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INFLUENCE OF STRENGTH REDUCTION OF TIMBER IN FIRE ON STRUCTURAL RESISTANCE

Keywords:
timber, wood, fire resistance, thermal analysis, strength reduction coefficient, fire test

Present research was dedicated to investigation of strength of timber structures in fire conditions. Two kinds of timber specimens were used: oak and pine.

Praca poświęcona jest badaniu wytrzymałości ogniowej budynków drewnianych. Do badań użyto próbek dwóch rodzajów drewna: dębu i sosny.

1. Introduction

Many buildings and civil engineering works are at high risk of fire. Therefore, accurate prediction of behaviour of the structures subjected to fire is of primary importance for the evacuation of persons, as well as for the safety of rescue teams.

Steel and concrete members [1,4,9] under fire have been extensively investigated in last decades. However, far fewer investigations have been carried out on timber structures [2, 3]. Wood is a perfect material for constructional purpose, but has a shortcoming: wood is flammable. The fire resistance of any wood structures is determined by the fire resistance of its components because joints and nodes between components provide no fire resistance. Fire resistance of wood structures depend on various factors, i.e. charring rate and charring shape, dimensions and strength of the undamaged components.

Wood combustion characteristics and the related fire hazard are shown in Table 1 [11].

The charring rate and the charred layer thickness are the starting points for determination of dimensions of the undamaged core at any fire time and for determination of temperature layout inside the core. These characteristics are important problems while determining the fire resistance of timber components by analytical method.

Table 1. Wood combustion characteristics and related fire hazard

Material warming up	100°C	Wood drying process. Loss of free water and bounded water.
	150°C	Changes to chemicellulose and lignin. Slow reaction. Any further temperature growth or keeping a constant temperature for a sufficiently long time can cause the material to ignite.
Critical temperature range for material decomposition	225°C	Commencement of decomposition gas generation, mainly CO_2, acetic acid, steam.
	250°C	Cellulose decomposition.
	270°C	Very quick generation of decomposition products. Any occurring flame can incinerate the gas mixture.
	290°C	Wood weight loss is close to 39 %. The material reaches the temperature necessary for its surface to ignite in the presence of a flame, and for self-acting combustion.
Ignition temperature range	330°C	Flames spreading over the surface; charred layer build-up commences.
	400°C	Exothermic course of the decomposition process. Fire transfer hazard. Maximum rate of flammable gas generation. Creation of glowing layers built mainly from high-energy lignin.
Combustion with open fire	450°C	Wood burning out inside the material.
	500°C	Charcoal residue burning.
Glowing and complete combustion of pyrolisis residue	700°C	Complete combustion of decomposition products (gases) on the material surface.
	800°C	Generation of flammable products is completed.
Cooling	1100°C	The wood glow results in the complete material destruction. Non-flammable mineral residue (ash) remains.

The charring rate is depending on a number of factors such as: timber species, timber density, moisture content, chemical composition, timber defects (e.g. fissures). Charring rate also depends on: the actual specimen geometry (dimensions, shape and surface quality), heat stream density (per component surface area), heat stream transport method to the specimen (radiation, convection and conduction), heat operation type depending on the ignition source layout (one, two, three, four-sided thermal exposition).

Particular attention was paid to the timber density influence on the charring rate. [18] is of opinion that timber species featuring a higher density range are specific for their lower charring rates.

Charring rate for various timber species are widely discussed in references [11, 15, 19]. As well, a discussion on the reduced charring rate versus increased timber moisture content is included.

Polish Standards (PN) does not cover the issues related to the structure dimensioning with regard to fire requirements. Therefore Eurocode 5 [6] is used in Poland to solve these problems.

Present research was dedicated to investigation of strength of timber structures in fire conditions. Two species of timber were used: oak and pine. Investigation included the following static test: tensile strength, compressive strength along fibres, compressive strength across fibres and bending strength. Specimens were tested under the following temperatures: 50°C, 100°C, 150°C, 200°C and 230°C.

2. Calculation of charred layer thickness and core strength of timber structure according to EC5 principles

The Eurocode 5 uses the term of 'effective cross-section', which means: cross-section obtained by subtracting charred layer thickness from the original cross-section. Charred layer thickness can be calculated as follows:

$$d_{char} = \beta t \tag{1}$$

where d_{char} is charred layer thickness in mm; β is charring rate; t is charring time in minutes.

The timber charring rate, β, in the standardized heat test is assumed constant and independent from the charring process direction. The value of $\beta = 0.6$ mm/min was adopted for analytical calculations of fire resistance. In practice, the charring rate varied within 0.5 – 0.9 mm/min, and as much as 1 mm/min for component corners [10].

Thickness of the layer of no mechanical strength should be determined by the following expression:

$$d_{ef} = d_{char} + d_0 k_0 \tag{2}$$

where d_{char} is calculating by formula (1); $d_0 = 7\ mm$ is thickness of additional layer with no mechanical strength; k_0 is coefficient taking from Eurocode 5 [6].

In practice, the effective core cross-section largely resembles oval due to a higher charring rate for component corners. The oval core cross-section was taken into account in several proposed calculation models [5].

While calculating the bearing capacity for timber structures, the material strength reduction due to the high temperature should be taken into account. Two issues should stand apart:

- temperature distribution inside the core;
- material strength reduction due to the temperature effect.

Thanks to its porous structure (approx. 15% of solid material is created in timber pyrolysis), the charred layer features a low heat conductivity coefficient of approx. 0.5 W/mK, thus limiting the access of both heat and oxygen to the non-charred structural component core, which reduces and delays the temperature growth inside the core. During the wood combustion process, the thickness of the superficial charred layer increases at the beginning as quickly as the core dimensions decrease, and then, this process slows down due to the protective properties of the charred layer and due to the moisture evaporating into the material. Fig. 1 shows the temperature distribution across a pine board of 16 × 36 (mm) after 60 min.

