Linda Makovická Osvaldová · Laura E. Hasburgh · Oisik Das *Editors*

Wood & Fire Safety 2024

Proceedings of the 10th International Conference on Wood & Fire Safety 2024

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Contents

Fire Safety in Wooden Objects

The Method of Interpolation of the Charred Zone in the Cross-Section of Wooden Beams with Fire-Resistant Cladding Based on Impregnated Plywood

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Abstract. This article discusses the developed method of interpolation of the charring zone in cross-sections of wooden beams with fire-resistant cladding based on impregnated plywood using a generalized mathematical description using Bezier curve based on experimental studies. In accordance with the obtained temperature distributions, using Bezier curve, with the help of modeling the charred zone, it was possible to depict in detail the process of charring of samples-fragments of a wooden beam without fire protection and with fire-resistant cladding based on impregnated plywood with a layer thickness of 10 mm and 20 mm. Also, in accordance with the standard temperature regime of the fire, the dependences of the side and end thicknesses, charring rates of the examined fragments-samples of wooden beams depending on the exposure time were determined, and the appearance with the corresponding regression coefficients was determined. The results of exposure of samples-fragments of wooden beams with fireproof lining on the basis of impregnated plywood of different thicknesses and without fireproof lining are also revealed. Sample research was based on visual and graphic analysis of charring depth, which testified to the effectiveness of fire-resistant cladding based on impregnated plywood.

Keywords: fire · wood · plywood · mathematical modeling of charring depth · Bezier lines

According to EN 1995–1-2:2004 Eurocode 5: Design of timber structures - Part 1–2: General - Structural fire design requirements for mechanical resistance during fire are established, structures must be designed and manufactured so that they retain their load-bearing capacity during fire impact [1].

Within the limits of a part of the structural system for the calculation, it is necessary to take into account the characteristic type of destruction under the influence of fire, which are dependent on temperature: material properties and stiffness of a separate element, the effect of heat propagation, temperature deformations. To do this, it is necessary to

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describe a mathematical model for predicting the geometric shape of the cross-section of fire-resistant wooden beams under fire conditions, which is an urgent task for the construction industry.

Taking into account the above, it should be noted that the establishment of regularities determined by the geometric configurations of the charring zone of wooden beams with fire-resistant cladding based on impregnated plywood from their structural parameters is an urgent task.

The speed of thermal processes depends on the intensity of heat release in the charring zone. The temperature regime is a quantitative characteristic of the change in heat release during a fire depending on different burning conditions. The temperature regime during a fire in the premises is understood as the change in the average volume temperature of the environment during the burning time. The time during which a structure or its element loses its functional properties (load-bearing, heat-insulating, enclosing) when heated at a standard temperature regime is called fire resistance.

Solving the problem of non-stationary thermal conductivity is reduced to determining the temperature T at any point of the body with coordinates (x; y; τ) at any instant of time. At the same time, boundary conditions of the 1st, 2nd, and 3rd kind are taken into account. And also allow solving the problem of "fire resistance" of building structures (with a certain accuracy) and predicting their behavior during a fire [2].

The most widespread are the experimental-calculation methods, as they are based on the data of the conducted fire tests, and then the calculation method is used to conduct the required number of experiments. Thus, the need to carry out experimental and calculation methods will more effectively establish the dependence of the burning speed of the surface of the plywood board on the presence of a fire-retardant substance, while the fire-resistant plywood slows down the onset of thermal destruction of wooden beams as a cladding element.

To conduct experimental studies, samples were made of solid pine beams with dimensions of 70 × 250 × 350 mm OSB-3Kronospan 350 × 350 mm, board with a thickness of 18 mm, dry peeled birch veneer of the second grade with a thickness of 2 mm, and a fire retardant solution of the company "Kompozit BS- 13", selected glue based on Epoxy resins with a working temperature range from -50°C to 120°C.

The method of manufacturing fire-resistant plywood includes impregnation of sheets of 2 mm peeled veneer with fire retardant in a cold bath, their drying, application of glue, formation of veneer packages, pressing of veneer with a term press [5]. Dry sheets of peeled veneer with a moisture content of 7–10% were immersed in a hot bath with impregnation solution at a temperature of 80–90 °C and kept in it for 30 min, after which the sheets of peeled veneer were removed from the hot bath and immersed in a cold bath with impregnation solution at a temperature of 20 °C and kept in it for 40 min. Next, the impregnated sheets of peeled veneer were taken out of the bath, they were kept above it for the excess impregnation solution to drain back into the bath, and they were stacked in feet with mutually perpendicular direction of the fibers in adjacent layers to redistribute the fire retardant in the veneer, that is, to diffuse salts from the surface of the veneer to the inside, and kept in feet for 1 h. After that, the impregnated sheets of veneer were dried to a moisture content of 8% and submitted to the operations of applying glue, forming and pressing veneer packages, and pressing plywood. As a fire retardant substance for veneer impregnation, we used Kompozit BS-13 fire bioprotective impregnation substance for wooden structures. As a substance for gluing, epoxy glue "Khim kontakt-Epoxy" [3, 4] is used. Seven-layer plywood with a thickness of 10 mm was produced according to the following operating parameters: temperature of the press plates - 120–125 °C, pressing pressure 1.8–2.0 MPa, pressing duration - 10 min, glue consumption - 1202 g/m. [5, 6].

