design approaches in structural fire engineering is gaining increasing momentum. These approaches are usually applied in deterministic assessments (Bernardi et al. 2020; Fischer et al. 2019; Gernay and Elhami Khorasani 2020; Martinez and Jeffers 2021), where the effects of randomness in input parameters are not explicitly quantified. Deterministic analyses do not consider the full set of likely outcomes. Yet structural fire analyses involve a large number of uncertain parameters. These include the permanent and live loads, fire load density, and temperature-dependent material properties, among others. Therefore, probabilistic analyses constitute a more reliable approach to support fire safety designs of new structures. Moreover, as suggested by Garcia-Castillo et al. (2021), probabilistic analyses can also help to preserve existing structures (e.g., historic ones) designed when modern codes did not exist, thereby contributing to more sustainable construction.

Probabilistic fire analyses require stochastic models able to capture the inherent variability of the input parameters involved in the corresponding thermal and mechanical simulations. For this reason, probabilistic models for specific parameters within structural fire engineering have already been developed. Some examples are the probabilistic model proposed by Jovanović et al. (2020) for permanent and live loads and that suggested by Khorasani et al. (2014) for the fire load density in office buildings. The temperature-dependent mechanical properties of the materials are also a determining parameter when assessing the fire performance of structures. Thus, probabilistic models of the retained strengths of steel and concrete at elevated temperatures have been recently proposed (Qureshi et al. 2020). However, to the authors' knowledge, no such models exist for timber, despite the increasing popularity in its use as a building material and its associated environmental benefits (Barber 2018; Hildebrandt et al. 2017; Hill 2019). Standards and research efforts have focused solely on the probabilistic characterization of timber's strength at room temperature (JCSS PMC 2006; Sørensen and Hoffmeyer 2001; Volynsky 2006).

Currently, fire design of timber structures can be addressed through either prescriptive or performance-based approaches. Within the former, the reduced cross-section method of EN 1995-1-2 (CEN 2004c) and the 2018 *National Design Specification (NDS) for Wood Construction* (AWC 2018) proposed to assume an effective cross section for structural calculations in fire situation. The effective cross section is obtained by reducing the original cross section by the charring depth and an additional thickness that accounts for the decrease in strength and stiffness of the thermally affected timber behind the char front. Thus, the aforementioned codes provide charring rate values and expressions to determine these parameters.

Alternatively, EN 1995-1-2 (CEN 2004c) suggests temperature-dependent thermal and mechanical properties of timber for use in numerical simulations when assuming performance-based approaches. Specifically, for the mechanical properties, EN 1995-1-2 (CEN 2004c) established bilinear relationships that define the reduction in timber strength and stiffness with increasing temperature. These deterministic relationships were back-calculated by König and Walleij (2000) based on the structural response of timber frame assemblies submitted to the standard ISO 834-1 (ISO 1999)

[1]Ph.D. Candidate, Instituto Universitario de Ciencia y Tecnología del Hormigón, Universitat Politècnica de València, Camino de Vera s/n, Valencia 46022, Spain (corresponding author). ORCID: https://orcid.org/0000-0003-4665-730X. Email: esgarcas@upv.es

[2]Assistant Professor, Dept. of Civil and Systems Engineering, Johns Hopkins Univ., Latrobe Hall, 3400 N. Charles St., Baltimore, MD 21218. ORCID: https://orcid.org/0000-0002-3511-9226. Email: tgernay@jhu.edu

[3]Professor, Instituto Universitario de Ciencia y Tecnología del Hormigón, Universitat Politècnica de València, Camino de Vera s/n, Valencia 46022, Spain. ORCID: https://orcid.org/0000-0002-3995-8772. Email: igpaza@upv.es

Note. This manuscript was submitted on February 1, 2022; approved on October 25, 2022; published online on November 28, 2022. Discussion period open until April 28, 2023; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Structural Engineering***, © ASCE, ISSN 0733-9445.

fire exposure in a limited number of experimental tests. Several authors have suggested similar deterministic models (Thomas 1996; Van Zeeland et al. 2005). More recently, Naser (2019) used artificial intelligence to develop temperature-dependent constitutive material models for timber based on experimental data and deterministic models collected from the literature. As a result, simple expressions to predict the thermal and mechanical properties of timber as a function of temperature were derived.

Multiple published studies have provided experimental data on the reduction of timber strength at high temperatures. As indicated by Kuronen et al. (2021), Manríquez Figueroa and Dias De Moraes (2016), Wiesner et al. (2021), and Zaben et al. (2020), this topic is of major concern, especially with the advent of mass timber construction. Recently, several sources have collated the experimental data reported in the literature (LaMalva and Hopkin 2021; Naser 2019), revealing a large variability among these. This variability could be partly explained by the differences in heating and loading conditions assumed in the experimental tests, among other factors related to the features of the specimens.

In fact, as concluded in a literature review conducted by Gerhards (1982) and in various subsequent works (Manríquez Figueroa et al. 2015; Östman 1985; Wiesner et al. 2021), moisture content has a strong influence on timber strength at high temperatures. However, the influence that other factors and their possible interactions might have on the variability of the experimental data remains uncertain. These factors include the wood species, the density and size of the specimen, and the presence or absence of knots and other wood defects, among others. Therefore, notwithstanding the relevance of this type of studies to better understand the effects of elevated temperatures on timber strength reduction, their results might be highly influenced by numerous factors, and their findings may not apply to all cases. In addition, the lack of normalization of the experimental tests complicates discernment of the reasons for the observed differences.

The deterministic nature of the current temperature-dependent timber strength-reduction models hinders the consideration of the observed variability in probabilistic fire risk analyses. Furthermore, the evident disparity between the commonly adopted models of EN 1995-1-2 (CEN 2004c) and the experimental data from the literature calls into question the reliability of the fire safety designs of timber structures. Thus, the development of robust models for timber strength as a function of temperature is pressing.

Within this context, this paper proposes probabilistic models that capture the uncertainty of the compressive and tensile strengths of timber at high temperatures. These models are based on experimental data gathered from an extensive literature review. The importance of the contribution lies in the fact that these models can be applied to the probabilistic assessment of the structural performance of timber structures against fire to evaluate their reliability. In addition, the suggested models can be easily implemented in a numerical code, facilitating their use in analytical and computational approaches. Therefore, this work aims to promote the design of reliable and efficient timber structures with respect to fire safety.

Finally, by reducing the inherent uncertainty, this study fosters the use of timber as a building material in new construction, as well as the rehabilitation and preservation of timber elements in historic buildings. Both involve important environmental benefits. Wood requires less energy in its manufacture and has a lower environmental impact and fewer toxic emissions than other contemporary building materials (Sathre and Gustavsson 2009; Woodard and Milner 2016), making it more sustainable. Rehabilitation of historic structures, on the other hand, in addition to allowing the conservation of built heritage, generates less environmental impact, waste, and ecological footprint than new construction (Alba-Rodríguez et al. 2017) because it takes advantage of existing resources.

Materials and Methods

The objective of this paper is to propose probabilistic models for the temperature-dependent compressive and tensile strength–reduction factors of timber that capture the variability shown in the data. The strength-reduction factor (k) represents the loss of strength of a structural material with increasing temperature and is defined as the ratio of the material strength at a given temperature to the material strength at ambient temperature.

To achieve this objective, first, a comprehensive literature review was carried out to collect experimental data on timber compressive and tensile strengths at elevated temperatures. Then, the collected experimental data points were grouped into bins of 20°C temperature intervals based on a data binning technique commonly adopted in statistical analysis (Montgomery and Runger 2019; Zheng and Casari 2018). The temperature bins were denoted by their corresponding central value (T_{CV}), as usual, starting with 20°C. Therefore, each temperature bin contains experimental data within the following temperature range: ($T_{\mathrm{CV}} - 10$°C, $T_{\mathrm{CV}} + 10$°C). Next, multiple probability density functions (PDFs) were fitted to each temperature bin of both compressive and tensile strengths, and three different information criteria based on the likelihood function were assumed to quantify the relative quality of goodness of fit of the candidate PDFs and select the one that provided the best fit. The following sections provide additional information on the selection, definition, and validation of the proposed probabilistic models, as well as the main features of the experimental data on temperature-dependent timber compressive and tensile strengths.

Regarding the scope of the literature review, experimental data were gathered on both timber compressive and tensile strengths parallel to grain at elevated temperatures. Due to the inherent anisotropy of the material, timber mechanical properties differ depending on the direction (i.e., longitudinal, radial, or tangential) considered (Ross 2010). Most of the timber structural elements work in compression (e.g., columns) or in bending (e.g., beams). In both cases, the forces acting on the structural element generate compressive or compressive and tensile stresses of significant magnitude in the longitudinal direction of the element. Therefore, in this study, the longitudinal (parallel to grain) direction was assumed because it is the one that bears the highest stresses in most timber structural elements and, consequently, is the most relevant.

Thus, the temperature-dependent reduction factor for timber compressive strength parallel to grain ($k_{c,0,T}$) is the result of the compressive strength parallel to grain measured at a certain high temperature ($f_{c,0,T}$) divided by the mean value of the measured strength at ambient temperature ($f_{c,0,20}$); the reduction factor for timber tensile strength parallel to grain ($k_{t,0,T}$) can be obtained in the same way by adopting the corresponding values of retained tensile strength parallel to grain at an elevated temperature ($f_{t,0,T}$) and the mean of the experimental measured strength at ambient temperature ($f_{t,0,20}$). Hence, the reduction factor at ambient temperature is equal to unity.

The collected experimental data points come from high-temperature mechanical tests performed on both solid and engineered timber specimens of numerous species. The data set covers a temperature range from ambient temperature to 300°C, the latter being the commonly accepted charring temperature of wood (CEN 2004c) beyond which timber strength and stiffness are practically negligible. Additionally, only experimental results from wood specimens with values of initial moisture content up to 20% have been included because, even in unfavorable atmospheric conditions with high relative humidity and low temperatures, these are not maintained for a sufficiently long period of time for wood to reach higher moisture contents (Ross 2010).

In this way, experimental data from 30 different studies were included in the data set on temperature-dependent timber strengths. These studies cover the period from 1940 to present and the experimental data were available in tabular or graphical form. Those in the latter form were processed using computer-aided design (CAD) software to obtain the corresponding experimental data values. Finally, experimental data at elevated temperatures were either available in terms of strength or reduction factor. In the former case, studies that performed more than one experimental test for a given temperature generally reported the different strength values achieved. Thus, for those strength data points within the same study that were obtained under identical experimental conditions, the mean values associated with each temperature were assumed to calculate the reduction factors presented in this study.

