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Fire resistance of square timber columns: simplified models for predicting the charring rate and failure time

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Abstract: To study the fire resistance performance of square timber columns, fire test data were collected, and the charring depth of timber columns was analyzed in detail. An optimization model for predicting the charring rate was provided. Based on the bearing capacity requirements of timber columns, a model for predicting the failure time of timber columns exposed to fire is proposed. The proposed model has high calculation accuracy. In addition, the influence of various design parameters on the failure time of timber columns was discussed. The failure time is significantly affected by factors such as slenderness ratio, cross–sectional size, axial compression ratio, and density. Increasing the slenderness ratio or axial compression ratio will shorten the failure time while increasing the cross–sectional width or wood density will prolong the failure time.

Keywords: fire resistance; square timber column; charring depth; failure time; analysis model

1. Introduction

Building fire refers to an event that occurs inside or around a building, causing significant property damage and endangering the safety of human life [1]. In 2022, more than 825000 building fires occurred in China, resulting in 2053 deaths, 2122 injuries, and direct property losses of 7.16 billion yuan. Among these building fires, the proportion of timber building fires is relatively high due to the combustibility of wood [2]. Statistics show that timber residential, heritage, and cultural buildings are the main fire–prone buildings, as shown in Figure 1.

In timber buildings, timber columns are extremely important structural components, and their fire resistance performance will directly affect the fire resistance performance of the whole building. Therefore, scholars from various countries have conducted extensive research on the fire resistance performance of timber columns. Schnabl *et al*. [3] proposed a mathematical model to predict the bearing capacity of timber columns under fire. Hirashima *et al*. [4] studied the charring rate and failure time of the glulam columns, and calibrated the residual cross–sectional areas. Gernay [5] conducted finite element analysis on glulam columns under standard fire, the fire resistance and burnout resistance were discussed in detail. Ali and Kavanagh [6] investigated the fire resistance of heavy timber columns, and

the impact of loading and slenderness on fire resistance were analyzed. In addition, many scholars have conducted fire tests on timber columns, delving into the charring depth and residual bearing capacity of timber columns [7–9].

Figure 1. Timber building fires.

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It should be noted that although there are many studies on the charring performance of timber columns in existing studies, the conclusions are different. The developed models for predicting charring depth and failure time are diverse, but there are certain differences. Therefore, this study aims to establish simplified models for predicting the charring depth and failure time of timber columns based on existing research data. Thus, the research findings can provide a reference for practical engineering applications.

2. Charring rate analysis

2.1. Test data and predictive model

When wood is exposed to fire, its temperature increases, and water loss occurs, leading to changes in its microstructure and chemical composition. After the temperature further increases, a charring layer is formed on the surface, which to some extent prevents the transfer of heat to the interior, thus forming cross–sectional layering with different temperatures. In which, the strength of the charring layer is lost, and the strength of the high–temperature layer decreases, which will lead to component failure. Hence, determining the charring rate of timber columns under fire is the basis for analyzing the fire resistance of timber columns.

The European code EC 5 [10] provides a charring rate for wood with a moisture content of 12%. When the density of hardwood exceeds 450 kg/m^3, the charring rate is 0.5 mm/min. When the density of softwood is greater than 290 kg/m^3, the carbonization rate is 0.65 mm/min. The Australian standard AS 1720.4 [11] provides a relationship between charring rate and wood density at a moisture content of 12%, and the calculation expression of the charring rate is expressed as Equation. (1). Njankouo *et al*. [12] studied the charring rates of seven types of wood with densities ranging from 500 to 1050 kg/m^3 and proposed a calculation model for charring rates. The calculation expression is shown as Equation. (2).

$$\beta = 0.4 + \left(280/\rho_{12}\right)^2 \tag{1}$$

$$\beta = 0.60 - 0.10\frac{\rho - 500}{300} \ge 0.40 \tag{2}$$

where β is the charring rate of wood, ρ and ρ_{12} are the wood density and the density at a moisture content of 12%, respectively.