The first stage of the production of samples was the drying of a solid wooden bar with dimensions of 250x350x70 mm, which took place in open areas until the moisture content of the wooden bars reached no more than 20%, since a high moisture content significantly reduces the flammability of wood and does not lose its protective action. The second stage of the production of the samples was the direct facing of the wooden beam with fire-resistant plywood, made in the above-described manner, with the help of self-tapping screws. Temperature measurement in wooden beams with fire-resistant cladding made of coniferous wood species showed that due to the moisture content of the wood - as a rule, 12% - the conditional delay of the temperature rise above 100 °C becomes relatively shorter. The charring zone is within the temperature range of 200–300 °C, while the charring zone for pine is 200 °C (Fig. 1).

Fig. 1. Schematic view of the experimental metal sample fragment.

These samples-fragments of wooden beams were tested on the experimental fire installation shown in Fig. 2. The standard fire temperature regime was used in the fire chamber of the installation [4, 5]. This figure also shows the appearance of the sample after testing, and the method of measuring charring thicknesses.

Thermocouples were used to measure the temperature in the furnace with a wire diameter of 1.5 mm, chromel-alumel thermocouples TXA-VIII, which can be used to measure temperature in the range from 0 °C to 1100 °C. To remove digital values of temperature in places of installation of thermocouples used secondary electronic instruments complete with Digitalmultimeter DT 838ºC, which are connected to thermocouples. Range temperature measurement of this device is from -20ºC to 1370ºC. During fire tests, indicators were taken every minute from four devices and were entered into the protocol during 15, 30, 60 min of heating.

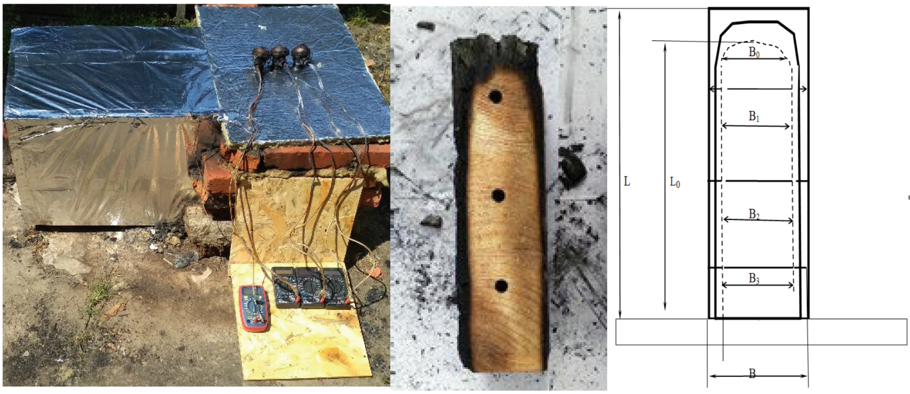

Fig. 2. View of the experimental setup and sample after testing. Schematic representation of measuring areas on the sample: L – length of the sample before the start of the test; L_0 - is the length of the non-charred layer of the sample; B_0, B_1, B_2, B_3 – width on each fragment of the glued bar after the fire test; B is the width of the sample before the fire test.

Applying the data obtained from the fire tests conducted by the author's team, the limits of charring zone of samples-fragments of wooden beams were determined with their approximation using flat Bezier curves of the third order, according to the exposure time. An example of obtaining distribution data is shown in Fig. 3.

Some scientists whose work is highlighted [6–11] made the assumption that the isotherms of the temperature field under the influence of the standard temperature regime of a fire with a critical temperature $Tk_r = 200$ °C there is a contour line of the charring zone of the cross section of the wooden beam.