Data on Temperature-Dependent Material Strength of Timber

Of the 30 studies selected from the literature review, 13 provided experimental data at elevated temperatures on timber compressive strength (Goodrich et al. 2010; Kollmann 1940, 1951; Manríquez Figueroa et al. 2015; Manríquez Figueroa and Dias De Moraes 2010, 2016; Sulzberger 1953; Wiesner et al. 2021; Young and Clancy 2001; Zaben et al. 2020); 10 on timber tensile strength (Do and Springer 1983; Frangi et al. 2012; Klippel et al. 2014; Kollmann and Schulz 1944; Kuronen et al. 2021; Lau and Barrett 1997; Manríquez Figueroa 2008; Nielsen and Olesen 1982; Östman 1985; White et al. 1993; White 1996; Yue et al. 2021; Zelinka et al. 2019); and seven on both compressive and tensile strengths (Glos and Henrici 1990; Khmelidze 1986; Knudson and Schniewind 1975; Nyman 1980; Rykov 1980; Schaffer 1973, 1984). According to the publications for which information was available, data were obtained from experimental tests performed on clear specimens (Knudson and Schniewind 1975; Kollmann 1940; Manríquez Figueroa 2008; Manríquez Figueroa et al. 2015; Manríquez Figueroa and Dias De Moraes 2010, 2016; Nyman 1980; Östman 1985; Schaffer 1973, 1984; Young and Clancy 2001; Yue et al. 2021; Zaben et al. 2020; Zelinka et al. 2019) as well as on specimens with presence of knots or other defects (Frangi et al. 2012; Glos and Henrici 1990; Klippel et al. 2014; Lau and Barrett 1997; Nielsen and Olesen 1982; White 1996; White et al. 1993; Wiesner et al. 2021).

Table 1 summarizes, in chronological order, the main features of the experimental tests associated with the experimental data gathered from the literature, focusing on the characteristics of the wood specimens, as well as the fire and load test conditions. It is important to highlight that some experimental data were collected from sources other than the original studies. Specifically, compressive and tensile strengths data of Khmelidze (1986), Nyman (1980), and Rykov (1980) reported by Aseeva et al. (2014), tensile strength data of Kollmann and Schulz (1944) reported by Kollmann and Côté (1968), and compressive strength data of Kollmann (1951) reported by König and Walleij (2000) were considered. In these cases, the sources consulted did not provide details of the experimental tests from which the data were derived. Hence, Table 1 does not include information on the experimental tests performed by Khmelidze (1986), Kollmann (1951), Kollmann and Schulz (1944), Nyman (1980), and Rykov (1980).

Before discussing Table 1, a few observations are in order. Firstly, in several tensile tests, specimens with a reduced cross section in the central part were used to reach failure in that region. In these cases, the width and thickness of both the full and reduced cross sections of the specimens are given in the table, with the dimensions corresponding to the full cross section indicated in parenthesis. Secondly, for those works addressing the mechanical behavior of finger joints at high temperatures (Frangi et al. 2012; Klippel et al. 2014; Nielsen and Olesen 1982; Yue et al. 2021), as well as the assessment of adhesive performance at elevated temperatures using half-lap joints (Zelinka et al. 2019), only experimental data from reference specimens without joints were included in the data set. Finally, the results provided by Young and Clancy (2001) were normalized to the strength of dry specimens at ambient temperature to be consistent with the rest of the data.

Except for the experimental tests conducted by Wiesner et al. (2021) on cross-laminated timber (CLT) specimens, all experimental data collected come from solid timber specimens. As can be observed in Table 1, wood specimens of multiple densities, moisture contents, and dimensions were assumed in the different experimental tests. Although the experimental tests conducted by Östman (1985) considered specimens with moisture contents up to 30%, only the results from specimens with moisture contents up to 20% were included in the data set.

Concerning the heating of the specimens, with the exception of the experimental tests carried out by Wiesner et al. (2021), heating was carried out prior to loading and, hence, under unstressed conditions. The information collected shows that, in general, specimens reached steady-state conditions in the experimental tests conducted by the different authors; however, transient conditions were also assumed by several authors (Glos and Henrici 1990; White 1996; White et al. 1993; Wiesner et al. 2021).

Overall, specimens were heated either with drying ovens or chambers or with heating plates. Exceptionally, temperature-controlled silicone oil baths (Östman 1985) and a combustion furnace with diffuse-flame natural gas burners (White 1996; White et al. 1993) were used to heat the specimens. In the case of the experimental tests performed by Do and Springer (1983), White (1996), and White et al. (1993), only the results from specimens exposed to heat for 60 min were considered because they are assumed to be closer to a steady-state condition than those with shorter time exposures. Finally, displacement-controlled loading (i.e., the load is applied at a constant displacement rate) was the most common mechanical test procedure for determining the timber strength.

In total, 302 experimental data points for $k_{c,0,T}$ and 182 data points for $k_{t,0,T}$ were collected from the literature review. Figs. 1 and 2 show the variability in the reduction of timber compressive and tensile strengths at high temperatures. Although 20°C is the commonly adopted value for ambient temperature (CEN 2004c), the reason why the timber strength at ambient temperature has been referred to as $f_{c,0,20}$ or $f_{t,0,20}$ in this paper, experimental tests from the literature showed some dispersion in the reference ambient temperature from which the data were normalized.

Figs. 1 and 2 also include the deterministic reduction factor models of EN 1995-1-2 (CEN 2004c) for timber strength parallel to grain. The Eurocode models appear conservative compared with the experimental data collected, especially in the case of compressive strength.

Next, the influence of specimen's density, initial moisture content, and size on timber compressive and tensile strengths parallel to the grain at elevated temperatures was qualitatively analyzed. Such effects do not necessarily have to be manifested because the experimental data points are normalized by the strength at room temperature of specimens of similar characteristics. First, Fig. 3 shows the effect of the specimen density on $k_{c,0,T}$ and $k_{t,0,T}$. The mean densities of compressive tests specimens ranged from 133 to 785 kg/m^3, and those of tensile strength varied between 347 and 606 kg/m^3. Even though timber strength tends to be higher as

Table 1. Main characteristics of the specimens and heating and loading conditions for the experimental data collected from the literature

References	Test type	Wood density (kg/m^3)	MC (%)	Specimen size (mm)	Heating	Loading
Kollmann (1940)	C	$\bar{x} = 426$, 785, 635, and 133	0	$30 \times 20 \times 20$	U/—/DO	—
Sulzberger (1953)	C	—	0–20	$50.8 \times 12.7 \times 12.7$	U/—/DO	Load. rates: 20.7 and 6.9 MPa/min
Schaffer (1973, 1984)	CT	432–522 ($\bar{x} = 474$)	0	C: $95.2 \times 25.4 \times 3.2$ T: $254 \times 25.4 \times 3.2$	U/St/HP	Strain rate: 2.3 mm/min (equivalent displacement rates: 6.3 mm/min for C; and 19 mm/min for T
Knudson and Schniewind (1975)	CT	420–570	0, 12	$19 \times 4.8 \times 4.8$	U/St/HP	—
Nielsen and Olesen (1982)	T	—	12	$3{,}100 \times 90\,(140) \times 33$	U/St/HP	—
Do and Springer (1983)	T	—	0	$100 \times 25.4 \times 6.35$ $100 \times 25.4 \times 3.18$	U/—/DO	—
Östman (1985)	T	$\bar{x} = 420$ ($\sigma = 25$)	0–30	$170 \times 10 \times 1$	U/St/Ot	Displacement rate: 8 mm/min
Glos and Henrici (1990)	CT	C: $\bar{x} = 380$ ($\sigma = 34$) T: $\bar{x} = 430$ ($\sigma = 38$)	8, 12	C: $180 \times 120 \times 50$ T: $1{,}700 \times 120 \times 50$	U/St/DO U/Tr/DO	Constant displacement rate
White (1996) and White et al. (1993)	T	$\bar{x} = 555.2$ ($\sigma = 27.8$)	9	$5{,}000 \times 89 \times 38$	U/Tr/Ot	Strain rate: 0.0003 mm/mm per min
Lau and Barrett (1997)	T	—	9–11	$4{,}480 \times 90 \times 35$	U/St/HP	Loading rates: 1.85, 0.2, and 0.067 kN/s
Young and Clancy (2001)	C	—	0, 12	$300 \times 90 \times 35$	U/St/HP	Strain rate: 0.001 min^{-1} (0.3 mm/min)
Manríquez Figueroa (2008)	T	$\bar{x} = 347$ ($\sigma = 42.7$)	≈12	$450 \times 20\,(50) \times 5\,(20)$	U/St/DO	Displacement rate: 2 mm/min
Goodrich et al. (2010)	C	$\bar{x} = 150$ ($\sigma = 45$)	2–8	$30 \times 30 \times 15$	U/St/—	Displacement rate: 0.5 mm/min
Manríquez Figueroa et al. (2015) and Manríquez Figueroa and Dias De Moraes (2010)	C	$\bar{x} = 379.3$ ($\sigma = 37.9$)	12	$150 \times 50 \times 50$	U/St/DO	Displacement rate: 2 mm/min
Frangi et al. (2012)	T	$\bar{x} = 435$ ($\sigma = 31$)	12	$800 \times 140 \times 40$	U/St/DO	Displacement rate: 0.02 mm/s
Klippel et al. (2014)	T	$\bar{x} = 412$	≈12	$150 \times 20\,(40) \times 5$	U/St/DO	Displacement rate: 0.8 mm/min
Manríquez Figueroa and Dias De Moraes (2016)	C	$\bar{x} = 776$ ($\sigma = 25$) $\bar{x} = 434$ ($\sigma = 46$)	12	$150 \times 50 \times 50$	U/St/DO	Displacement rate: 2 mm/min
Zelinka et al. (2019)	T	—	0	$460 \times 9.5\,(25) \times 4.8\,(25)$	U/St/DO	Displacement rate: 1 mm/min
Zaben et al. (2020)	C	$\bar{x} = 670$	12	$140 \times 45 \times 35$	U/St/DO	Displacement rate: 0.5 mm/min
Kuronen et al. (2021)	T	—	0, ≈10	$800 \times 20\,(45) \times 7\,(15)$	U/St/DO	Strain rate: 0.00005 s^{-1}
Wiesner et al. (2021)	C	$\bar{x} = 465.2$ ($\sigma = 23.2$)	9	$200 \times 100 \times 100$	U/St/DO S/Tr/DO	St: constant displacement rate; Tr: 25% or 50% of ambient temperature compressive failure load
Yue et al. (2021)	T	$\bar{x} = 531$, 606, and 557	10–12	$550 \times 40\,(70) \times 25$	U/St/DO	Displacement rate: 1 mm/min

Note: C = compressive strength test; T = tensile strength test; S = stressed; U = unstressed; St = stationary; Tr = transient; DO = drying/muffle oven and heating/drying chamber; HP = heating plates; Ot = other; $\bar{x}$ = mean value; σ = standard deviation; MC = moisture content; and an m-dash indicates information not available. The values in parentheses correspond to the dimensions of the full cross section of specimens with a reduced cross section in the central part.

