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BEARING CAPACITY OF AXIALLY LOADED TIMBER MEMBERS – ESTIMATION UNDER UNEVEN FIRE ACTION

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Abstract. The article deals with the peculiarities of calculating bearing capacity for axially loaded timber members under uneven fire action. According to LST EN 1995-1-2 and finite element modelling for determining temperature fields and variations in timber strength under elevated temperature, the method of simple calculations was applied. Calculations are based on the data and results of experimental investigations into the resistance of axially loaded members to fire. Data on variations in timber strength were obtained conducting laboratory tests using the specimens of Lithuanian pine under elevated temperature.

Keywords: timber, compression, bending, fire action, charring, standard fire curve, fire resistance, strength variation, bearing capacity.

1. Introduction

Timber structures in a fire situation are commonly rated as more dangerous if compared with steel and concrete structures. Due to the low conductivity of timber, the bearing capacity of timber structures decreases slower in a fire situation if compared with other mentioned types of structures. The behaviour of timber in fire, its charring rate, humidity influence on the charring rate, strength variation at elevated temperatures are investigated profoundly by Jong and Clancy (2004), Frangi *et al.* (2008). Modification factors of strength in a fire situation are provided in LST EN 1995-1-2:2005. Under a typical fire situation, the charring of timber goes at a constant rate, which depends on the shape and size of the member. Investigations into charring rates depend on different fire scenarios, parameters and fire protection means and were executed by Lipinskas and Mačiulaitis (2005), Półka (2008). Many investigations were carried out to obtain changes in timber properties at elevated temperatures. They were performed by König (2005), Bednarek and Kamocka (2006), Bednarek and Kaliszuk-Wietecka (2007), Bednarek *et al.* (2009). According to LST EN 1995-1-2:2005 for solid timber with the density of more than 290 kg/m^3, the design charring rate will be 0,8 mm/min. For members with a higher cross section reduction ratio for a cross section area, the strength and modulus of elasticity decrease due to rising temperature. Temperature distribution in timber members under heating from one or all sides was analyzed by Frangi and Fontana (2003) and Reszka and Torero (2006).

Articles about investigations into the behaviour of compressed timber members under direct flame action without the means of protection are very rare (Šaučiuvėnas, Griškevičius 2009). More extensive investigations are executed on the studs of the framed wall elements by direct flame action on a wall fragment (Young, Clancy 2001; Clancy 2002; Richardson 2001; Hadvig 1981).

The latest investigations deal with modelling fire conditions (Gałaj 2009) and analysis of temperature distribution in a cross section of the members (Reszka, Torero 2006). Up to now, the software of finite elements has not been so widely used for determining temperature fields. Blaževičius and Kvedaras (2007) employed this method for temperature fields of composite sections and Erchinger *et al*. (2010) – for temperature fields of timber members.

The uneven charring of a timber cross section can induce a bending moment even under axial loading conditions. Streiger and Fontana (2005) pointed to the influence of a bending moment on the bearing capacity of timber columns; however, the results of these investigations were based on data obtained at ambient temperatures and details set out in expressions taken from LST EN 1995-1-1:2005. Data on experimental investigations into timber in a fire situation was collected by Šaučiuvėnas and Griškevičius (2009) and applied for analysis presented in this article. It can be stressed that investigations into the behaviour of a compressed timber member under the fire conditions of uneven charring are very rare, and therefore it is not possible to make reliable conclusions about this phenomena.

2. Method for calculating timber members under axial force and under axial force and the bending moment

Calculations of a timber member under axial force and combining axial force and the bending moment are performed using the same method of a reduced cross-section. The aim of the made calculations was to obtain the influence of eccentricities induced by uneven charring on the behaviour and bearing capacity of a timber member under fire conditions. The bearing capacity of the reduced fire cross-section can be calculated according to chapter 6.3.2 of LST EN 1995-1-1:2005. The resistance of the member in case axial compression force and the bending moment are acting if $\lambda_{rel,z} \leq 0.3$ and $\lambda_{rel,y} \leq 0.3$ must be calculated according to the below formulas:

$$\left(\frac{\sigma_{c,0,d}}{f_{c,0,d}}\right)^2 + \frac{\sigma_{m,y,d}}{f_{m,y,d}} + k_m \frac{\sigma_{m,z,d}}{f_{m,z,d}} \leq 1 \quad (1)$$

and

$$\left(\frac{\sigma_{c,0,d}}{f_{c,0,d}}\right)^2 + k_m \frac{\sigma_{m,y,d}}{f_{m,y,d}} + \frac{\sigma_{m,z,d}}{f_{m,z,d}} \leq 1 . \quad (2)$$