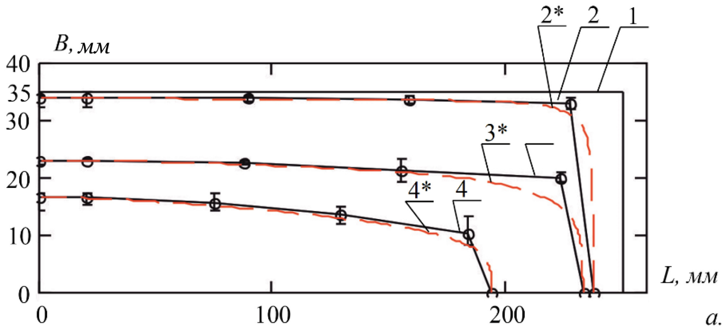

Fig. 3. Lines of the boundary of the charring zone with their approximation by means of Bezier curves: (a) without fire protection; 1) the initial sample fragment before the test; 2) charring zone for 15 min of testing; 2 *) Bezier curve for 15 min of testing; 3) charring zone for 30 min of testing; 3 *) Bezier curve e for 30 min of testing; 4) charring zone for 60 min tests; 4 *) Bezier curve for 60 min tests.

According to the results presented in works [7, 8], it is possible to approximate the contour of the charring zone using a certain parametric curve, for such approximation it is convenient to use parametric Bézier curves. In this case, the configuration of Bézier lines can be determined using 5 characteristic points, which are fixed on isotherms with a critical temperature. To avoid the main drawback of this approach, which is the insufficient accuracy of isotherm approximation, the approach described in [8] is used. According to this approach, the position of the first three key points is fixed at the vertices of the rectangle into which the isotherm fits, and the last two are fixed between them on the sides of the described rectangle. Considering Figs. 2 and 3, as well as the above assumptions and references, a scheme for determining the position of these key points was built, shown in Fig. 4.

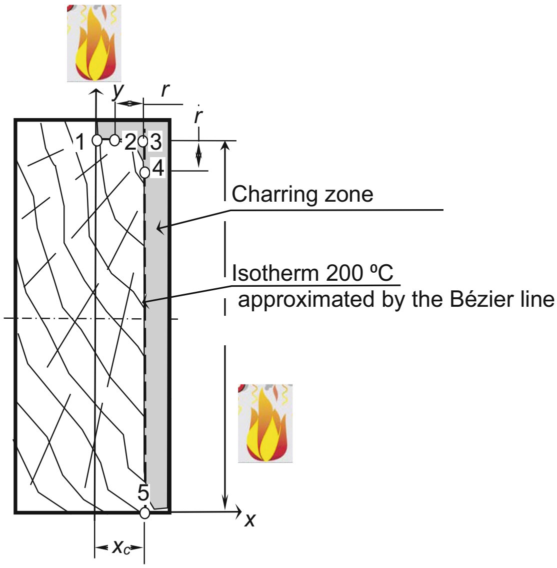

Fig. 4. Scheme of positions of key points for establishing parametric functions of Bezier curve, approximating the corresponding isotherms with the critical temperature of initiation of the charring process, r-distances between key points 2,3 and 3,4 for the construction of Bezier lines, x_c - parametric characteristic of the end side mm and y_c - the parametric characteristic of the side of mm.

According to this scheme, the number of key points was determined for approximating the contours of the charring zone using Bezier lines. Using the coordinates of the five key points determined in the manner described above, the corresponding parametric function of the Bezier curve is determined, which has an implicit form according to the expression [8]:

$$\Omega(u) = \sum\nolimits_{k=1}^{n} \omega_k B_{k,n}(u), \quad 0 \le u \le 1, \tag{1}$$

where n - 5 is the number of key points; $B_{k,\,n}(u)$ – are Bernstein polynomials for describing the parametric functions of Bezier curves; ω_k – is a vector of corresponding coordinates of key points for describing the parametric functions of Bezier curves.

Bernstein polynomials are written in the form of a formula:

$$B_{p,n}(u) = \frac{n!}{p!(n-p)!} u^p (1-u)^{n-p} \tag{2}$$

where p - the degree of the Bernstein polynomial; u-is a parameter of implicit coordinate functions.

The matrix Eq. (1) under the following conditions is written as an algebraic system of two parametric equations:

$$x(u) = \sum_{p=1}^{n} x_p B_{p,n}(u), \quad y(u) = \sum_{p=1}^{n} y_p B_{p,n}(u), \tag{3}$$

Coordinate vectors are written through the following expressions:

$$\omega_x = \begin{cases} (0\ x_c - r\ x_c\ x_c\ x_c)^T;\ x_c > r \\ (0\ 0\ x_c\ \ x_c\ x_c)^T;\ x_c \le r \end{cases},\ \omega_y = (y_c y_c y_c y_c - r\,0)^T;\ 0 \le r \le y_{c.}, \tag{4}$$

Coordinates, which are components of vectors (4), are calculated according to the scheme shown in Fig. 4. Parameterization of Bezier curve functions is based on assumptions that the parameter r is determined by the largest overall size cross-section of the beam in a dimensionless relative representation in the form of the parametric function $r = f(y_c/h)$.