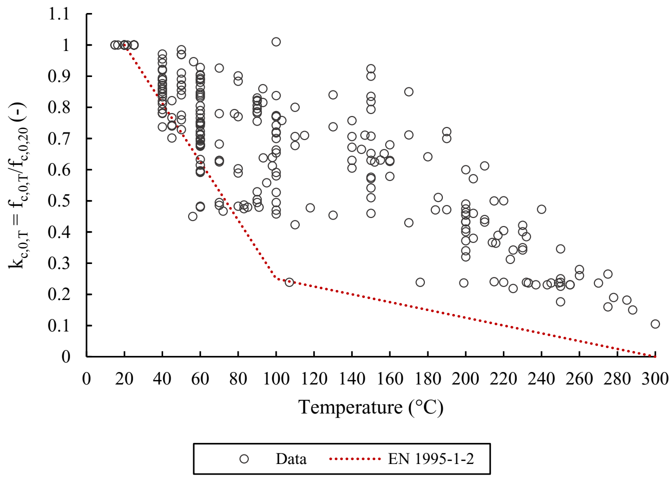


Fig. 1. Reduction factor data points for timber compressive strength parallel to grain ($k_{c,0,T}$).

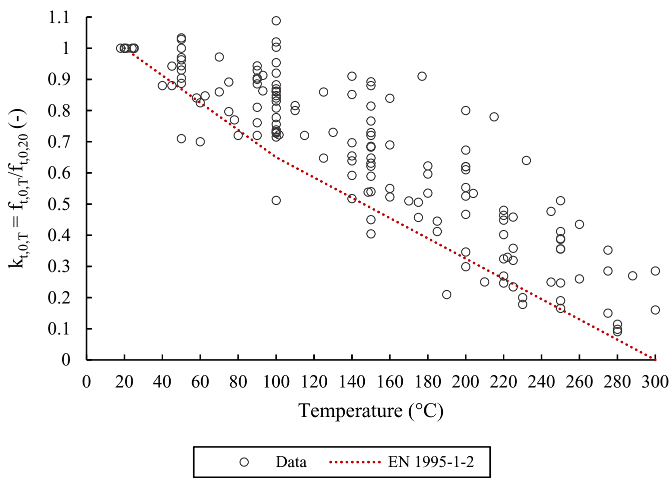


Fig. 2. Reduction factor data points for timber tensile strength parallel to grain ($k_{t,0,T}$).

density increases (CEN 2016), the strength reduction as a function of temperature did not seem to be governed by the density.

Fig. 4 shows the effect of the initial moisture content of the specimen on $k_{c,0,T}$ and $k_{t,0,T}$. The collected data come from experimental tests performed mainly on dry specimens or with initial moisture contents of 9% to 12%. For compressive strength, the results at temperatures below 100°C showed that the higher the moisture content, the lower the value of $k_{c,0,T}$ and thus the greater the reduction in strength.

For tensile strength, the experimental data were limited, and no obvious correlation was observed. This is in line with the findings of the literature review conducted by Gerhards (1982), which reported, inter alia, that timber mechanical properties decreased with increasing moisture content and that temperature and moisture content appeared to have the least influence on timber tensile strength parallel to the grain compared with the results for other timber mechanical properties. Experimental data were limited above 100°C for specimens with initial moisture contents different from 9% to 12%, so limited observations could be made on the effect that different values of initial moisture content might have on timber strength above 100°C. However, some of the data from moist specimens showed an increase in timber compressive and tensile strengths from 100°C to reach a peak at around 150°C (Do and Springer 1983; Manríquez Figueroa and Dias De Moraes 2010, 2016; Wiesner et al. 2021; Zaben et al. 2020).

Several authors suggested that this increase in strength could be due to the reduction in moisture content as free moisture is driven off from wood (Frangi et al. 2012; Klippel et al. 2014; Manríquez Figueroa and Dias De Moraes 2016), but the question of whether this strength increase occurs and, if so, how initial moisture content influences it, requires further research (Buchanan and Abu 2017). In addition, moisture migration into the heated wood, whose gradients and thus effects will be greater in larger cross sections, could also significantly affect the experimental tests results. Due to the significant role that moisture content seems to play on timber strength at elevated temperatures, its interaction with temperature needs to be further investigated.

Finally, Fig. 5 shows the effect of the cross-sectional area of the specimen on $k_{c,0,T}$ and $k_{t,0,T}$. The experimental data associated with larger cross sections are represented in the figure by larger circles. The cross-sectional areas of the specimens from the experimental tests found in the literature ranged from 0.23 to 100 cm^2 for $k_{c,0,T}$

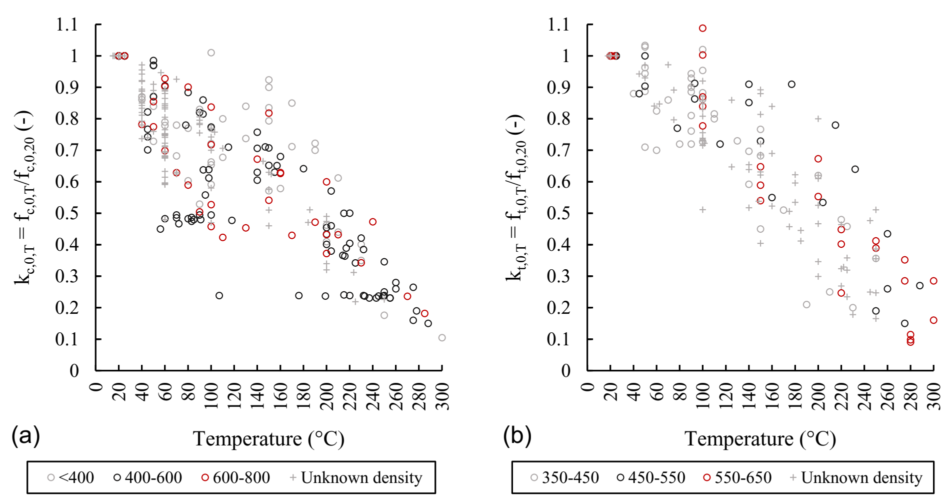


Fig. 3. Effect of the density of the specimen on (a) $k_{c,0,T}$; and (b) $k_{t,0,T}$. The legend indicates ranges of densities (kg/m^3).

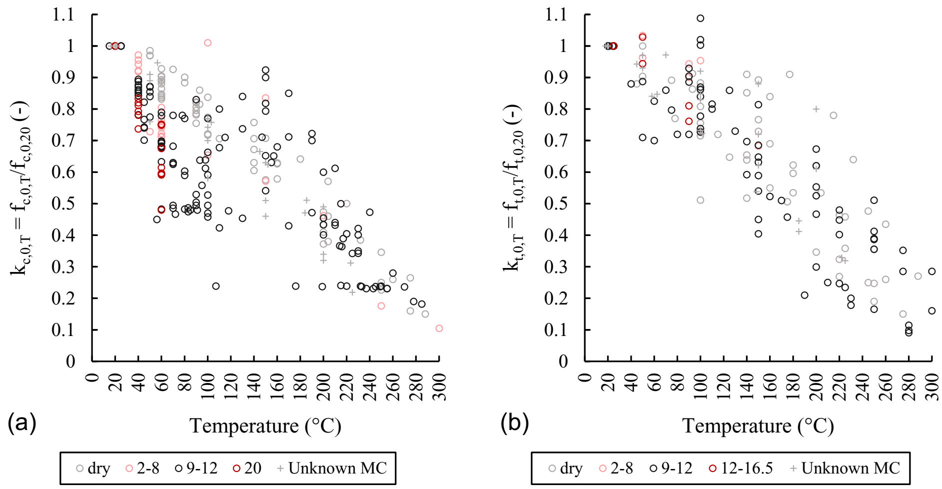


Fig. 4. Effect of the initial moisture content of the specimen on (a) $k_{c,0,T}$; and (b) $k_{t,0,T}$. The legend indicates values/ranges of initial moisture content as a percentage.

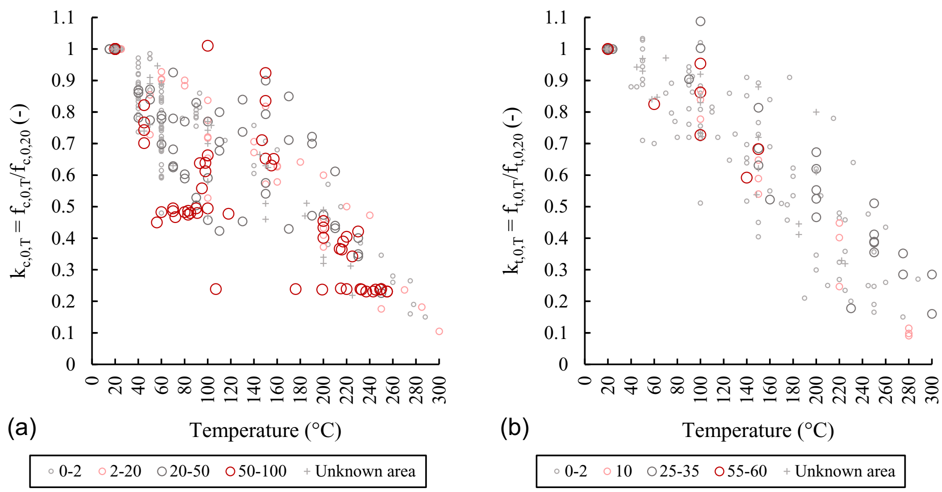


Fig. 5. Effect of the cross-sectional area of the specimen on (a) $k_{c,0,T}$; and (b) $k_{t,0,T}$. The legend indicates ranges of cross-sectional areas (cm^2).

and from 0.10 to 60 cm^2 for $k_{t,0,T}$. Tensile tests were generally performed on specimens with smaller cross sections, and dimensions of the specimens for compressive tests are quite variable. Specimen size directly influences the time of exposure to heat to reach steady state conditions because thermal and moisture gradients will be higher in larger specimens.

According to Buchanan and Abu (2017), larger timber members are more likely to fail at lower stresses compared with similar smaller members because the former will have a greater number of potential defects. These size effects are recognized in design codes (CEN 2004b). However, the experimental data did not show clear correlation between the cross-sectional dimensions of the specimens and the timber strength reduction, so further research might be needed. In the case of $k_{c,0,T}$, many experimental data points from specimens whose cross-sectional areas were between 50 and 100 cm^2 showed relatively high reductions of timber compressive strength at elevated temperatures. These data points are mainly the results of the experimental tests carried out by Wiesner et al. (2021), which considered exclusively specimens of CLT, where the influence of adhesive and ply configuration plays an important role in timber strength, whereas the rest of the papers provided data from experimental tests performed on solid timber specimens.