In addition, scholars have also conducted a large number of fire tests on timber columns and obtained the charring information of the timber columns. In this study, the cross–sectional dimensions, density, moisture content, and charring rate of square timber columns were collected. All the collected timber specimens were tested according to ISO 834. Table 1 lists the collected test data.

Table 1. Test data of timber columns' charring information.

Literature	Width (mm)	Depth (mm)	Density (kg/m^3)	Moisture content (%)	Heating time (min)	Charring depth (mm)	Charring rate (mm/min)
Xu *et al*. [8]	106	98	448	14.8	10	7.25	0.725
	101	100	448	14.8	15	10.75	0.717
	103	96	448	14.8	30	18.50	0.617
	155	155	448	14.8	10	9.25	0.925
	154	152	448	14.8	15	15.50	1.033
	155	152	448	14.8	20	16.25	0.813
	150	150	448	14.8	30	23.25	0.775
	152	151	448	14.8	45	41.75	0.928
	196	191	448	14.8	10	8.25	0.825
	198	193	448	14.8	15	11.50	0.767
	197	195	448	14.8	20	16.25	0.813
	200	198	448	14.8	30	21.50	0.717
	197	194	448	14.8	45	33.75	0.750
	304	301	448	14.8	10	11.50	1.150
	303	301	448	14.8	15	15.25	1.017
	302	302	448	14.8	30	25.25	0.842
Chen *et al*. [9]	200	200	469	14.4	34	28.00	0.824
	200	200	469	14.4	16	12.90	0.806
	300	300	469	14.4	68	57.65	0.848
	300	300	469	14.4	32	25.00	0.781

2. 2. Model validation

The relationship between the charring rate of timber columns and various parameters was studied based on the collected test data. Figure 2 displays the relationship between the charring rate of timber columns and various parameters. From Figure 2 (a), it can be seen that as the width of the square timber column increases, the charring rate also slightly increases, which can be reflected by the correction factor η. In addition, it can be observed from Figure 2 (b) that as the heating time of the square timber column increases, the charring rate shows a non–linear decreasing trend, which can be reflected by the correction factor γ.

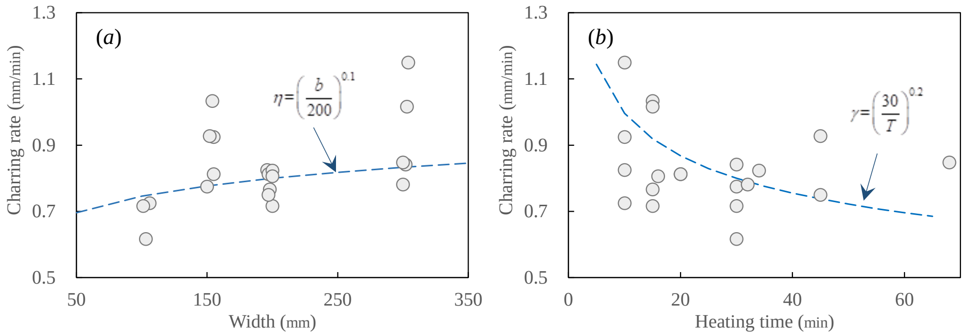

Figure 2. Relationship between charring rate and various parameters.

The existing charring rate prediction models were validated using collected test data, and it was found that the AS 1720.4 model had the highest accuracy. Hence, this study introduces correction factors η and γ to improve the prediction accuracy of the AS 1720.4 model. The formula for calculating the charring rate of timber columns is shown below.

$$\beta = \left(\frac{b}{200}\right)^{0.1} \times \left(\frac{30}{T}\right)^{0.2} \times \left[0.4 + \left(\frac{280}{\rho_{12}}\right)^{2}\right] \quad (3)$$

where b is the width of timber columns, and T is the heating time (from ignition to failure).