In other cases:

$$\frac{\sigma_{c,0,d}}{k_{c,y} f_{c,0,d}} + \frac{\sigma_{m,y,d}}{f_{m,y,d}} + k_m \frac{\sigma_{m,z,d}}{f_{m,z,d}} \leq 1 ; \quad (3)$$

$$\frac{\sigma_{c,0,d}}{k_{c,z} f_{c,0,d}} + k_m \frac{\sigma_{m,y,d}}{f_{m,y,d}} + \frac{\sigma_{m,z,d}}{f_{m,z,d}} \leq 1 , \quad (4)$$

where: k_m – a factor considering the re-distribution of bending stresses in a cross-section; $f_{m,y,d}$ – design bending strength about the y axis; $f_{m,z,d}$ – design bending strength about the z axis;
where:

$$k_{c,y} = \frac{1}{k_y + \sqrt{k_y^2 - \lambda_{rel,y}^2}} ; \quad (5)$$

$$k_{c,z} = \frac{1}{k_z + \sqrt{k_z^2 - \lambda_{rel,z}^2}} ; \quad (6)$$

$$k_y = 0,5(1 + \beta_c(\lambda_{rel,y} - 0.3) + \lambda_{rel,y}^2) ; \quad (7)$$

$$k_z = 0,5(1 + \beta_c(\lambda_{rel,z} - 0.3) + \lambda_{rel,z}^2) ; \quad (8)$$

β_c – a straightness factor for members the straightness limits of which are described in LST EN 1995-1-1 :2005 chapter 6.3. For solid timber $\beta_c = 0.2$.

The calculations of the strength of the members loaded with axial force and bending as well as induced by uneven cross-section charring was based on the remaining cross-section method and experimental charring depth obtained for each side of the member. Following LST EN 1995-1-2:2005 chapter 3.4.2, the radius of the roundings of the remaining cross-section corner $r = d_{char,0}$ and eccentricities were calculated. For a more precise estimation of the remaining geometrical parameters of a cross-section-a section area, the second moment of the area, section modulus and eccentricities – the section was divided into four parts (see Fig. 1). The radius of the roundings of the cross-section corner was calculated like the average for adjacent horizontal and vertical section faces ($R_{1a} = \frac{d_{char,n,ha1} + d_{char,n,ba1}}{2}$). Zero strength layer thickness – $k_0 d_0$ – was not rated in calculations. Eccentricities used in calculations consist of the mean value of the measured bow imperfection equal to 8 mm and eccentricities due to reduction in the cross-section induced by charring (see Fig. 2).

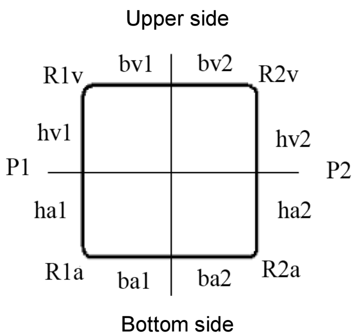


Fig. 1. Relative breaking into the parts of the cross-section for calculating cross-section parameters

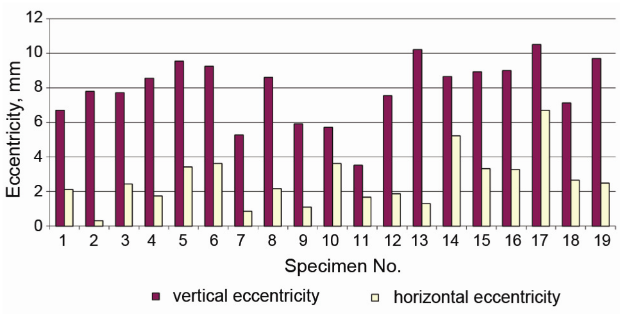


Fig. 2. Eccentricities of the residual cross-section

The made calculations have revealed that bending moments in a member can appear due to the nonuniform charring of a cross-section and can be increased by the eccentric action of axial force. The imperfection of the initial bow has not been taken into account. Along with discussed assumptions, the strength of residual cross-sections is presented in Fig. 2. For some specimens (1, 4, 10, 14, 15, 16, 22), the strength of the residual cross section that corresponds to the experimental limit state is higher than experimental strength shown in Fig. 3. The average values of the bearing capacity ratio calculated according to LST EN 1995-1-1:2005 (6.23) are equal to 1.19 and according to LST EN 1995-1-1:2005 (6.24) – to 0.8.