Furthermore, except for the specimens from the experimental tests conducted by Klippel et al. (2014), the aforementioned experimental tests performed on specimens with presence of knots or other defects are linked to the categories with the larger cross-sectional areas, varying between 29.7 cm^2 (Nielsen and Olesen 1982) and 100 cm^2 (Wiesner et al. 2021). Consideration of specimens with larger cross-sectional dimensions allows a better assessment of the influence of defects on timber strength because they will be present to a greater extent. Because multiple variables were involved in the experimental tests carried out by Wiesner et al. (2021) and no additional experimental data were found from other sources, possible correlations concerning engineered timber systems cannot be confirmed at this point.

It is important to highlight that besides the cross-sectional area, the length of the specimens influences the timber compressive and tensile strengths parallel to grain (Fryer et al. 2018; Moshtaghin et al. 2016a; Showalter et al. 1987; Totsuka et al. 2022). In particular, several studies (Moshtaghin et al. 2016b; Showalter et al. 1987) proposed models to consider the size effects on timber tensile strength, which are based on the weakest link theory for brittle failures. However, the possible effect of the specimen length on the reduction of timber strength at elevated temperatures was not statistically significant in the data set collected in the present study.

In summary, the literature review revealed a lack of standardization in the testing methods of timber specimens at elevated temperatures. Great variability was found among experimental tests from different sources, especially in specimen dimensions, as well as heating and loading conditions. The lack of standardization, together with the large number of variables involved, limits our common understanding of the effect of elevated temperatures on timber strength. Because the experimental data collected are influenced by multiple variables and experimental conditions, the possible effect of a single variable on the reduction of timber strength at high temperatures cannot be discerned and, therefore, observations derived from Figs. 3–5 should be taken as indicative. Greater standardization is desirable. In the meantime, the data exhibit large scatter and currently adopted models such as Eurocode appear very conservative, especially in compression. This calls for a probabilistic approach to refine the evaluations of the structural fire response of timber structures.

Probabilistic Modeling of the Temperature-Dependent Material Strength

Model Selection and Definition

For the purpose of defining robust stochastic models for the temperature-dependent compressive and tensile strengths of timber, first, eight different PDFs were considered as candidates. These are among the most widely used continuous functions and include the lognormal, gamma, loglogistic, normal, logistic, Laplace, two-parameter Weibull, and extreme value PDFs. Subsequently, each of the candidate PDFs was fitted to the data sets for each of the temperature bins considered for timber compressive and tensile strengths. Fig. 6 shows the number of experimental data points included in each temperature bin. Only those temperature bins with more than five experimental data points were considered to select and define the probabilistic models of the temperature-dependent timber strengths.

The relative quality of goodness of fit of each candidate model in each temperature bin was then measured through three information criteria. The considered information criteria include the Akaike information criterion (AIC) (Akaike 1974), the AICc (Hurvich and Tsai 1993), and the default Bayesian information criterion (BIC) (Schwarz 1978). All three are based on the likelihood function, $\mathcal{L}(\theta|\mathcal{D},\mathcal{H})$, which represents, for a specific predicting model

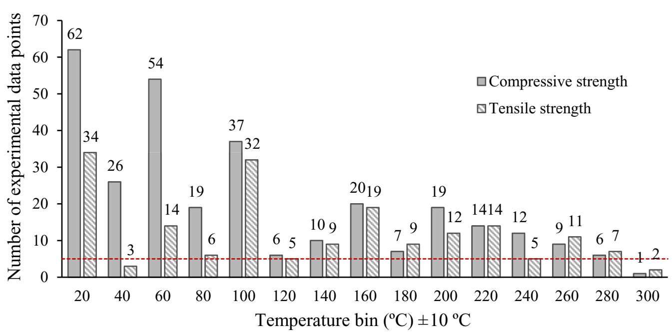


Fig. 6. Number of experimental data points per temperature bin for compressive and tensile strengths parallel to grain.

($\mathcal{H}$), the likelihood of the model parameters (θ) given the observed data ($\mathcal{D}$). Therefore, the model with the highest likelihood would be the one that best fits the data. The AIC consists of two terms, one that penalizes the AIC value depending on the number of explanatory variables of the model and the other one that assesses the goodness of fit of the model (i.e., the relative amount of information lost by the model) through the likelihood function. Because likelihood tends to increase as the number of parameters increases, the penalty term, which favors the selection of simpler models, prevents overfitting. The value of AIC can be derived as follows:

$$\mathrm{AIC} = 2k - 2\ln(\hat{\mathcal{L}}) \tag{1}$$

where k = number of parameters estimated in the model; and $\hat{\mathcal{L}}$ = maximized value of the likelihood function.

Because the AIC might still be prone to select models with a larger number of parameters when sample size is small (Claeskens and Hjort 2008), the AICc is essentially the AIC with a correction for small data set sizes that adds an extra penalty term and, thus, the AICc is formally defined as follows:

$$\mathrm{AIC}_c = \mathrm{AIC} + \frac{2k^2 + 2k}{n - k - 1} \tag{2}$$

where n = sample size.

Finally, the BIC is closely related to the AIC, but considers a different penalty term for the number of parameters in the model. The value of BIC can be obtained as follows:

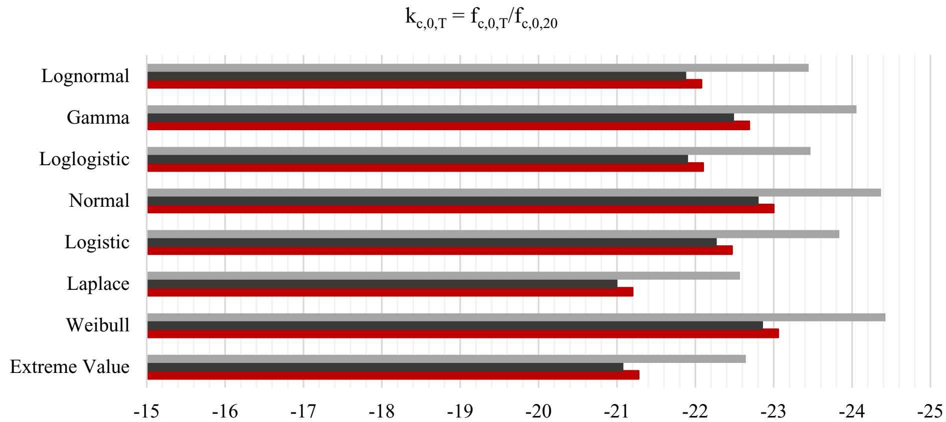
$$\mathrm{BIC} = k\ln(n) - 2\ln(\hat{\mathcal{L}}) \tag{3}$$

The lower the values of AIC, AICc, or BIC, the better the quality of the model. It is important to note that these information criteria do not provide information on the absolute quality of the model and, therefore, their results are only meaningful when compared with those of different models fitted to the same data. An analysis of how well the selected probabilistic models represent the experimental data is included in the "Model Validation" section of this paper.

For each information criterion, a measure of the goodness of fit was obtained for the eight candidate PDFs fitted to the different temperature bins of both compressive and tensile strengths. Then, the mean values of the information criteria estimates for each temperature bin were computed to select the PDF that provided the best fit. Fig. 7 shows the mean values obtained for each information criterion and PDF for timber compressive strength, and Fig. 8 shows those obtained for timber tensile strength.

The results show that the Weibull PDF best represents the timber compressive strength data, whereas the gamma PDF, closely followed by the Weibull PDF, would be the most appropriate to describe the reduction of timber tensile strength as a function of temperature. Given that the mean values obtained for gamma and Weibull PDFs information criteria estimates are very close, it seems reasonable to assume the same distribution for both compressive and tensile strengths, thereby facilitating the implementation of the probabilistic models in a numerical code. Furthermore, the use of the Weibull PDF to characterize timber strength is supported by several reliable sources (CEN 2002; SFPE 2016; Thelandersson and Larsen 2003) when there are no constraints or established bases for selecting a specific PDF. On the other hand, findings from an exhaustive study involving roughly 6,700 specimens of structural timber (Sørensen and Hoffmeyer 2001) showed that the Weibull PDF provided the best fit to the ambient-temperature strength data. Finally, the Weibull PDF has been also assumed in several works to describe timber strength at ambient

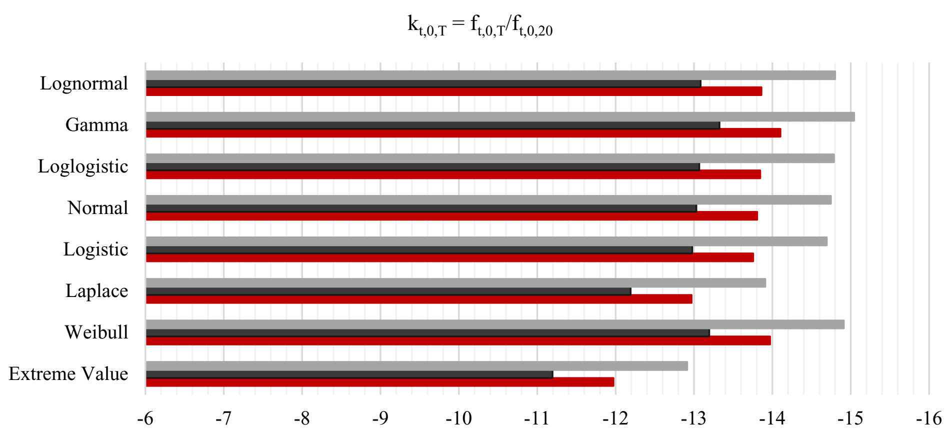
J. Struct. Eng., 2023, 149(2): 04022239



	Extreme Value	Weibull	Laplace	Logistic	Normal	Loglogistic	Gamma	Lognormal
AIC	-22.645	-24.426	-22.569	-23.837	-24.370	-23.469	-24.056	-23.447
AICc	-21.071	-22.852	-20.996	-22.263	-22.796	-21.896	-22.483	-21.873
BIC	-21.276	-23.057	-21.201	-22.468	-23.001	-22.101	-22.688	-22.078

AIC AICc BIC

Fig. 7. Mean values of the three information criteria considered for each candidate PDF for timber compressive strength parallel to grain. Lower values represent better fit to the data.



	Extreme Value	Weibull	Laplace	Logistic	Normal	Loglogistic	Gamma	Lognormal
AIC	-12.913	-14.912	-13.910	-14.696	-14.748	-14.786	-15.044	-14.803
AICc	-11.195	-13.194	-12.192	-12.978	-13.030	-13.069	-13.326	-13.085
BIC	-11.972	-13.972	-12.970	-13.755	-13.807	-13.846	-14.104	-13.862

AIC AICc BIC

Fig. 8. Mean values of the three information criteria considered for each candidate PDF for timber tensile strength parallel to grain. Lower values represent better fit to the data.

temperature (Christoforo et al. 2020; Moshtaghin et al. 2016a; Pang et al. 2020). Thus, the Weibull PDF was selected to define the probabilistic models for both compressive and tensile strengths of timber at elevated temperatures.