Such a record is necessary for the description of cross-sections with other overall dimensions and their different ratios.

According to the work [11], the described rectangle for constructing Bezier curve is determined by the parameters x_c and y_c, which are defined as functions using dependencies (2) and (4). In this case, these functions are written in the form:

$$x_c(t, t_{0s}) = \begin{cases} 0.5b - d_s(t, t_{0s}),\ b > 2d_s(t, t_{0s}) \\ 0,\ b \le 2d_s(t, t_{0s}) \end{cases};\ y_c(t, t_{0e}) = \begin{cases} h - d_e(t, t_{0e}),\ h > d_e(t, t_{0e}) \\ 0,\ h \le d_e(t, t_{0e}) \end{cases}, \tag{5}$$

where b and h are the width and height of the beam section, respectively.

The parameter r, which determines the conditional radius of rounding of the contour line of the charring zone, is defined as a parametric function similar to the parameters of the described rectangle according to expressions (6) and (7):

$$r(t, t_{0e}) = \begin{cases} \mathbf{Lu}(t, t_{0e}) \cdot \mathbf{a},\ \mathbf{Lu}(t, t_{0e})^{\mathrm{T}} \mathbf{a} > 0 \\ 0 \qquad \mathbf{Lu}(t, t_{0e}) \cdot \mathbf{a} \le 0 \end{cases} \tag{6}$$

where, vector functions are defined by expressions using regression equations obtained in [8]:

$$\begin{aligned} &\mathbf{Lu}(t, t_{0e}) = \left[1\ y_c(t, t_{0e}) \cdot h^{-1}\ \cdots\ y_c(t, t_{0e})^6 \cdot h^{-6}\right]^T \\ &a = (0.979\ 0.064\ 3.6\ -32.339\ 59.242\ -41.82\ 10.273), \end{aligned} \tag{7}$$

Using formulas (4)–(6), the algebraic system of equations for describing the contour of the charring zone of the cross-section of fire-resistant wooden beams takes the form:

$$
\begin{aligned}
&x_b(u,t,t_{0s}) = \sum_{p-1}^{n} \boldsymbol{\omega}_x(t,t_{0s}) B_{p,n}(u) \\
&\boldsymbol{\omega}_x(t,t_{0s}) = \begin{cases} (0 \;\; x_c(t,t_{0s}) - r(t,t_{0e}) \;\; x_c(t,t_{0s}) \;\; x_c(t,t_{0s}) \;\; x_c(t,t_{0s}))^T; & x_c(t,t_{0s}) > r(t,t_{0e}) \\ (0 \;\; 0 \;\; x_c(t,t_{0s}) \;\; x_c(t,t_{0s}) \;\; x_c(t,t_{0s}))^T; & x_c(t,t_{0s}) \le r(t,t_{0e}) \end{cases}
\end{aligned}
\tag{8}
$$

$$
\begin{aligned}
&y_b(u,t,t_{0e}) = \sum_{p-1}^{n} \boldsymbol{\omega}_y(t,t_{0e}) B_{p,n}(u) \\
&\boldsymbol{\omega}_y(t,t_{0e}) = \begin{cases} (y_c(t,t_{0e}) \;\; y_c(t,t_{0e}) - r(t,t_{0e}) \;\; y_c(t,t_{0e}) \;\; y_c(t,t_{0e}) \;\; 0)^T; & y_c(t,t_{0e}) > r(t,t_{0e}) \\ (y_c(t,t_{0e}) \;\; y_c(t,t_{0e}) \;\; y_c(t,t_{0e}) \;\; 0 \;\; 0)^T; & y_c(t,t_{0e}) \le r(t,t_{0e}) \end{cases}
\end{aligned}
\tag{9}
$$

Using this mathematical apparatus, the main parameters for the construction of Bezier curves for wooden beams, which are listed in the table, were determined 1, delineating the contour of the charring zone of the cross-section of the beams with and without fire-resistant cladding based on impregnated plywood. The constructed curves are shown in Fig. 5.