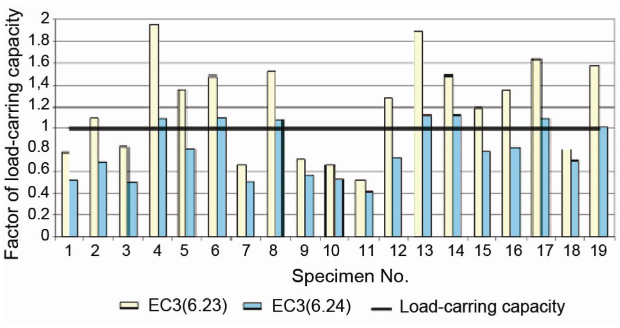


Fig. 3. The design results of the load-carrying capacity of residual cross-sections of timber elements according to EN 1995-1-2: 2005

It can be assumed that the above introduced situation occurred due to the fact that some factors were not considered during calculations. The carried out calculations showed it was not sufficient to take into account only a reduction in the geometry of the cross section, because a reduction in timber strength at elevated temperatures may also considerably influence the bearing capacity of the member. To prove it, a more complex calculation model discussed in LST EN 1995-1-2:2005 Annex B, was applied. In such a case, it was necessary to estimate temperature distribution fields in a cross-section of a timber element. For solving this problem, finite element software *SolidWorks Simulation* was used.

3. Results of a numerical simulation of the behaviour of slender timber members

Temperature distribution fields in a member cross-section were estimated for each interval of 60 seconds according to approximate temperature curves obtained during tests. Experimental temperature curves are presented in Fig. 4. During simulation, the bottom side of a cross-section (below the horizontal section axis) was affected by temperature according to the approximate temperature curve of the bottom side and the upper cross-section side (above the horizontal section axis) – according to the approximate temperature curve of the top side. It was assumed that:

- the specimen cross-section – 50×50 mm;
- the buckling length of member – 1200 mm;
- timber average density – 580 kg/m^3.

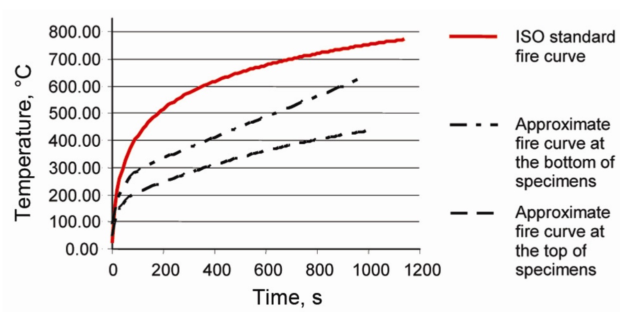


Fig. 4. Approximate relationships between fire exposed time and temperature

For solving the problem of temperature field distribution, as in the case of stress analysis with FEM simulation, it is necessary to divide the model into finite elements. For this particular problem of temperature field distribution, the cross-section was subdivided into 2.5 mm square finite elements.

FEM simulation was used only for temperature distribution in a cross-section. It was caused by the complexity and lack of information related to the relationships of strength and deformations at elevated temperatures. For more complex FEM simulation considering the behaviour of a timber member in a fire situation, it is not enough to know the relationship between strength and temperature as the influence of temperature on deformations must also be taken into account. Thus, for a general case, 3D relationship for strength, deformations and temperature must be used in FEM simulation. EC 1-1-2:2004 and other literature sources do not determine similar relationships. In the absence of the before discussed relationships, the application of popular FEM software *SolidWorks Simulation* for timber member complex analysis taking into consideration the strength and deformation of timber at elevated temperatures seems to be limited. It was not possible to find publications related to investigation into the stresses and behaviour of timber members in a normal environmental situation employing FEM software. Temperature distribution to the various types of cross-sections of timber wall posts and the charring process of them was investigated by means of software Frangi *et al*. (2008). Timber members were affected by elevated temperature from three sides. The comparison results of data on experimental and computer simulations were presented. In both cases, a standard fire curve was applied.