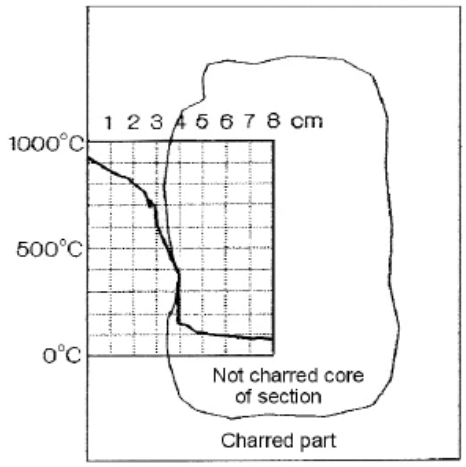

Fig. 1. *Temperature distribution across the board [10]*

It was determined by tests that the specimens is still keeping a sufficient bearing capacity, temperature in the core middle does not exceed 100°C in most cases. At the same time, the core has temperature up to 200°C.

The core temperature has a significant influence on the component bearing capacity and fire resistance. For the standard fire, the average core temperature can be determined by the following formula [6]:

$$T = \left(1 + k\frac{b}{h}\right) \cdot \left[20 + \frac{180\left(\beta t_f\right)^{\eta}}{(1-\eta)\left(\frac{b}{h} - \beta t_f\right)}\left(\left(\frac{b}{2}\right)^{1-\eta} - \left(\beta t_f\right)^{1-\eta}\right)\right] \text{ where}$$

$\eta = 0.398 t_f^{0.62}$; b and h are initial width and height of the element cross-section, respectively; t_f is fire duration time; β is timber charring rate; k is coefficient accounting number of sides for fire exposition:

- two-sided $k = 0$;
- three-sided $k = 0.25$;
- four-sided $k = 0.4$;

The later expression has good agreement with test result given in reference [13].

According to Eurocode 5, the core strength can be calculated by:

$$f_{fi,d} = \frac{\left(k_{\text{mod } fi} \cdot f_k\right)}{\gamma_{m,fi}} \tag{3}$$

where $f_{fi,d}$ is reduced strength; $\gamma_{m,fi}$ is partial safety coefficient for fire condition, which is equal 1.0; k_{fi} is coefficient accounting safety level in fire condition, for solid wood $k_{fi} = 1.25$; f_k is specific strength in normal conditions; $k_{\text{mod},fi}$ is coefficient accounting strength reduction due to high temperature.

3. Experimental investigation

Main objective of the test was to investigate influence of high temperature on strength of timber structures. Test results were presented in the term of coefficients making consideration for wood strength reduction in high temperatures, which are recommended for analytical calculation of fire resistance. Investigation included the following static tests:

- Tensile strength;
- Compressive strength along fibres;
- Compressive strength across fibres;
- Bending strength.

Static investigation was performed in The Main School of Fire Service (MSFS) in Warsaw, in the department of applied mechanics. Special test stand was manufactured for this investigation, which was placed in heating chamber.

3.1. Thermal investigation

Before commencing the tests, a comparative thermal investigation was performed. Results of this test are shown in Fig. 2. Tests were made with Q500 thermo gravimetric analyzer, which supports the substance weight change response with temperature. Tests were performed in the atmosphere of environment air. The warming-up rate of 10°C/min was adopted.

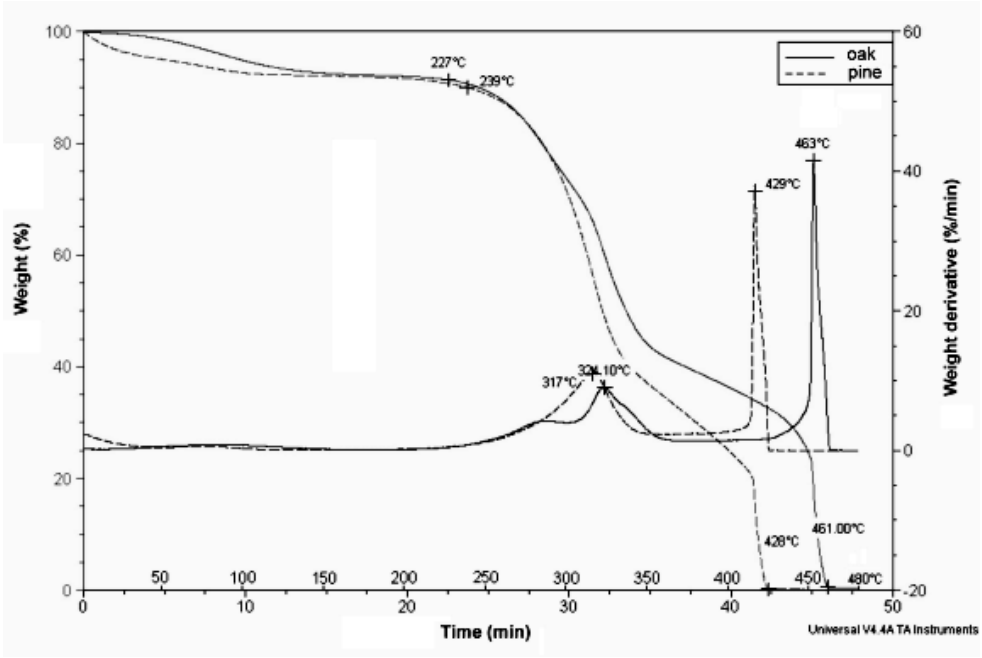

***Fig. 2**. Thermographic specimen analysis*

It can be assumed for pine and oak wood specimens that the thermal decomposition begins at approx. 240°C. The thermal decomposition is carried out in two stages, this being related probably to the creation of a charred layer, which reduces the thermal decomposition ratio for a certain time length. For pine wood, the weight loss is quickest at temperature of 430°C; whereas for oak wood – at 460°C. The pine wood self-ignition temperature was determined at approx. 400°C, and oak wood – approx. 430°C. As the figures show, both curves for both specimens are very similar and located close to each other.