The two-parameter Weibull PDF is defined as follows:

$$f(x;k,\lambda) = \begin{cases} \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-\left(\frac{x}{\lambda}\right)^{k}}, & x \geq 0 \\ 0, & x < 0 \end{cases} \quad (4)$$

where k and λ = shape and scale parameters of the two-parameter Weibull distribution, respectively. Thus, the proposed probabilistic models define these parameters as a function of temperature.

On the other hand, the selection of the PDF has been made considering only the temperature bins at elevated temperatures, therefore excluding those at ambient temperature. Therefore, it was necessary to assume a criterion for defining the Weibull parameters at ambient temperature to ensure continuity of the fitted equations for the temperature-dependent parameters of the Weibull fit between ambient and elevated temperatures. According to the Joint Committee on Structural Safety (JCSS) probabilistic model code

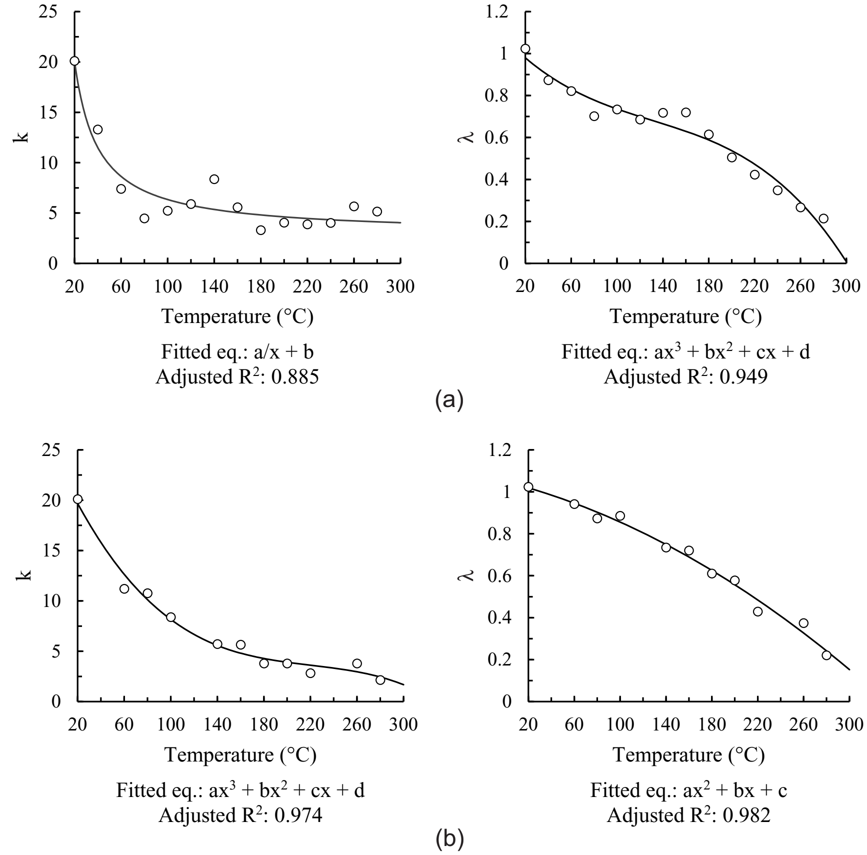


Fig. 9. Temperature-dependent regression equations for parameters k and λ of the Weibull distribution for (a) compressive strength–reduction factor $k_{c,0,T}$; and (b) tensile strength–reduction factor $k_{t,0,T}$.

(JCSS PMC 2006), it can be assumed that both compressive and tensile strengths parallel to the grain at ambient temperature follow a lognormal distribution. Given that the reduction factor data points collected from the literature were normalized to be equal to 1.0 at ambient temperature, a lognormal PDF with mean equal to 1.0 and coefficient of variation (COV) equal to 0.05 was defined to characterize $k_{c,0,T}$ and $k_{t,0,T}$ at ambient temperature.

The normalization of the data with respect to the measured value at ambient temperature allows treating the natural variability of the timber strength separately from the variability of the strength reduction with temperature. The former can be considered either deterministically, assuming a specific value for all simulations, or probabilistically, selecting random values from PDFs that capture the variability of timber strength at ambient temperature [PDFs of this type have already been suggested in various sources (JCSS PMC 2006; Sørensen and Hoffmeyer 2001)]. The latter was considered through the probabilistic retention factor models proposed in the present study. Therefore, in theory, the COV for the reduction factor at 20°C is null. However, to allow calibration of a continuous temperature-dependent function for the parameter k in the range 20°C–300°C, a COV of 0.05 was adopted at 20°C. Next, from the defined lognormal PDF, 10,000 random values were generated to which a Weibull PDF was fitted. A sensitivity analysis was conducted to confirm that the number of random values considered was such that the Weibull parameters obtained were not sensitive to alternative sets of random values.

Several types of equations were then considered to fit the k and λ parameters of the fitted Weibull PDFs as a function of temperature. They should be simple, continuous, and closed-form equations to facilitate the implementation of the models in finite-element applications, as well as bounded to positive values. The adjusted R^2 statistical measure was used to select the regression equation that provided the best fit to the Weibull parameters in each case. Unlike R^2, adjusted R^2 accounts for the number of explanatory variables of the regression model and penalizes those models that add extra variables that do not contribute to significantly improve the goodness-of-fit. The selected regression equations as a function of the temperature for k and λ were, respectively, a rational equation and cubic polynomial for $k_{c,0,T}$ and a cubic and a quadratic polynomial for $k_{t,0,T}$. The final fitted equations for the temperature-dependent parameters of the Weibull fits for $k_{c,0,T}$ data are

$$k(T) = 344.50/T + 2.892 \tag{5}$$

$$\lambda(T) = -8.015 \times 10^{-8} \times T^3 + 3.155 \times 10^{-5} \times T^2 - 5.843 \times 10^{-3} \times T + 1.085 \tag{6}$$

where T = temperature (°C), for which the Weibull PDF is to be evaluated. Likewise, those obtained for the temperature-dependent parameters of the Weibull fits for the $k_{t,0,T}$ data are as follows:

$$k(T) = -1.653 \times 10^{-6} \times T^3 + 1.093 \times 10^{-3} \times T^2 - 2.547 \times 10^{-1} \times T + 24.35 \tag{7}$$

$$\lambda(T) = -5.289 \times 10^{-6} \times T^2 - 1.402 \times 10^{-3} \times T + 1.049 \tag{8}$$

Figs. 9(a and b) show the values of k and λ obtained for the fitted Weibull PDFs for the different data sets corresponding to the considered temperature bins for timber compressive and tensile strengths, respectively, as well as a representation of the fitted equations and the associated adjusted R^2 values. As required by the Weibull PDF, the proposed equations for k and λ yield to positive and nonzero values within the range of temperatures considered (i.e., from the ambient temperature to 300°C).

Model Validation

The aim of this section is to assess how well the proposed probabilistic models represent the original experimental data collected from the literature. First, the two-sample Kolmogorov-Smirnov test (K-S test) was considered to test, for both compressive and tensile timber strengths, whether the original experimental data set and a synthetic data sample generated from the proposed probabilistic model come from the same probability distribution. Briefly, the two-sample K-S test quantifies the distance between the empirical CDFs of two data sets. Besides the $D_{n,m}$ statistic, which provides the aforementioned quantification by computing the maximum distances between the empirical distributions of the two samples, the K-S test returns the p-value as an output. P-values lower than the significance level reject the null hypothesis (i.e., falsify that the two data sets were drawn from the same distribution). A 5% significance level was assumed in this case. Regarding the synthetic data set considered, for each temperature bin, 10,000 random values of $k_{c,0,T}$ and $k_{t,0,T}$ were generated every 5°C (i.e., 40,000 random values per temperature bin) assuming the Weibull PDFs defined by Eqs. (4)–(8).

Importantly, a sensitivity analysis was carried out to ensure that the number of random values generated was sufficient to provide reliable and not very sensitive K-S test results when considering different synthetic data sets. The temperature bins contain experimental data within a range of ±10°C with respect to the central value. Therefore, it is logical to apply the K-S test assuming small-sized temperature bins (i.e., 5°C bins) of synthetic data because the developed probabilistic models are intended to be applied to determine the timber strength reduction at any temperature between 20°C and 300°C. For a given temperature bin, each of the four synthetic data sets generated was compared with the original experimental data of the whole bin. Table 2 presents the p-value results of the K-S test for both compressive and tensile timber strengths. Results for the 40°C, 120°C, and 240°C bins of tensile strength are not provided because these did not contain more than five experimental data points and, therefore, were not considered to define the probabilistic model. According to the two-sample K-S test results, the 80°C bin for compressive strength was the only one for which a p-value lower than 0.05 has been obtained and, consequently, for all other temperatures in the range 20°C–300°C, the null hypothesis that original and synthetic data sets come from the same distribution at the 5% significance level is verified.

On the other hand, Fig. 10 compares for the 100°C, 200°C, and 280°C bins the Weibull PDFs fitted to the experimental data and those defined by the probabilistic models for $k_{c,0,T}$ and $k_{t,0,T}$. The experimental data associated with these temperature bins are also included in the figure in the form of histograms with intervals of 0.1 width. Lastly, dashed lines represent the value of the strength-reduction factor proposed by EN 1995-1-2 (CEN 2004c) associated with each temperature.

As can be observed, Weibull PDFs fitted to the original data (i.e., Weibull PDFs defined by the parameters corresponding to the circles in Fig. 9) agreed with those proposed by the probabilistic models with continuous functions from Eqs. (5)–(8). For the 100°C and 280°C bins of the $k_{c,0,T}$, the compared Weibull PDFs differed slightly from each other. The latter can be attributed to the difference between the values of the Weibull's shape parameter, k, as shown in Fig. 9. In any case, the distributions proposed by the

Table 2. P-value results of the K-S test to compare original and synthetic timber strength data samples

Temperature bin (°C)	$k_{c,0,T}$	$k_{t,0,T}$
40	0.315	—
60	0.259	0.814
80	*0.001*	0.729
100	0.432	0.453
120	0.866	—
140	0.211	0.751
160	0.068	0.847
180	0.878	0.476
200	0.053	0.719
220	0.245	0.132
240	0.051	—
260	0.191	0.264
280	0.367	0.477

Note: P-values lower than 0.05 falsify the hypothesis that the synthetic Weibull data sets were drawn from the same distribution as the original experimental data set. P-values lower than 0.05 are indicated in italics.

probabilistic model for these temperature bins still fit the experimental data accurately. It is also clear that Eurocode reduction factors are conservative, corresponding to low quantiles of the distributions. A more detailed analysis of the latter is included in the "Discussion" section of the present paper.