4. Thermal properties of timber

For modelling a designed fire situation, on the basis of LST EN 1995-1-2:2005 Annex B recommendations, thermal conductivity, specific heat and density ratio values of soft wood were applied according to curves presented in Figs 5, 6 and 7.

The caused charring layer thermal conductivity values are true, whereas those of timber charcoal conductivity are not measured. While increasing heat transfer due to shrinkage cracks at higher than 500 °C temperature,

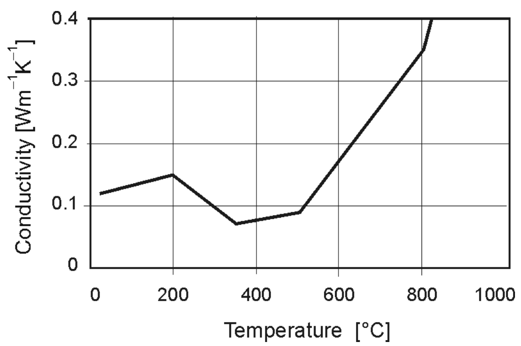


Fig. 5. Relationship between temperature and thermal conductivity for timber and the charred layer (LST EN 1995-1-2:2005)

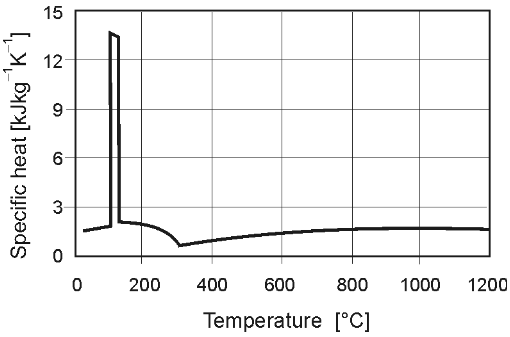


Fig. 6. Relationship between temperature and specific heat for wood and charcoal (LST EN 1995-1-2:2005)

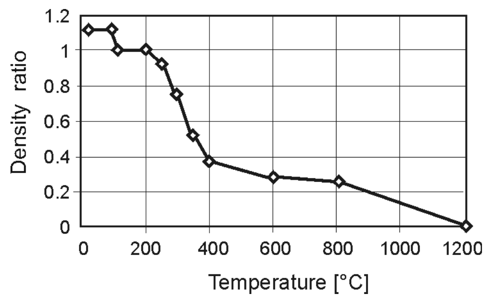


Fig. 7. Relationship between temperature and density ratio for softwood with the initial moisture content of 12% (LST EN 1995-1-2:2005)

the timber decay process at approximately 1000 °C was taken into account. The charring layer cracks increased heat transfer by radiation and convection. It is generally prevalent not to consider these factors in computer models (LST EN 1995-1-2:2005).

5. Temperature distribution fields in the cross-section

Let us focus on temperature distribution fields at 840 s (14 min) after fire starts. This corresponds to the average experimental fire resistance. Temperature distribution fields after 14 min are presented in Fig. 8. Temperature in the cross-section considering this situation is higher than that in a normal environment, thus, the strength of timber in a big part of the section is reduced and must be considered for calculations.

According to temperature distribution in the cross-section, the charring boundary corresponding to 300 °C isotherm was found. According to the rules of the code for timber behaviour in a fire situation, this isotherm can be considered as the charring boundary. It was estimated that according to simulation results, the thickness of the average charring layer for the bottom was 4.5 mm and according to experimental data – 7.7 mm. For the top side of the cross-section, it made 1.9 mm and 0.9 mm respectively. For the left and right side faces of the cross-section, only computer simulation results were obtained. The picture in Fig. 10 clearly shows that the thickness of the average charring layer will be more than 2.7 mm. The differences between computational and experimental investigation results can be explained by some inaccuracy in the approximation of the relationship between time and temperature assuming that one relation is suitable for all the area of the top part of the section and the other – for all the area of the bottom part of the cross-section.

For comparison, Fig. 9 displays the temperature fields of the same cross-section after 14 min period of fire according to the standard temperature curve when heating is affecting the member from all sides.

6. Bearing capacity of timber members having material properties at elevated temperature

The radius of the charred corner rounding according to temperature distribution fields and geometrical parameters of the areas bounded by different temperature isobars are presented in Table 1.

For each area bounded by the isotherm starting from 300 °C, the basic cross-section properties were calculated and presented in Table 1.