3.2. Preparation of the test

Specimens were manufactured from timber without fissures. Dimension and shape of the specimens were selected according to regulation. Specimens were taking from pine and oak sapwoods. Figure 3 shows the manner taking specimens from sapwood.

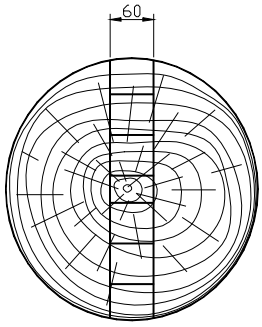

***Fig 3**. Specimens manufacture from sapwood*

Compressive strength test

The specimens dimension was 20 × 20 × 30 mm (see Fig 4.). These specimens were tested along and across its fibres directions. Overall 720 elements were manufactured (360 for compressive strength test along fibres direction and 360 for compressive strength test across fibres direction).

***Fig. 4**. Specimens for compressive strength test*

Bending strength test

The specimens dimension was 20 × 20 × 300 mm (see Fig. 5.). Overall 120 elements were manufactured.

***Fig. 5**. Specimens for bending strength test*

Tensile strength test

The shape of the specimens for tensile strength test is shown in Fig. 6.

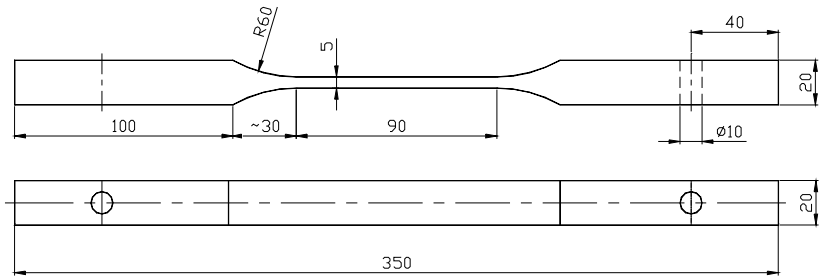

***Fig. 6**. Specimens for tensile strength test*

Tests were performed at the following thermal conditions:

Start temperature approx. 20 °C (room temperature), within 50 °C − 230 °C. Taken into account that temperature increases inside the undamaged component core from 20 °C to 200 °C, and that the thermal decomposition begins at approx. 240 °C, test temperatures were selected as follows for the determination of strength reduction: 50 °C, 100 °C, 150 °C, 200 °C, 230 °C.

Preliminary tests were used for determination of the sample heating program in order to uniformly raise the whole sample material temperature.

4. Analysis of test results

Strength test results were collected as average results from 10 tests at high temperatures for both wood species, and compared to those at 20 °C are shown in Figures 7 − 10.