By using the collected test data, various models for predicting the charring rate of timber columns were validated, and the validation results are shown in Figure 3. Figure 3 (a) shows the validation results of models recommended in EC 5 [10], AS 1720.4 [11], and Njankouo *et al*. [12], and it is evident that the predicted values calculated by the three models have changed relatively little. Among them, the predicted values of models recommended in EC 5 [10] and Njankouo *et al*. [12] are significantly smaller than the measured values, while the predicted values of the model recommended in AS 1720.4 [11] are relatively closer to the measured values. For the optimized model developed in this study, the predicted values are relatively closer to the measured values, and the error is basically within 15%. This shows that the optimized model has good calculation accuracy.

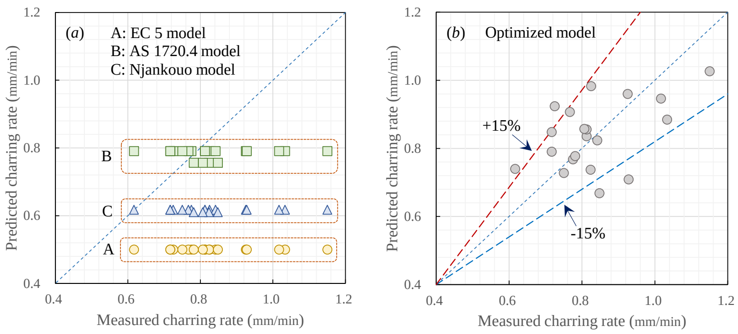

Figure 3. Verification of charring rate models.

3. Failure Time Analysis

3.1. Establishment of model

There are currently two main types of failure time prediction models for timber columns exposed to fire, one is the reduced strength and stiffness model, and the other is the effective cross–section model [13]. However, both of these models were developed based on test data, and their applicability is not good enough. In addition, some scholars have developed a machine learning–based model for predicting the failure time of timber columns under fire [14], but the generalizability of this method is relatively poor.

In this study, a load–bearing demand–based method was developed to predict the failure time of timber columns exposed to fire. The basic calculation process of this method is as follows: (1) Design the section size of the timber column $b_0 \times h_0$ based on the actual load demand P and axial compression ratio n; (2) Set the actual load P as the ultimate bearing capacity and calculate the minimum cross–sectional requirement $b_1 \times h_1$ for the timber column; (3) Using b_0–b_1 as the charring layer, calculate the failure time T based on the timber column charring model. The calculation process of the established model is shown in Figure 4.

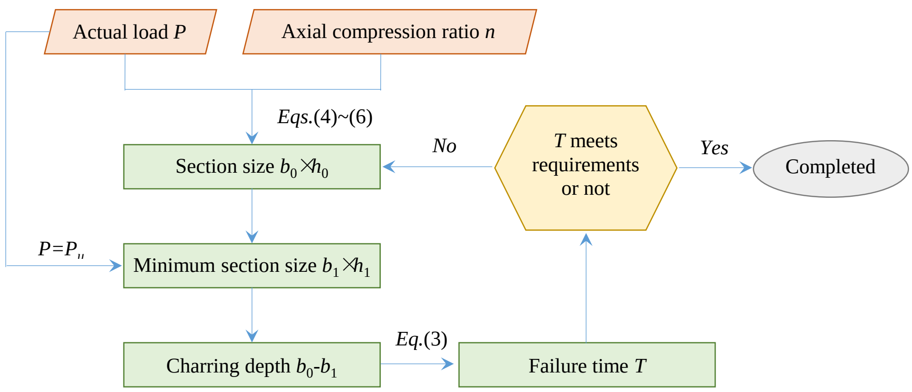

Figure 4. Calculation process of established model.

For the ultimate bearing capacity P_u of timber columns under axial compression, the formula recommended in GB50005–2017 [15] is adopted, as shown below.

$$P_u = n \times P = \varphi f_c (b_0 \times h_0) \tag{4}$$

where φ is the stability coefficient, f_c is the wood compressive strength parallel to the grain, b_0 and h_0 represent the width and depth of the cross–section, respectively. The stability coefficient of timber columns can be calculated using the following formula.

$$\varphi=\begin{cases}1/[1+(\lambda/80)^2] & (\lambda\le 75)\\ 3000/\lambda^2 & (\lambda>75)\end{cases} \tag{5}$$

$$\lambda=kl/i=kl/\sqrt{I/(b_0\times h_0)} \tag{6}$$

where λ is the slenderness ratio, l is the length of the timber column, k is the length calculation coefficient, i is the radius of gyration, and I is the moment of inertia of the timber column section.