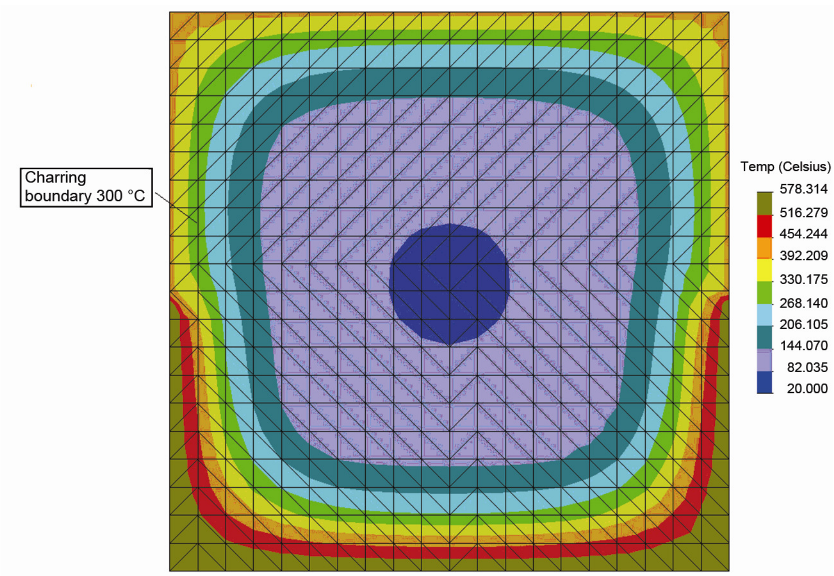


Fig. 8. The distribution of temperature fields after a 14 min exposure to fire

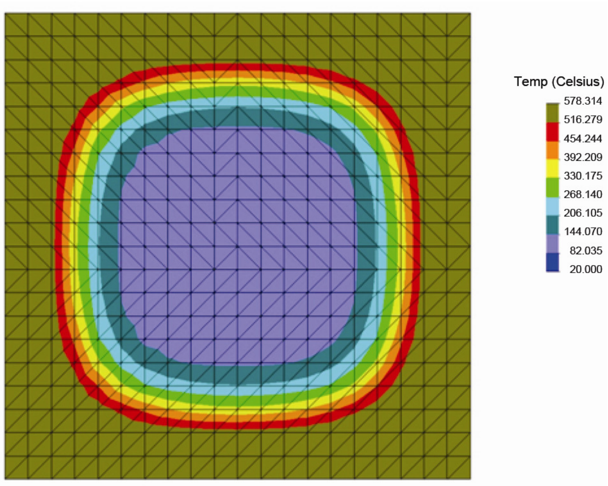


Fig. 9. The distribution of temperature fields following 14 min exposure to fire if temperature follows a standard fire curve

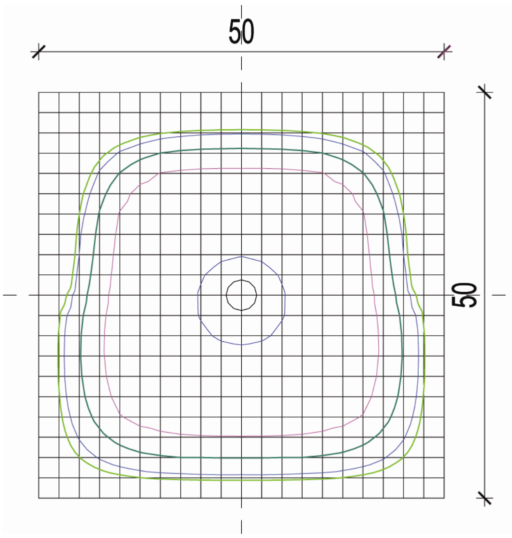
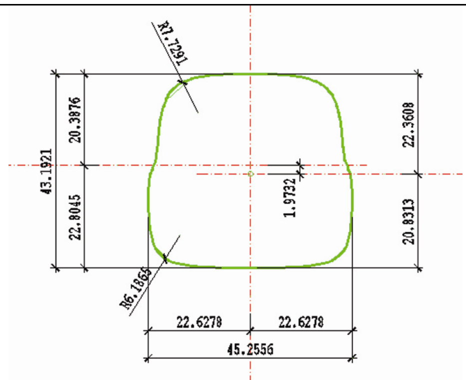
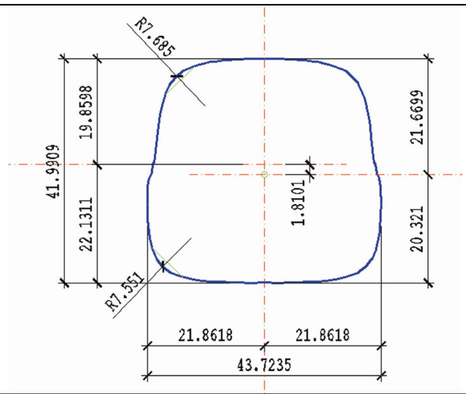