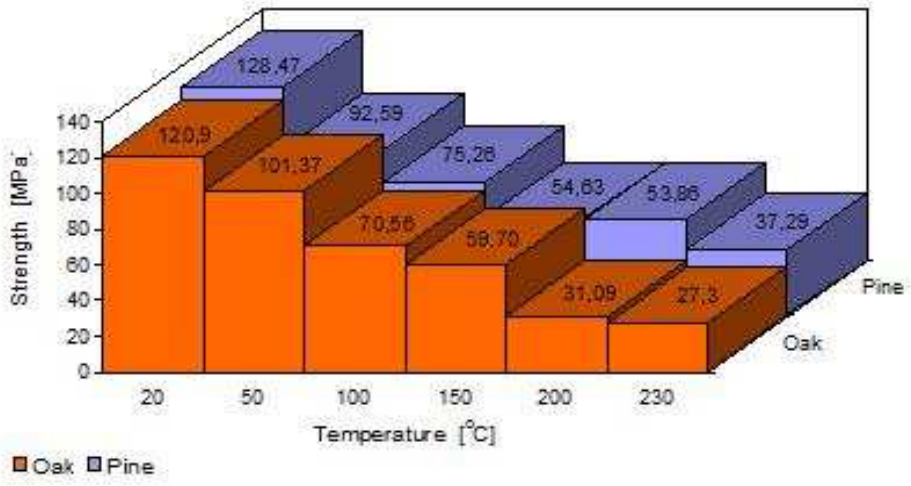

***Fig. 7**. Timber tensile strength diagram with varying temperature*

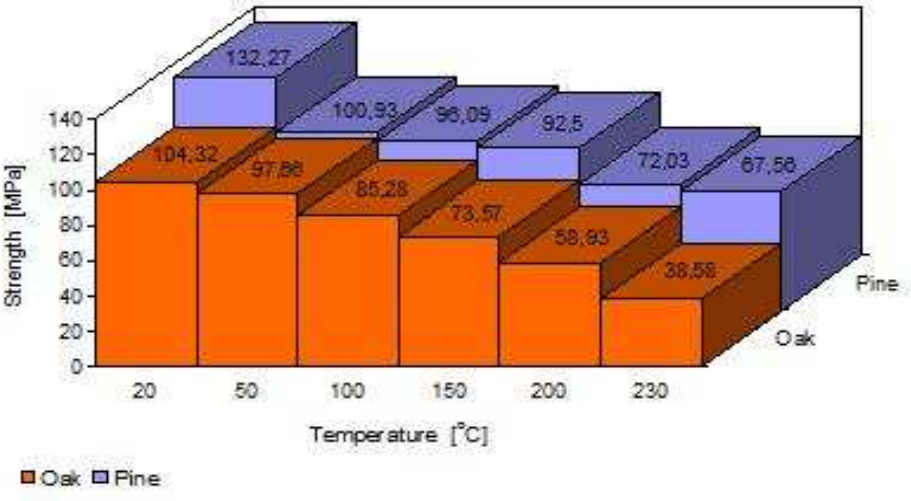

***Fig. 8**. Timber bending strength diagram with varying temperature*

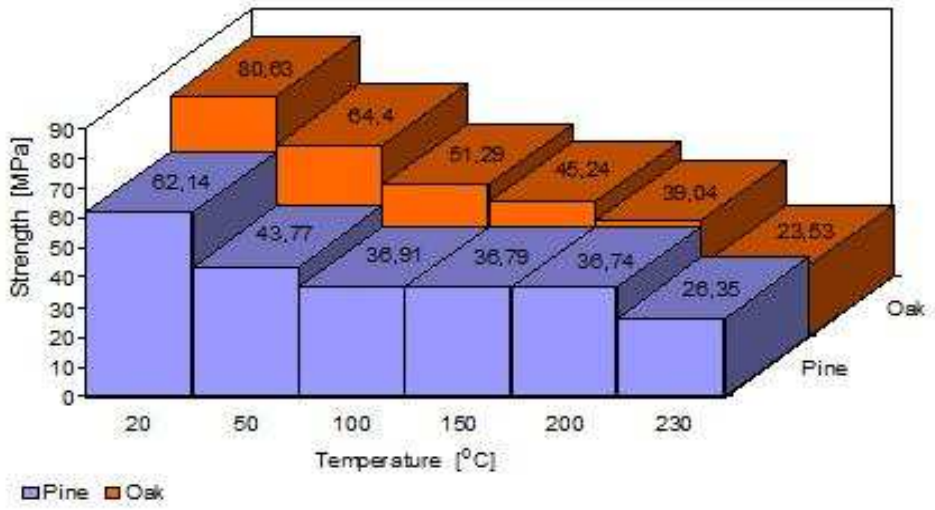

***Fig. 9**. Timber compressive strength across fibre diagram with varying temperature*

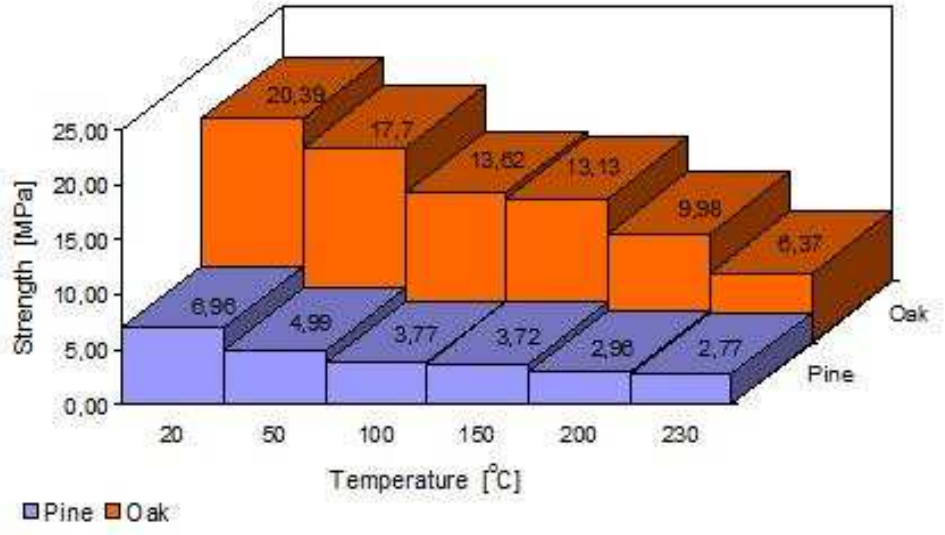

***Fig. 10**. Timber compressive strength along fibre diagram with varying temperature*

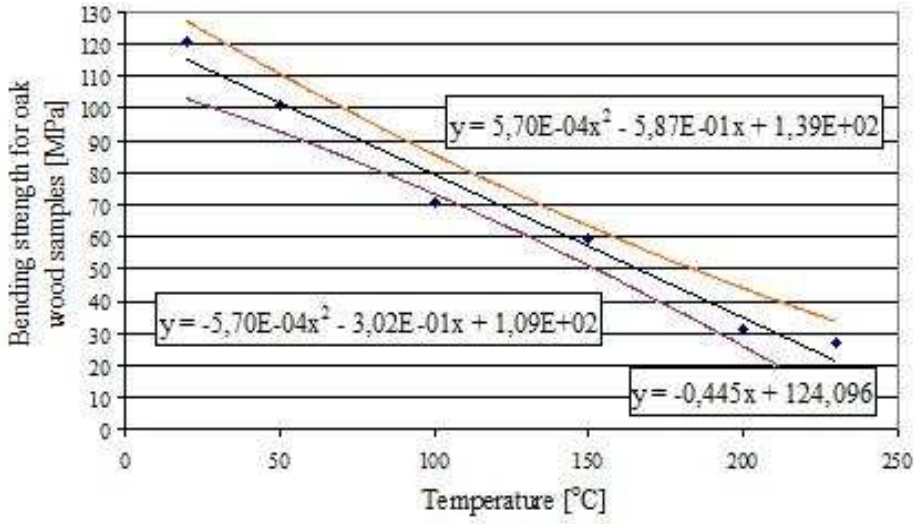

***Fig. 11**. Linear regression function and reliability curve for bending strength (oak specimen)*

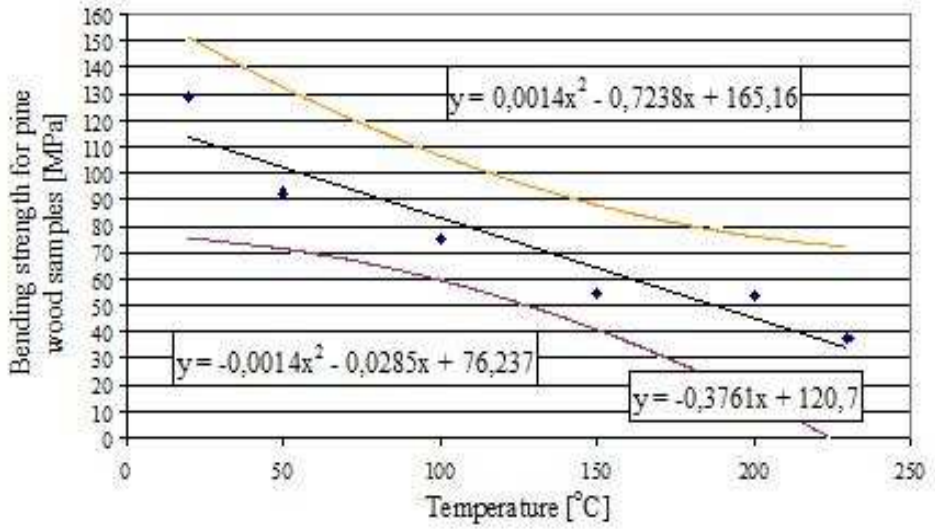