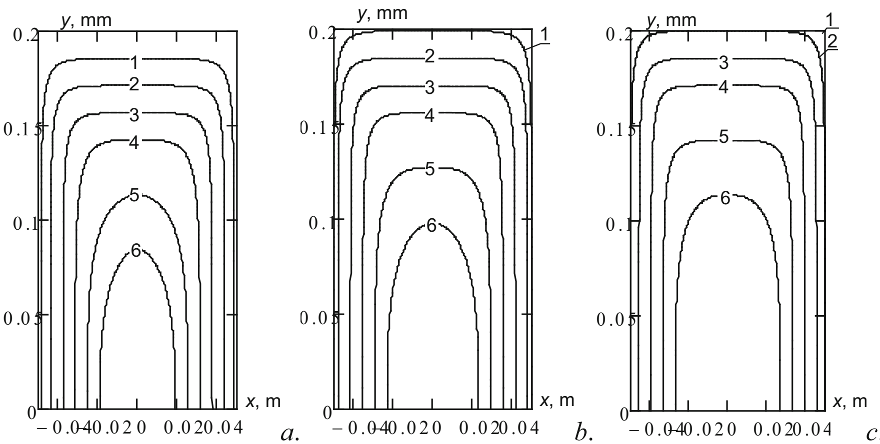

Fig. 5. The location of the contour line of the charring zone, approximated using the Bezier lines in the cross-section of a wooden beam 100 × 200 without fire protection (a), with fire-resistant cladding w = 10 mm (b); with fire-resistant cladding w = 20 mm (c) at different times of exposure to the standard fire temperature regime: 1–15 min.; 2–30 min.; 3–45 min.; 4–60 min.; 5–90 min.; 6–120 min.

Table 1. Structural parameters of cross-sections of wooden beams with fire protection based on impregnated plywood

Section width, *b*, mm	Cross section height, *h*, mm	The width of the fire protection layer, *w*, mm		
100	200	0	10	20

From Fig. 5, it can be seen that the proposed mathematical model allows to effectively predict the geometric configuration of the charring zone of wooden beams with and without fire-resistant cladding based on impregnated plywood, depending on the time of exposure to the standard fire temperature regime (see Table 1).

To analyze the accuracy of the obtained data regarding the carbonization zone, a comparative analysis of the data obtained experimentally and the data obtained on the basis of the calculation was carried out. For this, contours of carbonization zones were constructed for cross-sections of wooden beams, fragments of which were tested according to the above-mentioned method.

In Fig. 6 shows the contours of the charring zone of cross-sections of wooden beams with and without fire-resistant cladding based on impregnated plywood, which were obtained by experimental and calculation methods.

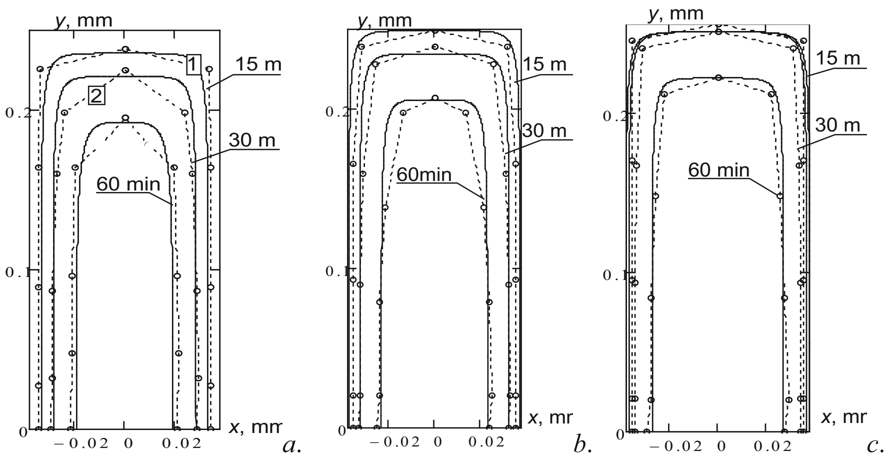

Fig. 6. The location of the contour line of the charring zone, approximated by the Bezier curve in the cross-section of a 70 × 250 wooden beam without fire protection (a), with fire-resistant cladding w = 10 mm (b); with fire-resistant cladding w = 20 mm (c) at different moments of exposure to the standard fire temperature regime: 1 – calculated results; 2 – experimental results.

Analysis of the graphs shown in Fig. 6, showed that the proposed method of approximating the contour of the charred cross-sectional area of wooden beams with fireproof cladding based on impregnated plywood is sufficiently accurate as it reproduces this contour well, while the average relative error of contour reproduction is no more than 6.4%. This allows you to recreate the charring zone for beams with other cross-sections.

1 Conclusions

1. In the article, mathematical support was developed, which allows to predict the configuration of the charred zone of wooden beams under the thermal influence of the standard fire temperature regime;
2. The results of the work show a good convergence of the obtained data when comparing them with experimental data, while the error, on average, is no more than 10%

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