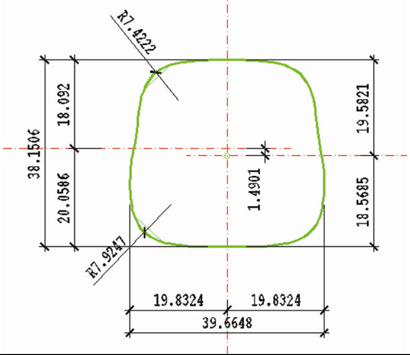
Fig. 10. The mean values of the intervals of temperature fields (inverted view)

Taking into account the properties of the bounded areas and the average values of the temperature interval, the weighted reduction factor for average properties related to the 300 °C isotherm bounded area (bright green) of bending and compression strength and the modulus of elasticity was calculated. The values of the reduction factor of compression and bending strength were considered according to experimental relationships presented by Bednarek *et al*. (2009). The reduction factor of the elasticity modulus was obtained from Eurocode 5 (LST EN 1995-1-2:2005) Annex B because of the lack of experimental data. Relationships with reduction factors used in calculations are presented in Fig. 11.

Table 1. The parameters of cross sections circumscribed by temperature isotherms displayed in Fig. 10

Bright green (the isotherm at a temperature of 300 °C) – A1	
Shape and dimensions, mm	
	
Geometrical properties of the area	Values
Area, mm^2	1748.2
Perimeter, mm	153.9
The second moment of the area about the horizontal axis, mm^4	252028
The second moment of the area about the vertical axis, mm^4	251327
The radius of gyration about the horizontal axis, mm	12.01
The radius of gyration about the vertical axis, mm	11.99
Blue – A2	
Shape and dimensions, mm	
	
Geometrical properties of the area	Values
Area, mm^2	1631.0
Perimeter, mm	148.0
The second moment of the area about the horizontal axis, mm^4	218957
The second moment of the area about the vertical axis, mm^4	217427
The radius of gyration about the horizontal axis, mm	11.59
The radius of gyration about the vertical axis, mm	11.55
Green – A3	
Shape and dimensions, mm	

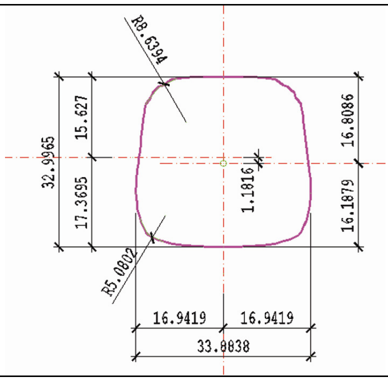
Continued Table 1



Geometrical properties of the area	Values
Area, mm^2	1346.2
Perimeter, mm	133.9
The second moment of the area about the horizontal axis, mm^4	148334
The second moment of the area about the vertical axis, mm^4	147769
The radius of gyration about the horizontal axis, mm	10.50
The radius of gyration about the vertical axis, mm	10.48

Violet – A4

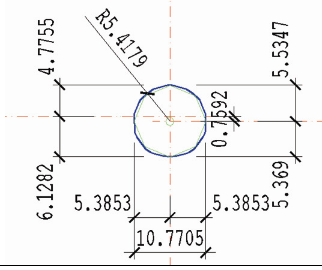
Shape and dimensions, mm



Geometrical properties of the area	Values
Area, mm^2	1004.9
Perimeter, mm	116.30
The second moment of the area about the horizontal axis, mm^4	83009
The second moment of the area about the vertical axis, mm^4	81812
The radius of gyration about the horizontal axis, mm	9.09
The radius of gyration about the vertical axis, mm	9.02