3.2. Method Validation

The failure time model of timber columns exposed to fire proposed in this study was validated using the data reported in reference [14], and the validation results are shown in Figure 5. From the figure, it can be seen that the error range between the predicted and measured values is between 0.86 and 1.25. The average ratio of predicted values to measured values is 1.049. Overall, the calculated failure time is not significantly different from the measured failure time, indicating that the model proposed in this study has high accuracy.

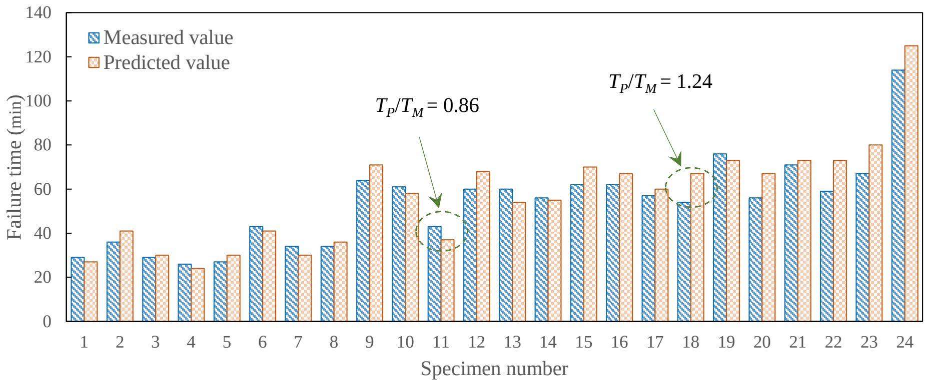

Figure 5. Comparison between measured and predicted values.

4. Parametric Analysis

To analyze the impact of various design parameters on the failure time of timber columns exposed to fire, parametric analysis was implemented. The design parameters of the control specimen are as follows: the cross–sectional width of the square timber column is 250 mm, the length is 3500 mm, the density of the wood is 450 kg/m^3, and the compressive strength along the grain is 40 MPa. Hinges connect the two ends of the timber column, and the designed axial compression ratio is 0.45. Four sets of parameters are analyzed, among which the first group only changes the slenderness ratio, while the other parameters are consistent with the control specimen parameters. The second group only changes the cross–sectional width, while other parameters such as slenderness ratio remain unchanged. The third group only changes the axial compression ratio, while the fourth group only changes the wood density. After calculation, the failure time trend of timber columns with parameter variation is shown in Figure 6.