Finally, for both $k_{c,0,T}$ and $k_{t,0,T}$ probabilistic models, 15 random values every 5°C from 20°C to 300°C were generated using the proposed probabilistic models to be graphically compared with the original experimental data points, as depicted in Fig. 11. The 0.05, 0.5, and 0.95 quantiles of the proposed probabilistic models, as well as the temperature-dependent timber strength-reduction models from EN 1995-1-2 (CEN 2004c) are also included in these figures. As can be inferred from the figure, the generated synthetic data captured the experimentally observed variability well.

Discussion

The proposed probabilistic models for $k_{c,0,T}$ and $k_{t,0,T}$ are, in essence, continuous and closed-form equations defining the temperature-dependent parameters of the Weibull PDFs. The simplicity of the proposed probabilistic models enable their simple implementation in a numerical code for modeling structures in fire. In future studies, the authors intend to implement the probabilistic timber material in the nonlinear finite-element software SAFIR (Franssen and Gernay 2017) to conduct probabilistic fire risk analyses of timber structures. Monte Carlo simulations can be performed by randomly selecting quantiles of the strength distribution when running the thermal-structural analyses. The parameters defining the Weibull PDFs can be evaluated for the temperatures obtained from the thermal analysis at each time step using Eqs. (5)–(8).

As already discussed, probabilistic models for the temperature-dependent strength of steel and concrete were recently proposed by Qureshi et al. (2020). In their study, those authors observed that the 0.5 quantiles (median) of the collected data for concrete and steel agreed quite well with the deterministic EN 1992-1-2 (CEN 2004a) and EN 1993-1-2 (CEN 2005) models, respectively. However, in the case of timber strength, the EN 1995-1-2 (CEN 2004c) model has turned out to be very conservative, especially for compressive strength at temperatures above 80°C (Fig. 11). This can be observed from the reduction factors of the EN 1995-1-2 (CEN 2004c) model plotted in Fig. 10 when compared with the corresponding proposed Weibull PDFs distributions. In the case of compressive strength, the

J. Struct. Eng., 2023, 149(2): 04022239

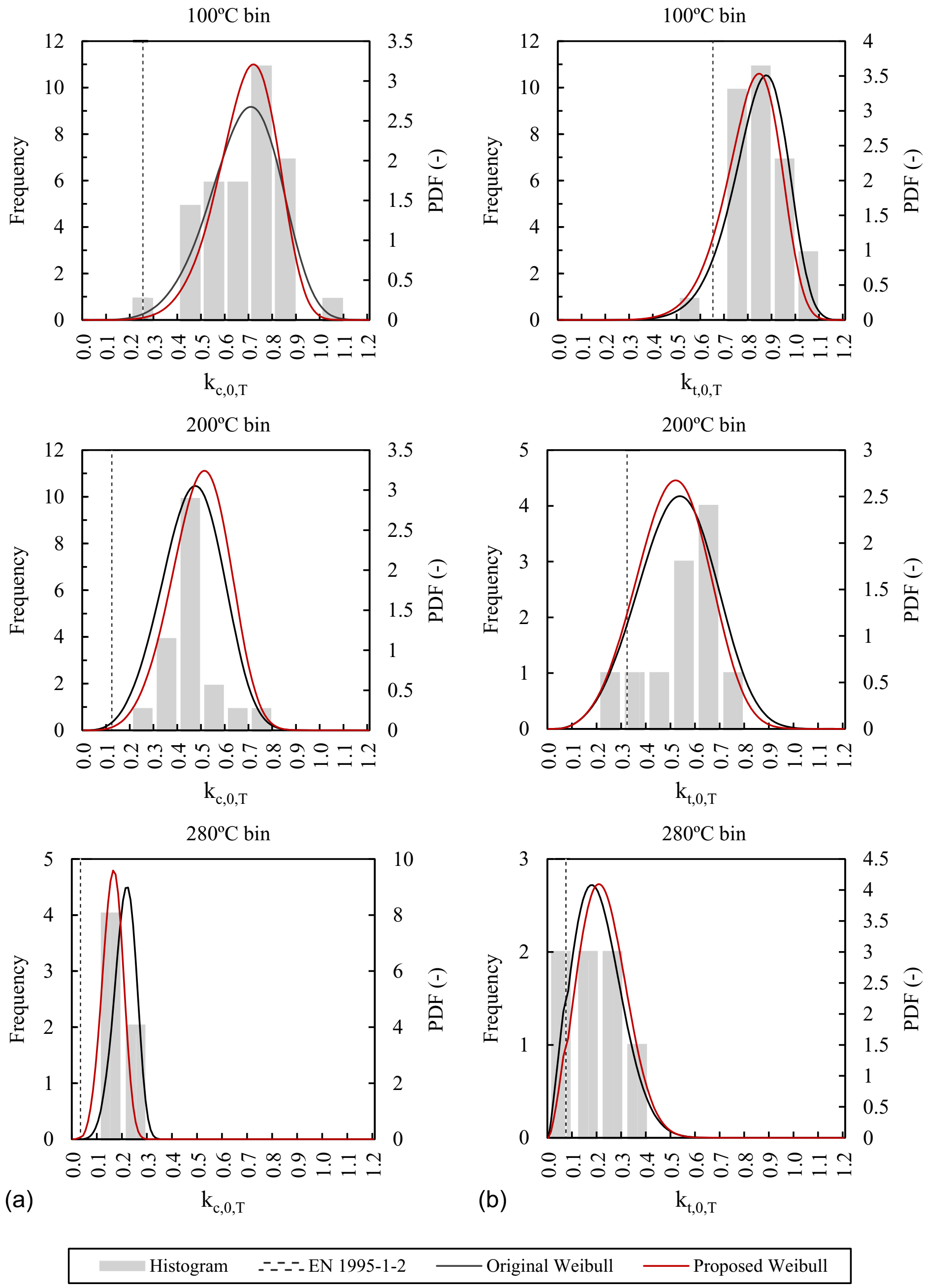


Fig. 10. For the 100°C, 200°C, and 280°C temperature bins, Weibull PDFs fitted to experimental data versus those proposed for (a) $k_{c,0,T}$; and (b) $k_{t,0,T}$.

values of $k_{c,0,T}$ of EN 1995-1-2 (CEN 2004c) correspond to approximately the 0.0011, 0.0012, and 0.0004 quantiles of the proposed probabilistic model at 100°C, 200°C, and 280°C, respectively, whereas for tensile strength, the associated quantiles are 0.101, 0.115, and 0.040.

On the other hand, timber strength values for fire design of EN 1995-1-2 (CEN 2004c) were not consistent with those proposed for concrete (CEN 2004a) and steel (CEN 2005). The latter assumed a value of design strength in fire that depends on the characteristic strength (i.e., fifth percentile value) at ambient temperature, whereas in the case of timber, it depends on the 20th percentile strength. This discrepancy has recently been examined to assess whether timber strength values for fire design are unconservative. Specifically, a study by Fahrni (2021) concluded that the 20th percentile assumption leads to appropriate reliability levels and, compared with the fifth percentile, provides lower reliability scatter. However, these findings are based on the standard ISO 834 fire exposure and, according to Fahrni (2021), the resulting reliability is significantly dependent on the fire exposure. Thus, further research would be advisable to ensure that the same reliability level is achieved in the fire design of timber structures under different fire exposures.

Regarding the trend of the timber strength reduction at elevated temperatures, as can be deduced from the 0.5 quantiles shown in Fig. 11, tensile strength showed an almost linear relationship in which the strength decreased as temperature increased. Compressive strength, in contrast, decreased rapidly in the temperature ranges from ambient temperature to 100°C and from 200°C to 300°C and considerably slower between 100°C and 200°C, approximately. As can be observed in Fig. 11, the probabilistic model

J. Struct. Eng., 2023, 149(2): 04022239

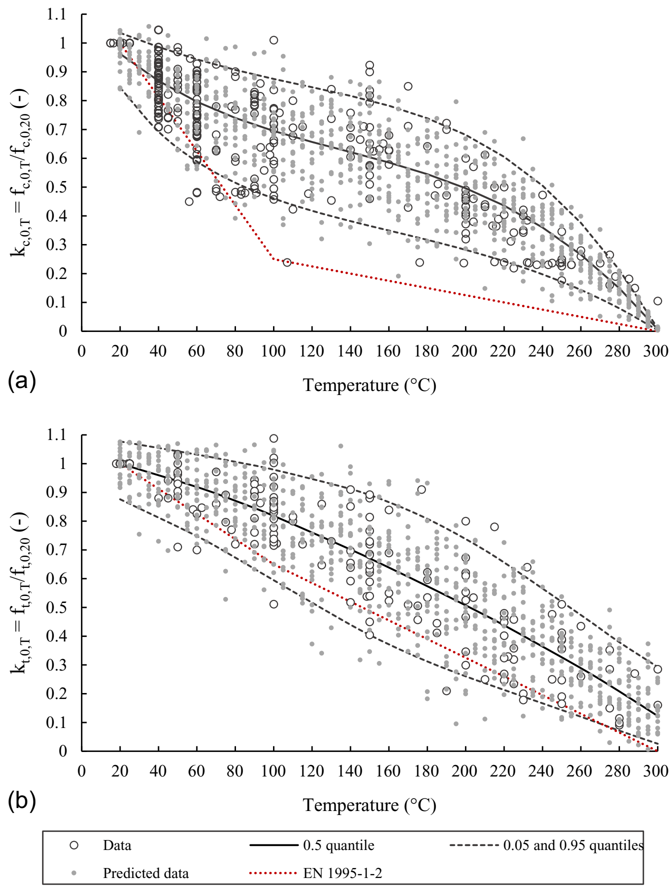


Fig. 11. Experimental and predicted data, together with the 0.05, 0.5, and 0.95 quantiles of the proposed probabilistic models for (a) $k_{c,0,T}$; and (b) $k_{t,0,T}$.

proposed for compressive strength yielded values very close to zero when 300°C is reached. Although this is in accordance with the standard provisions (CEN 2004c), experimental data appear to show that some strength is still retained at 300°C. This is particularly evident for $k_{t,0,T}$, which shows a wide scatter within the experimental data from 250°C to 300°C. However, due to the limited number of experimental data points around the charring temperature of wood, further research would be necessary to assess whether the assumption of neglecting the strength of timber above 300°C might be somewhat conservative.

In short, the proposed probabilistic models captured uncertainties in timber strength at elevated temperatures based on the experimental data collected from the literature. These robust models can be applied to the fire safety design of any timber structure to reach target reliability levels through a more realistic assessment, as well as to achieve more efficient and, therefore, cost-effective fire-resilient designs.