Small blue – A5

Shape and dimensions, mm



Geometrical properties of the area	Values
Area, mm^2	93.10
Perimeter, mm	34.4
The second moment of the area about the horizontal axis, mm^4	736
The second moment of the area about the vertical axis, mm^4	698
The radius of gyration about the horizontal axis, mm	2.81
The radius of gyration about the vertical axis, mm	2.74
Note. *Sketches of the areas are rotated about the horizontal axis.*	

The weighted average reduction factors of bending and compression strength and the modulus of elasticity for a concerned area according to the average temperatures of the area were calculated by the formula:

$$S_{p,vid} = S_{A1} + S_{A2}\frac{A_2}{A_1} + ... + S_{Ai}\frac{Ai}{A_1}, \quad (9)$$

where: $S_{p,vid}$ – the weighted average reduction factor value of the strength or modulus of elasticity; S_{Ai} – the reduction factor of the strength or modulus of elasticity depending on mean temperature for a concerned area; A_i – the concerned area.

Table 2 presents the values of reduction factors calculated according to expression (9).

The bearing capacity of the residual design cross-section (without the charring layer) was calculated according to the rules imposed in Eurocode 5 Part 1–2 (LST EN 1995-1-2:2005) and formulas (1)–(8). The calculations used the following initial mean values of experimental timber properties:

- compression strength – 43.3 MPa;
- bending strength – 87.1 MPa;
- the modulus of elasticity – 16355 MPa.

Table 2. The results of calculating reduction factors of timber parameters

Area symbol	Temperature	Mean temperature	Area, mm^2	Reduction factor of compression	Reduction factor of bending	Reduction factor of the modulus of elasticity (compression)
A1–A2	299	283.57	117.24	0.007143	0.004286	0.00175
A2–A3	268.14	237.07	284.74	0.227571	0.136543	0.055755
A3–A4	206	175.035	341.31	0.58	0.38	0.1295
A4–A5	144.07	113.0525	911.81	0.71186	0.61186	0.197878
A5	82.035	51.0175	93.10	0.83593	0.77186	0.395966
Weighted values of reduction factors for the whole area A1:				0.573	0.461	0.160

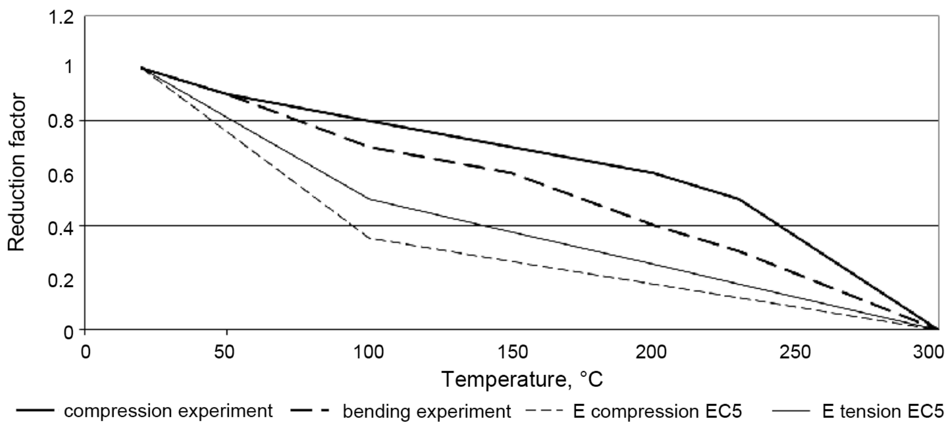


Fig. 11. Relationship between temperature and the strength reduction factor

The bearing capacity of a timber member in a fire situation was calculated two times. The member was calculated like a column subjected to compression and like a column subjected to combined bending and compression. Initial geometrical imperfections were not taken into account. An additional bending moment that caused axial load eccentricity due to uneven charring was evaluated.

The results of calculating bearing capacity considering code LST EN 1995-1-1:2005 may be observed in Table 3.