***Fig. 12**. Linear regression function and reliability curve for bending strength (pine specimen)*

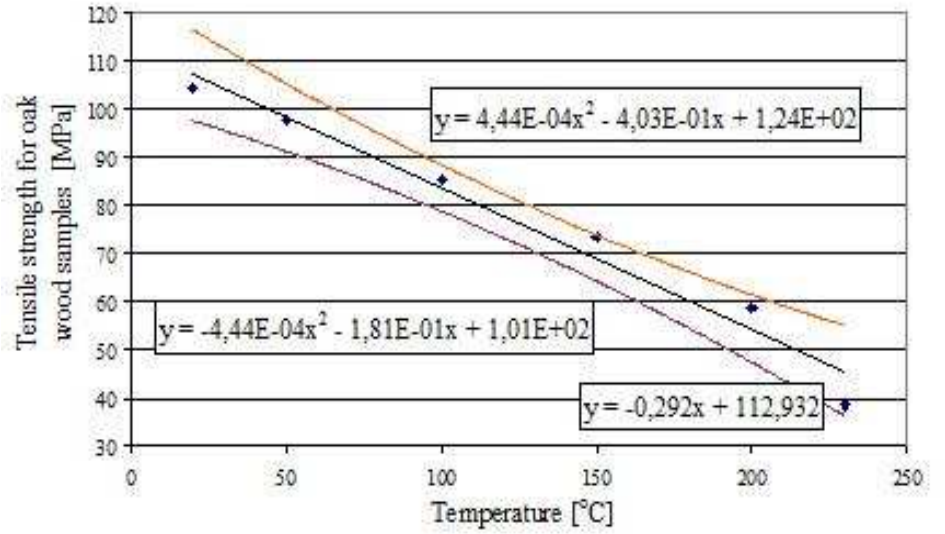

***Fig. 13**. Linear regression function and reliability curve for tensile strength (oak specimen)*

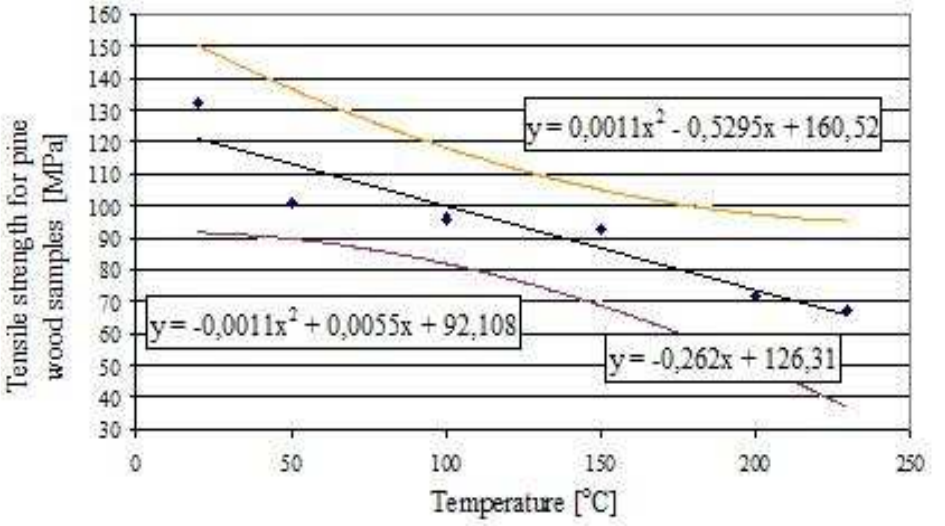

***Fig. 14**. Linear regression function and reliability curve for tensile strength (pine specimen)*

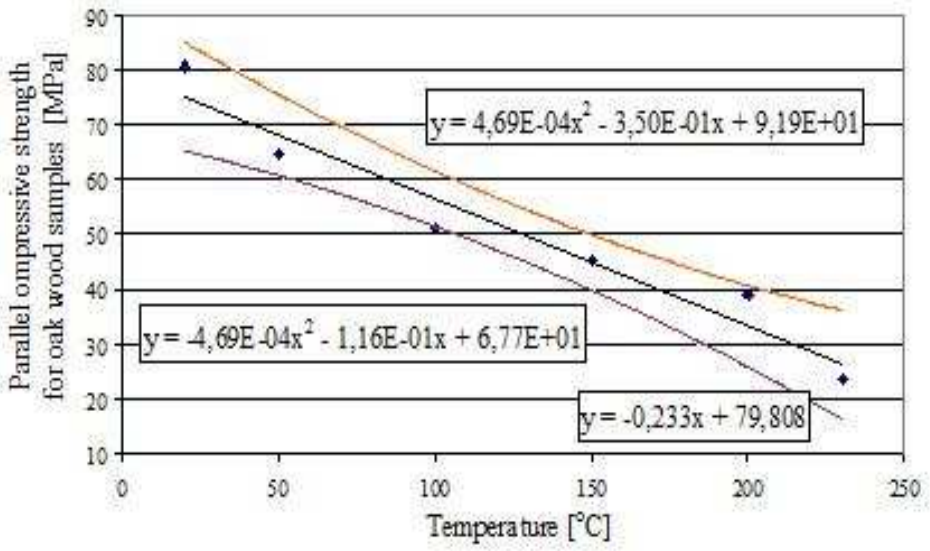

Fig. 15. *Linear regression function and reliability curve for compressive strength along grain (oak specimen)*