Conclusions

Probabilistic risk analyses to assess the reliability of structural fire designs require robust probabilistic models for the inputs that influence the response. In spite of the large variability of timber strength at elevated temperatures observed in the literature, there is a lack of models that quantify the uncertainty of the temperature-dependent timber strength. This paper collected a comprehensive database of experimental data on timber compressive and tensile strengths parallel to grain at elevated temperatures and proposed probabilistic models for the temperature-dependent strength-reduction factors that capture the observed scatter. From the literature review conducted to collect the experimental data and the proposed probabilistic model, the following findings can be drawn:

- A large variability in timber strength at elevated temperatures was observed in the literature. Although moisture content and migration have a significant effect on the reduction of timber strengths, the influence of factors such as specimen size, density, and so on, as well as the possible interactions between them, is not yet well understood.
- A lack of standardization of testing methods to determine the timber strength at high temperatures was observed in the literature. The experimental tests showed a wide variety of specimen sizes, as well as heating and loading conditions. Therefore, it remains unclear whether the variability observed in the collected experimental data is due to the use of different testing methods, the nature of the material, or both.
- The Weibull PDF was selected to characterize the reduction in timber compressive and tensile strengths at elevated temperatures. Simple, continuous, and closed-form equations defining the parameters of the distributions as a function of temperature for both strengths were then proposed. Goodness of fit of the proposed models was verified using quantitative statistical tests. The probabilistic models can be easily implemented in a numerical code, facilitating their use in analytical and computational approaches.
- The current deterministic model of timber strength reduction as a function of temperature from EN 1995-1-2 (CEN 2004c), which is usually adopted when assuming performance-based design approaches in structural fire engineering, appears to be very conservative compared with the experimental data. Therefore, the proposed probabilistic models based on the experimental data sets will presumably allow the design of more efficient timber structures. They could also aid in the rational preservation of historic timber structures designed prior to the enactment of current fire codes and for which prescriptive provisions are overly demanding.

In summary, the proposed probabilistic models are intended for application in performance-based design approaches for assessing the degree of confidence of new and existing timber structures regarding structural fire design. It is therefore envisaged that with the use of these models, more reliable and efficient timber structures can be designed with respect to fire safety, and that more existing historic structures can be preserved.

Based on the findings of the present study, future work by the scientific-technical community should include the development and recommendation of standardized test procedures to determine the timber strength at elevated temperatures. As a model calibrated on experimental data, the proposed probabilistic models are implicitly influenced by the methods and procedures employed for collecting the data in each of the studies considered. Thus, in the future, additional experimental data derived from such standardized procedures could be assumed to refine the proposed probabilistic models and perhaps reduce their COV.

In addition, further research could recommend the percentiles of the proposed probabilistic models that should be considered to achieve an adequate and reliable level of structural fire safety while designing more efficient timber structures. Finally, the proposed probabilistic models should be used when evaluating the response of timber members under the heating phase of a fire, but not under the cooling phase. Additional studies are needed to determine the relationships in cooling.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments

The authors wish to express their gratitude to the Spanish Ministry of Science, Innovation and Universities for supporting this research through Ph.D. Grant FPU18/00726 awarded to the first author, as well as to the Spanish Ministry of Science and Innovation for the funding provided through Project PID2021-128152NB-I00. The authors would also like to thank Professor Dr. M. Z. Naser for providing his database on timber properties at high temperatures, which includes part of the experimental data used in this paper. Finally, the authors would like to acknowledge Professor Dr. R. Qureshi and Professor Dr. S. Ni for sharing the code used to develop probabilistic models for temperature-dependent strength of steel and concrete. Funding for open access charge: Universitat Politècnica de València.

References

Akaike, H. 1974. "A new look at the statistical model identification." In *Selected papers of Hirotugu Akaike. Springer series in statistics (perspectives in statistics)*, edited by E. Parzen, K. Tanabe, and G. Kitagawa, 215–222. New York: Springer.

Alba-Rodríguez, M. D., A. Martínez-Rocamora, P. González-Vallejo, A. Ferreira-Sánchez, and M. Marrero. 2017. "Building rehabilitation versus demolition and new construction: Economic and environmental assessment." *Environ. Impact Assess. Rev.* 66 (Sep): 115–126. https://doi.org/10.1016/j.eiar.2017.06.002.

Aseeva, R., B. Serkov, and A. Sivenkov. 2014. *Fire behavior and fire protection in timber buildings: Springer series in wood science*. Edited by R. Wimmer. Dordrecht, Netherlands: Springer.

AWC (American Wood Council). 2018. *National design specification (NDS) for wood construction*. ANSI/AWC NDS-2018. Leesburg, VA: AWC.

Barber, D. 2018. "Fire safety of mass timber buildings with CLT in USA." *Wood Fiber Sci.* 50 (Special): 83–95. https://doi.org/10.22382/wfs-2018-042.

Bernardi, P., E. Michelini, A. Sirico, S. Rainieri, and C. Corradi. 2020. "Simulation methodology for the assessment of the structural safety of concrete tunnel linings based on CFD fire—FE thermo-mechanical analysis: A case study." *Eng. Struct.* 225 (Dec): 111193. https://doi.org/10.1016/j.engstruct.2020.111193.

Buchanan, A. H., and A. K. Abu. 2017. *Structural design for fire safety.* 2nd ed. West Sussex, UK: Wiley.

CEN (European Committee for Standardization). 2002. *Eurocode—Basis of structural design*. EN 1990. Brussels, Belgium: CEN.

CEN (European Committee for Standardization). 2004a. *Eurocode 2: Design of concrete structures—Part 1-2: General—Structural fire design*. EN 1992-1-2. Brussels, Belgium: CEN.

CEN (European Committee for Standardization). 2004b. *Eurocode 5: Design of timber structures—Part 1-1: General—Common rules and rules for buildings*. EN 1995-1-1. Brussels, Belgium: CEN.

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

CEN (European Committee for Standardization). 2005. *Eurocode 3: Design of steel structures—Part 1-2: General—Structural fire design*. EN 1993-1-2. Brussels, Belgium: CEN.

CEN (European Committee for Standardization). 2016. *Structural timber: Strength classes*. EN 338. Brussels, Belgium: CEN.

Christoforo, A. L., et al. 2020. "Alternative model to determine the characteristic strength value of wood in the compression parallel to the grain." *Maderas. Cienc. Tecnol.* 22 (3): 281–290. https://doi.org/10.4067/S0718-221X2020005000303.

Claeskens, G., and N. L. Hjort. 2008. *Model selection and model averaging*. Cambridge, UK: Cambridge University Press.

Do, M. H., and G. S. Springer. 1983. "Model for predicting changes in the strengths and moduli of timber exposed to elevated temperatures." *J. Fire Sci.* 1 (4): 285–296. https://doi.org/10.1177/073490418300100406.

Fahrni, R. 2021. *Reliability-based code calibration for timber in fire*. Zurich, Switzerland: ETH Zurich.

Fischer, E. C., A. H. Varma, and A. Agarwal. 2019. "Performance-based structural fire engineering of steel building structures: Design-basis compartment fires." *J. Struct. Eng.* 145 (9): 04019090. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002370.

Frangi, A., M. Bertocchi, S. Clauß, and P. Niemz. 2012. "Mechanical behaviour of finger joints at elevated temperatures." *Wood Sci. Technol.* 46 (5): 793–812. https://doi.org/10.1007/s00226-011-0444-9.

Franssen, J.-M., and T. Gernay. 2017. "Modeling structures in fire with SAFIR: Theoretical background and capabilities." *J. Struct. Fire Eng.* 8 (3): 300–323. https://doi.org/10.1108/JSFE-07-2016-0010.

Fryer, B. K., R. M. Foster, and M. H. Ramage. 2018. "Size effect of large scale timber columns." In *Proc., World Conf. on Timber Engineering (WCTE 2018)*. Yokohama, Japan: International Tropical Timber Organization.

Garcia-Castillo, E., I. Paya-Zaforteza, and A. Hospitaler. 2021. "Analysis of the fire resistance of timber jack arch flooring systems used in historical buildings." *Eng. Struct.* 243 (Sep): 112679. https://doi.org/10.1016/j.engstruct.2021.112679.

Gerhards, C. C. 1982. "Effect of moisture content and temperature on the mechanical properties of wood: An analysis of immediate effects." *Wood Fiber Sci.* 14 (1): 4–36.

Gernay, T., and N. Elhami Khorasani. 2020. "Recommendations for performance-based fire design of composite steel buildings using computational analysis." *J. Constr. Steel Res.* 166 (Mar): 105906. https://doi.org/10.1016/j.jcsr.2019.105906.

Glos, P., and D. Henrici. 1990. "Festigkeit von Bauholz bei hohen Temperaturen." In *Untersuchungsbericht des Instituts für Holzforschung*, 87505. München, Germany: Technische Universität München.

Goodrich, T., N. Nawaz, S. Feih, B. Y. Lattimer, and A. P. Mouritz. 2010. "High-temperature mechanical properties and thermal recovery of balsa wood." *J. Wood Sci.* 56 (6): 437–443. https://doi.org/10.1007/s10086-010-1125-2.

Hildebrandt, J., N. Hagemann, and D. Thrän. 2017. "The contribution of wood-based construction materials for leveraging a low carbon building sector in Europe." *Sustainable Cities Soc.* 34 (Oct): 405–418. https://doi.org/10.1016/j.scs.2017.06.013.

Hill, C. A. S. 2019. "The environmental consequences concerning the use of timber in the built environment." *Front. Built Environ.* 5 (Oct): 129. https://doi.org/10.3389/fbuil.2019.00129.

Hurvich, C. M., and C. L. Tsai. 1993. "A corrected Akaike information criterion for vector autoregressive model selection." *J. Time Ser. Anal.* 14 (3): 271–279. https://doi.org/10.1111/j.1467-9892.1993.tb00144.x.

ISO (International Organization for Standardization). 1999. *Fire-resistance tests—Elements of building construction—Part 1: General requirements*. ISO 834-1. Geneva: International Organization for Standardization.

JCSS PMC (Joint Committee on Structural Safety Probabilistic Model Code). 2006. *JCSS probabilistic model code. Part 3: Resistance models. Section 3.5: Properties of timber.* Zurich, Switzerland: JCSS.

Jovanović, B., R. Van Coile, D. Hopkin, N. Elhami Khorasani, D. Lange, and T. Gernay. 2020. "Review of current practice in probabilistic structural fire engineering: Permanent and live load modeling." *Fire Technol.* 57 (1): 1–30. https://doi.org/10.1007/s10694-020-01005-w.

Khmelidze, T. P. 1986. "Influence of temperature on strength and stiffness of wood of pine and larch." *Derevoobrabativaja Promyshlennost* 10 (Jun): 15–16.

Khorasani, N. E., M. Garlock, and P. Gardoni. 2014. "Fire load: Survey data, recent standards, and probabilistic models for office buildings." *Eng. Struct.* 58 (Jan): 152–165. https://doi.org/10.1016/j.engstruct.2013.07.042.