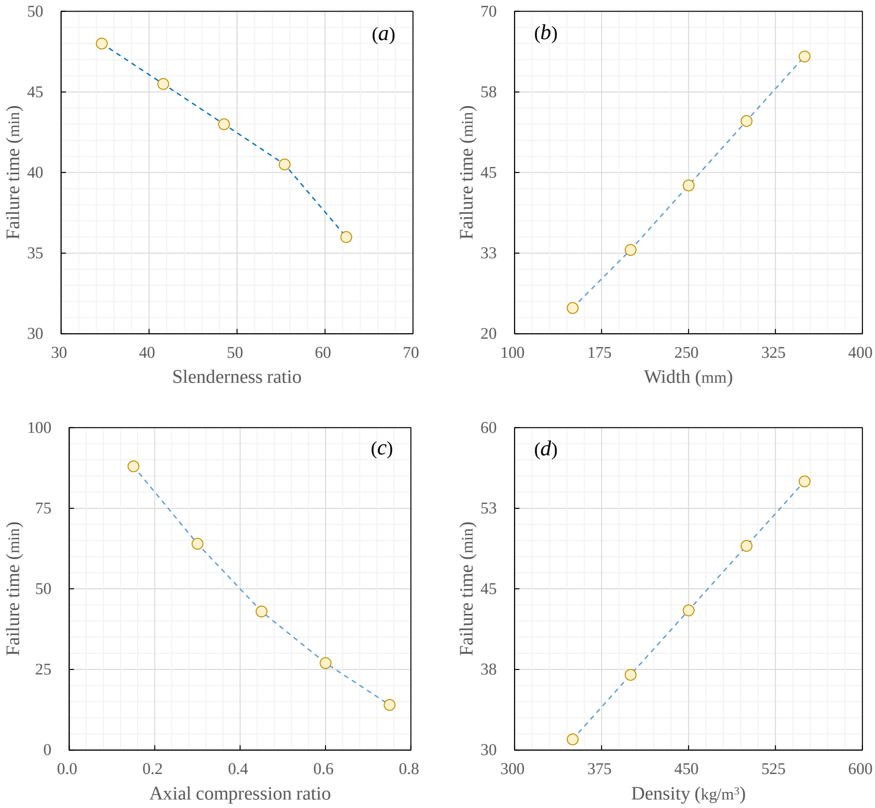

Figure 6. Influence of parameters on the failure time of timber columns.

It can be observed from Figure 6 (a) that increasing the slenderness ratio leads to a shorter failure time. When the slenderness ratio increases from 34.6 to 41.6, 48.5, 55.4, and 62.4, the failure time decreases from 48 to 45.5, 43, 40.5, and 36 min. This is because an increase in the slenderness ratio will lead to a decrease in the stability of the timber column. In Figure 6 (b), increasing the cross–sectional width increases the failure time of the timber column. When the cross–sectional width increases from 150 to 200, 250, 300, and 350 mm while maintaining the same slenderness ratio, the failure time increases from 24 to 33, 43, 53, and 63 min. Indicating that large–section timber columns have better fire resistance performance. It can be seen from Figure 6 (c) that the higher the axial compression ratio of the timber column, the shorter the failure time. When the axial compression ratio increases from 0.15 to 0.30, 0.45, 0.60, and 0.75, the failure time will decrease from 88 to 64, 43, 27, and 14 min. The reduction in failure time is very significant. The density of wood also has an impact on the failure time. From Figure 6 (d), it can be seen that as the density increases from 350 to 400, 450, 500, and 550 kg/m^3, the failure time increases from 31 to 37, 43, 49, and 55 min. Overall, the higher the density of wood, the more difficult it is to burn and the longer its failure time.

5. Conclusions

In this study, the charring rate and failure time of square timber columns were investigated, and models for predicting the charring rate and failure time were established. In addition, the influence of design parameters on the failure time of square timber columns was also studied, and the main conclusions are as follows.

(1) Research on existing test data has found that the charring rate of timber columns is influenced by the cross–sectional size and heating time. Based on the model recommended in AS 1720.4, the cross–sectional size and heating time correction coefficients were introduced to optimize the prediction model for the charring rate of timber columns. The optimized model has high calculation accuracy.

(2) Based on the bearing capacity requirements of timber columns, the charring depth of timber columns is determined from the minimum cross–sectional size at the time of failure, and the failure time is calculated according to the charring rate model. Also, the calculation process and formula of this method are provided. The verification results indicate that the proposed method has high prediction accuracy.

(3) The influence of timber column design parameters on failure time was analyzed. the results show that the failure time decreases with the increase of the slenderness ratio, and decreases with the increase of the axial compression ratio. Moreover, increasing the cross–sectional width will lead to an extension of the failure time, and increasing the density of wood will also prolong the failure time.

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Conflicts of interests

The authors declare no conflict of interest.

Authors' contribution

Conceptualization, Li Zhou and Yong Huang; methodology, Li Zhou; validation, Lei Gong; formal analysis, Honggang Tang; investigation, Fanjun Zeng, Li Zhou and Yuchuan Chen; resources, Yong Huang; data curation, Li Zhou and Fanjun Zeng; writing—original draft preparation, Li Zhou; writing—review and editing, Yong Huang; supervision, Yong Huang; project administration, Li Zhou; funding acquisition, Li Zhou. All authors have read and agreed to the published version of the manuscript.

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