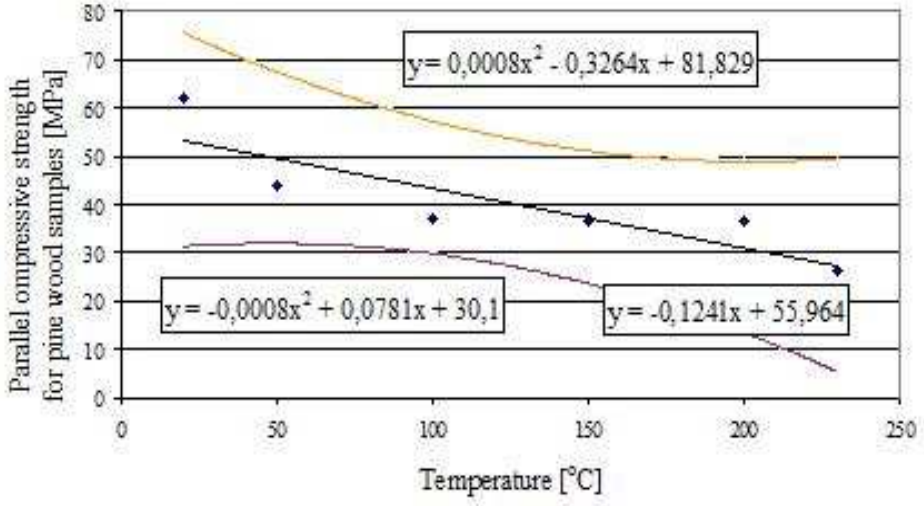

Fig. 16*. Linear regression function and reliability curve for compressive strength along grain (pine specimen)*