Table 3. Calculation results

Compression		Values of experimental loads 6.0 kN	7.5 kN
Equation	Design load, kN	Experimental and design load ratio	
(3) buckling about the horizontal axis	4.25	1.412	1.765
(4) buckling about the vertical axis	4.26	1.408	1.761
Combined bending about the horizontal axis and compression			
(3)	4.25 Eccentricity e = 1.973 mm	1.446	1.810

Data presented in Table 3 disclose that taking into account the experimental values of timber strength and reduction factors for the modulus of elasticity in compression according to Eurocode 5 Part 1–2 (LST EN 1995-1-2:2005), the calculated values of bearing capacity are conservative in comparison with experimental data. As for all strength properties, Eurocode 5 (LST EN 1995-1-1:2005) gives smaller reduction factors; if compared with experimental data, it seems to be that the factor for the modulus of elasticity is also conservative. To determine the impact of the modulus of elasticity, reduction factors for the results of bearing capacity calculations and the tension modulus coefficient of elasticity (which is higher) were used. In such a case, the factor for utilizing the bearing capacity of a slender timber member in a fire situation was:

- buckling about the horizontal axis – 1.07;
- buckling about the vertical axis – 1.06;
- combined bending and compression – 1.04.

It can be concluded that the rules of Eurocode 5 part 1–2 (LST EN 1995-1-2:2005) can be applied not only in the case of a standard fire curve situation, but also for other time-temperature relationships. When reduction in strength and deformation properties at elevated temperatures is taken into account, the results of capacity calculations are on the safe side if compared with experimental data.

7. Conclusions

1. The analysis of experimental data and calculation results of axially compressed timber members show that some additional factors can be significant and the influence of these factors must be investigated more thoroughly:
   - uneven temperature redistribution in furnace;
   - local flame effect;
   - additional eccentricity induced by a higher charring layer in the bottom zone of the member and timber exposed to reduction in higher temperature strength.
2. Mean experimental fire resistance of a timber member with a cross-section of 50×50 mm is equal to 15 min for the acting external force of 6 kN and 14 min for the external force of 7.5 kN. A relatively small increase in external force does not expose to a big influence on fire resistance.
3. Design fire resistance of a 50×50 mm cross-section member calculated applying the method of the reduced cross-section with the mean timber strength of specimens is 9.1 min for the external compressing force of 6 kN and 8.2 min for the external compressive force of 7.5 kN.
4. The influence of a horizontal position of specimens in the furnace during the experiment has not been accepted because of a small weight of test specimens.
5. A typical collapse mode of the members having one heated side was identified. Buckling a member appears in the direction of the heated side of specimens.

6. Measuring the residual section dimensions of the heated members shows the loss of a section depending on drying and charring.

7. The analysis of experimental data and calculation results shows that the rules established by Eurocode 5 Part 1–2 (LST EN 1995-1-2:2005) can be applied not only in case of a standard fire curve situation, but also for other time-temperature relationships (König 2005).

8. If a residual cross-section of a member affected by fire is known, it is possible to precisely calculate the reserve of the bearing capacity of such member using Eurocode 5 (LST EN 1995-1-1:2005) expressions for members under combined bending and compression, which is important for planning building rehabilitation and cleaning measures.

9. When small members of a cross-section, not covered by Eurocode 5 Part 1–2 (LST EN 1995-1-2:2005) are calculated, to figure out bearing capacity, it is reasonable to determine temperature distribution in the cross-section according to the Annex B of this code using weighted reduction factors for timber mechanical properties. If only axial force is acting, calculations can be done as for a simple axially loaded member.

10. Investigations reveal the weakness of FEM software in case of complex stress and deformation analysis of timber members at normal and elevated temperatures.

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MEDINIŲ CENTRIŠKAI GNIUŽDOMŲ ELEMENTŲ, NETOLYGIAI VEIKIAMŲ UGNIES LAIKOMOSIOS GALIOS, SKAIČIAVIMAS

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Santrauka

Atliekant šį tyrimą išnagrinėti netolygiai gaisro veikiamų neapsaugotų liaunų medinių centriškai gniuždomų elementų laikomosios galios skaičiavimo ypatumai, taikant paprastuosius skaičiavimo metodus, pateiktus LST EN 1995-1-2, ir naudojant baigtinių elementų programa nustatytus elemento skerspjūvio temperatūrinius laukus medienos stiprių pokyčiams įvertinti. Skaičiavimo duomenys grindžiami atliktais eksperimentiniais liaunų medinių centriškai gniuždomų strypų atsparumo ugniai tyrimo duomenimis ir rezultatais. Medienos stiprių pokyčiai, naudojami skaičiuojant, paimti remiantis Lietuvoje augančios pušies medienos stiprių pokyčių bandymo rezultatais.

Reikšminiai žodžiai: mediena, gniuždymas, gaisro poveikis, laikomoji galia, stiprių pokyčiai.

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