Klippel, M., S. Clauß, and A. Frangi. 2014. "Experimental analysis on small-scale finger-jointed specimens at elevated temperatures." *Eur. J. Wood Wood Prod.* 72 (4): 535–545. https://doi.org/10.1007/s00107-014-0810-z.

Knudson, R. M., and A. P. Schniewind. 1975. "Performance of structural wood members exposed to fire." *For. Prod. J.* 25 (2): 23–32.

Kollmann, F. 1940. *Die mechanischen Eigenschaften verschieden feuchter Hölzer im Temperaturbereich von -200 bis + 200°C: VDI-Forschungsheft No. 403*. Berlin: VDI-Verlag.

Kollmann, F. 1951. *Über das mechanische Verhalten von Kiefernholz bei Biegung und Temperaturen zwischen 20 und 100oC*, 1–22. Stockholm, Sweden: Svenska Träforskningsinstitutet.

Kollmann, F., and F. Schulz. 1944. *Versuche über den Einfluβ der Temperatur auf die Festigkeitswerte von Flugzeugbaustoffen, 2. Teilbericht*, 131. Eberswalde, Germany: Reichsanstalt für Holzforschung.

Kollmann, F. F. P., and W. A. Côté. 1968. *Principles of wood science and technology. I solid wood*. Berlin: Springer.

König, J., and L. Walleij. 2000. *Timber frame assemblies exposed to standard and parametric fires. Part 2: A design model for standard fire exposure*, 1–76. Stockholm, Sweden: Institutet for Trateknisk Forskning.

Kuronen, H., E. Mikkola, and S. Hostikka. 2021. "Tensile strength of wood in high temperatures before charring." *Fire Mater.* 45 (7): 858–865. https://doi.org/10.1002/fam.2813.

LaMalva, K., and D. Hopkin. 2021. *International handbook of structural fire engineering: The society of fire protection engineers series*. Cham, Switzerland: Springer.

Lau, P., and J. Barrett. 1997. "Modelling tension strength behaviour of structural lumber exposed to elevated temperatures." *Fire Saf. Sci.* 5: 1177–1188. https://doi.org/10.3801/IAFSS.FSS.5-1177.

Manríquez Figueroa, M. J. 2008. "Influência da temperatura sobre a resistência mecânica do paricá." Dissertação mestrado, Programa de Pós-graduação em Engenharia Civil, Universidade Federal de Santa Catarina, Centro Tecnologico.

Manríquez Figueroa, M. J., and P. Dias De Moraes. 2010. "Influence of the temperature on the compression strength parallel to grain of paricá." *Constr. Build. Mater.* 24 (1): 99–104. https://doi.org/10.1016/j.conbuildmat.2009.08.003.

Manríquez Figueroa, M. J., and P. Dias De Moraes. 2016. "Temperature reduction factor for compressive strength parallel to the grain." *Fire Saf. J.* 83 (Jul): 99–104. https://doi.org/10.1016/j.firesaf.2016.05.005.

Manríquez Figueroa, M. J., P. Dias De Moraes, and F. Almeida Maestri. 2015. "Temperature and moisture content effects on compressive strength parallel to the grain of paricá." *Ambiente Construído* 15 (1): 17–27. https://doi.org/10.1590/S1678-86212015000100003.

Martinez, J., and A. E. Jeffers. 2021. "Structural response of steel-concrete composite floor systems under traveling fires." *J. Constr. Steel Res.* 186 (Nov): 106926. https://doi.org/10.1016/j.jcsr.2021.106926.

Montgomery, D. C., and G. C. Runger. 2019. *Applied statistics and probability for engineers*. New York: Wiley.

Moshtaghin, A. F., S. Franke, T. Keller, and A. P. Vassilopoulos. 2016a. "Experimental characterization of longitudinal mechanical properties of clear timber: Random spatial variability and size effects." *Constr. Build. Mater.* 120 (Sep): 432–441. https://doi.org/10.1016/j.conbuildmat.2016.05.109.

Moshtaghin, A. F., S. Franke, T. Keller, and A. P. Vassilopoulos. 2016b. "Random field-based modeling of size effect on the longitudinal tensile strength of clear timber." *Struct. Saf.* 58 (Jan): 60–68. https://doi.org/10.1016/j.strusafe.2015.09.002.

Naser, M. Z. 2019. "Fire resistance evaluation through artificial intelligence—A case for timber structures." *Fire Saf. J.* 105 (Apr): 1–18. https://doi.org/10.1016/j.firesaf.2019.02.002.

Nielsen, P. C., and F. B. Olesen. 1982. *Tensile strength of finger joints at elevated temperatures*. Rep. No. 8205. Aalborg, Denmark: Aalborg University Center.

Nyman, C. 1980. "The effect of temperature and moisture on the strength of wood and glue joists." In *Proc., Symp. on Fire Resistance of Wood Structures*. Espoo, Finland: VTT Technical Research Centre of Finland.

Östman, B. A. L. 1985. "Wood tensile strength at temperatures and moisture contents simulating fire conditions." *Wood Sci. Technol.* 19 (2): 103–116. https://doi.org/10.1007/BF00353071.

Pang, S.-J., H.-J. Lee, K.-S. Ahn, and J.-K. Oh. 2020. "Sensitivity of censored data analysis to determine the characteristic value of structural timber." *J. Wood Sci.* 66 (1): 39. https://doi.org/10.1186/s10086-020-01885-0.

Qureshi, R., S. Ni, N. Elhami Khorasani, R. Van Coile, D. Hopkin, and T. Gernay. 2020. "Probabilistic models for temperature-dependent strength of steel and concrete." *J. Struct. Eng.* 146 (6): 04020102. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002621.

Ross, R. J. 2010. *Wood handbook: Wood as an engineering material*. General Technical Rep. No. FPL-GTR-190. Washington, DC: USDA.

Rykov, R. I. 1980. "Strength characteristics of timber at high temperatures." In *Proc., Symp. on Fire Resistance of Wood Structures*. Espoo, Finland: VTT Technical Research Centre of Finland.

Sathre, R., and L. Gustavsson. 2009. "Using wood products to mitigate climate change: External costs and structural change." *Appl. Energy* 86 (2): 251–257. https://doi.org/10.1016/j.apenergy.2008.04.007.

Schaffer, E. L. 1973. "Effect of pyrolytic temperatures on the longitudinal strength of dry douglas-fir." *J. Test. Eval.* 1 (4): 319–329. https://doi.org/10.1520/JTE10025J.

Schaffer, E. L. 1984. *Structural fire design*. Wood Research Paper FPL 450. Washington, DC: USDA.

Schwarz, G. 1978. "Estimating the dimension of a model." *Ann. Stat.* 6 (2): 461–464. https://doi.org/10.1214/aos/1176344136.

SFPE (Society of Fire Protection Engineering). 2016. *SFPE handbook of fire protection engineering*. 5th ed. Edited by M. J. Hurley, D. Gottuk, J. R. Hall, K. Harada, E. Kuligowski, M. Puchovsky, J. Torero, J. M. Watts, and C. Wieczorek. New York: Springer.

Showalter, K. L., F. E. Woeste, and B. A. Bendtsen. 1987. *Effect of length on tensile strength in structural lumber.* Research Paper FPL-RP-482. Washington, DC: USDA.

Sørensen, J. D., and P. Hoffmeyer. 2001. "Statistical analysis of data for timber strengths." In *Structural reliability theory.* Denmark: Dept. of Building Technology and Structural Engineering, Aalborg Univ.

Sulzberger, P. H. 1953. *The effect of temperature on the strength of wood, plywood and glued joints*. Rep. No. ACA-46. Melbourne, Australia: Aeronautical Research Consultative Committee.

Thelandersson, S., and H. J. Larsen. 2003. *Timber engineering*. New York: Wiley.

Thomas, G. C. 1996. *Fire resistance of light timber framed walls and floors*. Christchurch, New Zealand: Univ. of Canterbury.

Totsuka, M., R. Jockwer, H. Kawahara, K. Aoki, and M. Inayama. 2022. "Experimental study of compressive properties parallel to grain of glulam." *J. Wood Sci.* 68 (1): 33. https://doi.org/10.1186/s10086-022-02040-7.

Van Zeeland, I. M., J. J. Salinas, and J. R. Mehaffey. 2005. "Compressive strength of lumber at high temperatures." *Fire Mater.* 29 (2): 71–90. https://doi.org/10.1002/fam.871.

Volynsky, V. N. 2006. *Interrelation and variability of timber mechanical properties*. Arkhangelsk, Russia: AGTU Publishers.

White, R. H. 1996. "Tensile strength of fire-exposed wood members." In Vol. 2 of *Proc., Int. Wood Engineering Conf.*, 385–390. Baton Rouge, LA: Louisiana State Univ.

White, R. H., S. M. Cramer, and D. K. Shrestha. 1993. *Fire endurance model for a metal-plate-connected wood truss*. Research Paper FPL-RP-522. Washington, DC: USDA.

Wiesner, F., D. Thomson, and L. Bisby. 2021. "The effect of adhesive type and ply number on the compressive strength retention of CLT at elevated temperatures." *Constr. Build. Mater.* 266 (Jan): 121156. https://doi.org/10.1016/j.conbuildmat.2020.121156.

Woodard, A. C., and H. R. Milner. 2016. "Sustainability of timber and wood in construction." In *Sustainability of construction materials*, 129–157. Amsterdam, Netherlands: Elsevier.

Young, S. A., and P. Clancy. 2001. "Compression mechanical properties of wood at temperatures simulating fire conditions." *Fire Mater.* 25 (3): 83–93. https://doi.org/10.1002/fam.759.

Yue, K., F. Wang, W. Lu, Z. Tang, Z. Chen, and W. Liu. 2021. “Tensile properties of finger-jointed lumber under high-temperature and oxygen-free conditions.” *Holzforschung* 75 (9): 838–846. https://doi.org/10.1515/hf-2020-0066.

Zaben, A., D. Lange, and C. Maluk. 2020. “Compressive strength and MoE of solid softwood at elevated temperatures.” In *Proc., 11th Int. Conf. on Structures in Fire (SiF2020)*. Brisbane, Australia: Univ. of Queensland.

Zelinka, S. L., K. Sullivan, S. Pei, N. Ottum, N. J. Bechle, D. R. Rammer, and L. E. Hasburgh. 2019. “Small scale tests on the performance of adhesives used in cross laminated timber (CLT) at elevated temperatures.” *Int. J. Adhes. Adhes.* 95 (Dec): 102436. https://doi.org/10.1016/j.ijadhadh.2019.102436.

Zheng, A., and A. Casari. 2018. *Feature engineering for machine learning—Principles and techniques for data scientists*. Sebastopol, CA: O’Reilly Media.