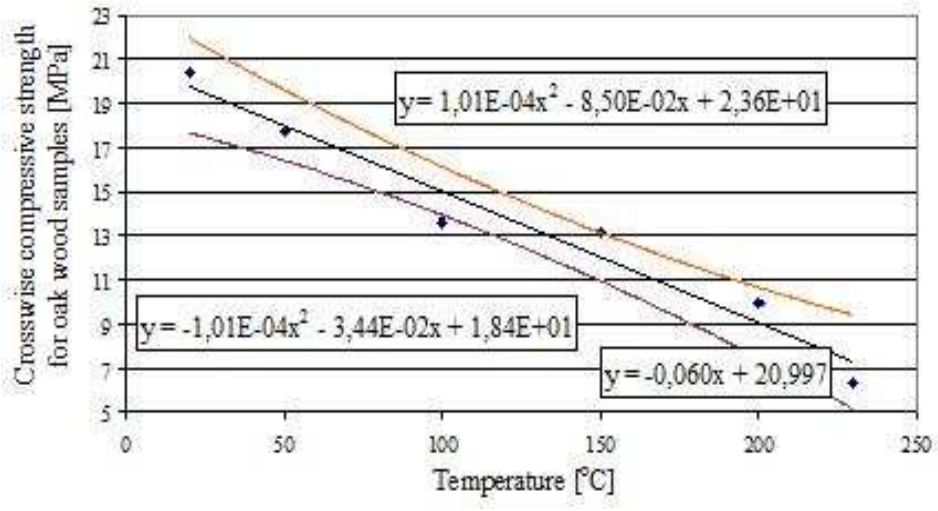

***Fig. 17**. Linear regression function and reliability curve for compressive strength across grain (oak specimen)*

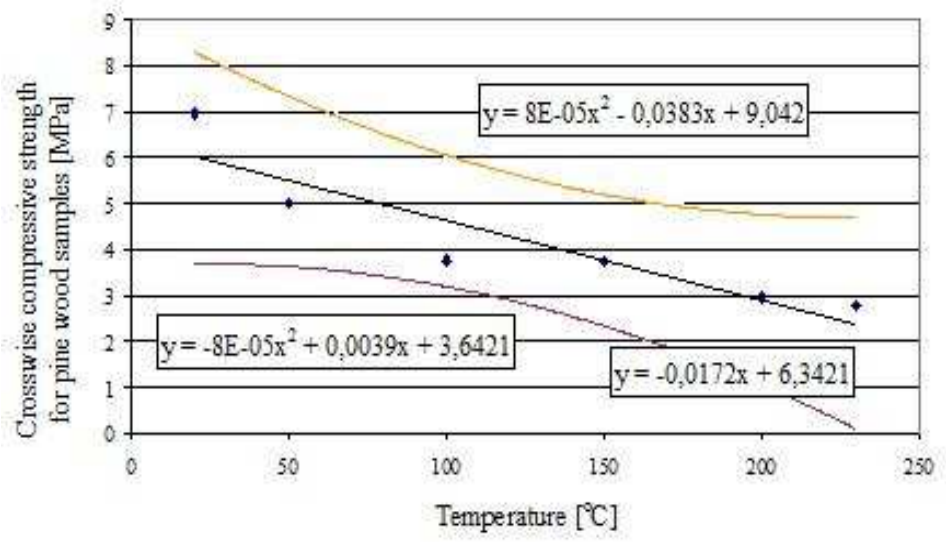

***Fig. 18**. Linear regression function and reliability curve for compressive strength across grain (pine specimen)*

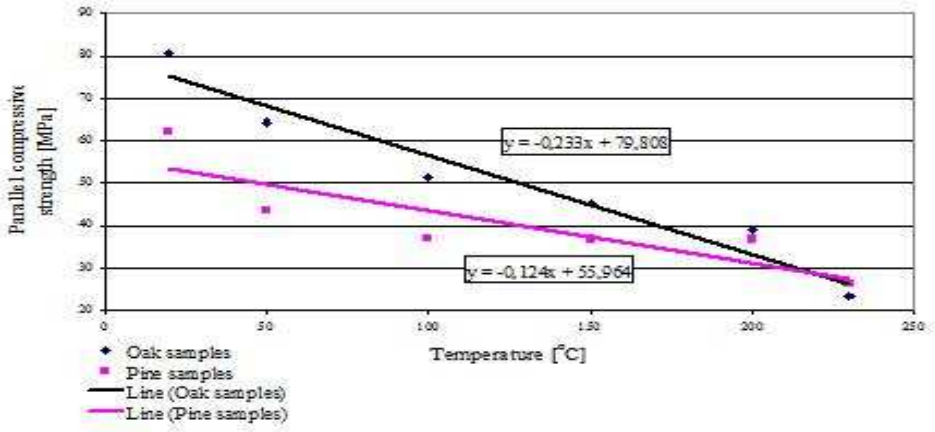

***Fig. 19**. Compressive strength along grain dependence on temperature*

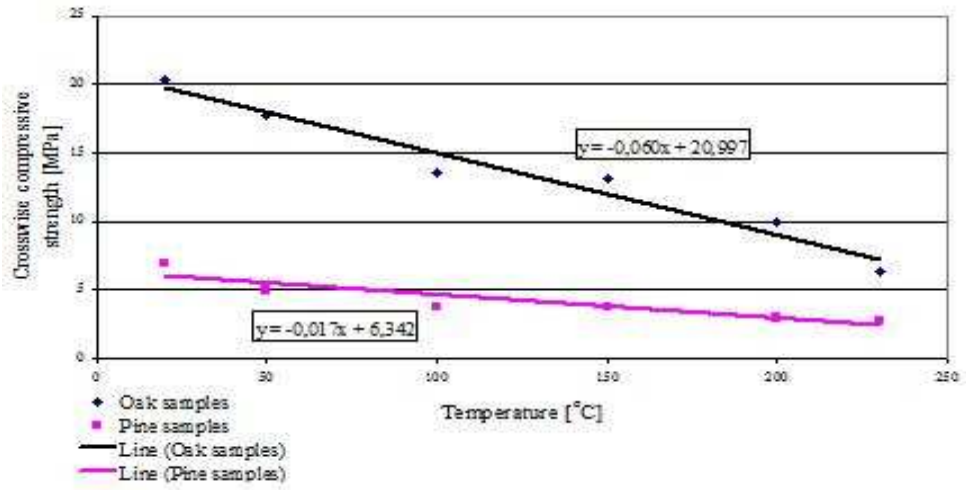

***Fig. 20**. Compressive strength across grain dependence on temperature*

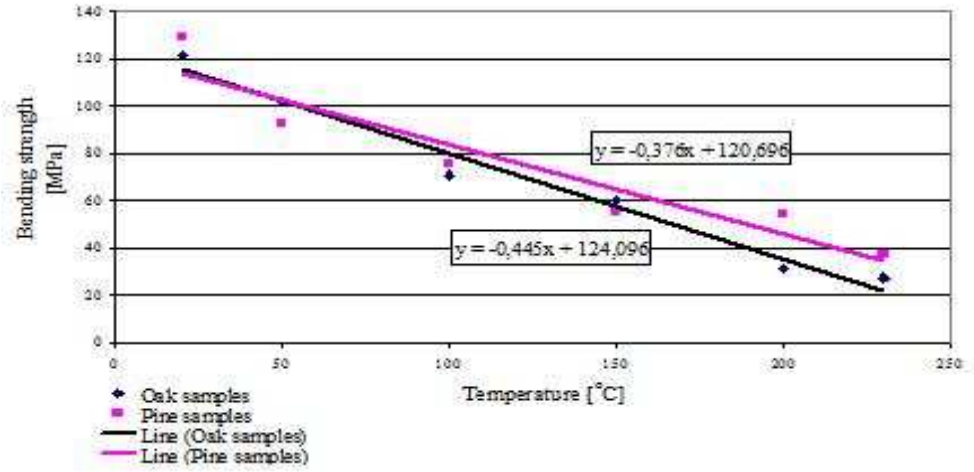

***Fig. 21**. Bending strength dependence on temperature*

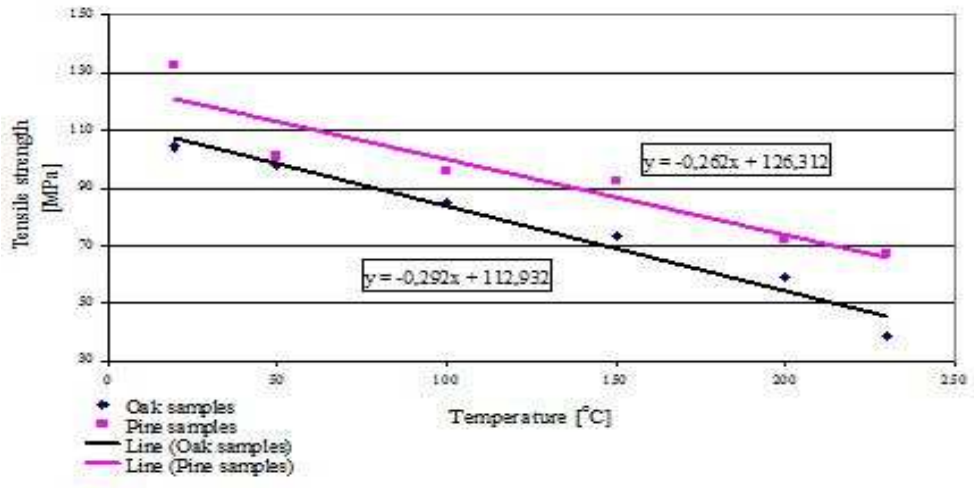

***Fig. 22**. Tensile strength dependence on temperature*

The strength reduction versus temperature was defined by a linear function $y = ax + b$ for both wood species. Figures 11 − 18 shows the linear regression functions with reliability level curves; Table 2 includes data (inclination, offset) for these functions, and correlation coefficients equal to approx. 1.

Table 2. Comparison of regression function and correlation coefficients for selected test type

Nr	Test type	Coefficients for regression function: $y = ax + b$				Correlation coefficient for strength versus temperature relations	
		Regression function declination – a coefficient		Regression function declination – b coefficient			
	S – pine specimens D – oak specimens	Specimen group		Specimen group		Specimen group	
		S	D	S	D	S	D
1	Tension	-0.262	-0.292	126.312	112.932	0.9372	0.9833
2	Bending	-0.376	-0.445	120.696	124.096	0.9477	0.9880
3	Compression along fibre	-0.124	-0.233	55.964	79.808	0.8598	0.9712
4	Compression across fibre	-0.017	-0.06	6.342	20.997	0.9126	0.9793

Table 3. Strength reduction coefficient $k_{\mathrm{mod}\,fi}$

Temperature [°C]	Bending		Tension		Compression along fibres		Compression across fibres	
	Pine	Oak	Pine	Oak	Pine	Oak	Pine	Oak
20	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
50	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
100	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8
150	0.6	0.5	0.7	0.6	0.7	0.6	0.6	0.6
200	0.4	0.3	0.6	0.5	0.6	0.4	0.5	0.5
230	0.3	0.2	0.5	0.4	0.5	0.3	0.4	0.4

Based on the test result analysis, strength reduction coefficients, $k_{\mathrm{mod}\,fi}$, were proposed. These coefficients should be applied for calculations of wood elements core strength in fire as required by Eurocode 5. The proposed coefficients are included in Table 3.

5. Concluding remarks

This study was conducted to investigate the fire resistance of timber specimens (pine and oak). The following conclusion can be drawn from this research:

- A significant influence of even small temperature growth on all strength types was observed. From the point of view of fire resistance evaluation, the temperature rise in the range 100 up to 200 °C is important.
- Two selected wood species with different density (pine − 539,0 g/cm^3, oak − 750,0 g/cm^3) provided with very interesting results when compared from the point of view of their fire profiles (flammability) and reduction of strength as influenced by high temperatures.
- Thermal analysis results showed that the fire profiles (flammability) of both wood specimens were similar. The thermal decomposition begins at 240 °C in both cases; the highest mass loss rate occurred at approx. 430 °C after 42 minutes (pine) and at approx. 460 °C after 47 minutes (oak). The self-ignition occurred at approx. 400 °C (pine) and 430 °C (oak). The TG and DTG curves were similar to each other.
- Oak specimens have an undisputable advantage over pine specimens at normal as well as high temperatures for compressive strength across grain; nevertheless, tests proved that the strength reduction rate versus temperature was higher for oak samples. For compressive strength along grain, oak specimens has higher values than pine within the entire temperature range, still, a higher strength reduction rate versus temperature was found also for oak specimens.
- In case of tensile strength and bending strength, pine specimens have better properties over the entire temperature range. Also for these strength types, oak specimens show a higher strength reduction rate than pine wood. Strength reduction comparison diagrams confirming these conclusions are shown in Figures 19 − 22.
- The above observations give reasons for stating that oak specimens (of a higher density than that of pine specimens) reacts with a quicker strength reduction against rising temperature than pine. The pine specimens strength reduction against temperature is not as quick.
- For calculations of wood strength in fire temperatures for both wood kinds, we propose to apply regression functions as shown in Figures 11 − 18 or with data included in Table 2. In all test types, the strength reduction against rising temperature is of a linear character.

- For the fire resistance evaluation of timber structures, we propose to apply the strength reduction coefficients, $k_{\mathrm{mod}\,fi}$, as listed in Table 3, for formula 3. These coefficients were determined based on statistical calculations of test results for pine and oak specimens.

S U M M A R Y

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S T R E S Z C Z E N I E

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Mečislavas GRIŠKEVIČIUS

WPŁYW ZMNIEJSZENIA ODPORNOŚCI OGNIOWEJ DREWNA NA WYTRZYMAŁOŚĆ BUDYNKÓW

W badaniach zastosowano testy statyczne badające następujące cechy: odporność na rozciąganie, wytrzymałość na ściskanie zarówno wzdłuż, jak i w poprzek włókien, jak również odporność na zginanie. Próbki poddano testom w temperaturach 50 °C , 100 °C, 150 °C, 200 °C oraz 230 °C. Wyniki pokazują, że próbki sosny posiadają lepsze właściwości odporności na rozciągania i zginanie we wszystkich temperaturach. W badaniach powyższych odporności próbki dębu wykazują większe zmniejszenie stopnia odporności aniżeli próbki sosny. Jednakże próbki dębu mają lepsze cechy odporności na ściskanie w poprzek włókien we wszystkich tem-

peraturach. Opierając się na analizie statystycznej zaproponowano liniowe wyrażenie dla współczynnika zmniejszenia odporności.

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